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DOE HANDBOOK

OPTIMIZING RADIATION PROTECTION OF THE PUBLIC AND THE ENVIRONMENT FOR USE WITH DOE O 458.1, ALARA REQUIREMENTS

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AREA ENVR

PREFACE

This Handbook provides information to assist Department of Energy (DOE) program and field offices in understanding what is necessary and acceptable for implementing the As Low As Reasonably Achievable (ALARA) provisions of DOE Order (O) 458.1, *Radiation Protection of the Public and the Environment*. It identifies the goals, requirements and issues that need to be addressed when developing ALARA analyses for optimization of various programs to support DOE's diverse missions. Various case studies and examples are also provided to further assist in implementing the ALARA process.

DOE's ALARA process helps ensure that optimization techniques will be integrated into the design and analyses of programmatic options necessary for the protection of the public and the environment in accordance with the requirements of DOE O 458.1. As much as possible, DOE sites should consider using existing processes, programs or documentation for addressing the provisions of DOE O 458.1 in the development and implementation of the ALARA requirements.

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Chapter 1. **INTRODUCTION**

For several decades, the position of the radiological protection community has been to keep exposures as low as reasonably achievable (ALARA). The International Commission on Radiological Protection (ICRP), following a review of past recommendations, reaffirmed this position in Publication 60 (1991) which recommended that the system of radiological protection for proposed and continuing practices be based on the following general principles:

1. **Justification:** No practice involving exposures to radiation should be adopted unless it produces sufficient benefit to the exposed individuals or to society to offset the radiation detriment it causes.
2. **Optimization:** The magnitude of individual doses, the number of people exposed, and the likelihood of incurring exposures where these are not certain to be received should be kept as low as reasonably achievable, economic and social factors being taken into account.
3. **Dose limits:** The exposure of individuals resulting from all relevant practices should be subject to dose limits such that no individual is exposed to radiation risks that are judged to be unacceptable from these practices in any normal circumstance.

The National Council on Radiation Protection and Measurements (NCRP) made similar recommendations (NCRP 1987, 1993). The ICRP general principles of radiological protection for proposed and continuing practices have been adopted almost universally and DOE has implemented the recommendations through Orders such as DOE O 458.1, and regulations, such as 10 Code of Federal Regulations (CFR) Part 835, *Occupational Radiation Protection*. This Handbook focuses on the ALARA requirements in DOE O 458.1 to implement a process that ensures all exposures are kept as low as reasonably achievable.

Since Department of Energy (DOE) programs and activities are established by Federal policy makers, and, for the most part, the justification part of the system is addressed through these policy decisions, this Handbook will not address *Justification*. Exposures of individuals will be managed in a manner that will ensure compliance with the **dose limits** for the individuals, regardless of the associated cost. For radiation protection purposes, *Optimization* considers the collective dose to the exposed population from radiation sources to be proportional to the number of radiation-induced health effects, and evaluates the cost or detriment of measures that would reduce the dose below applicable dose limits or dose constraints. Optimization provides a basis for judging the reasonableness of the selection of a particular radiological protection system after considering several alternatives. This Handbook strives to be consistent with the ICRP and NCRP recommendations and to supplement other Federal regulations with that same intent.

> It should be stressed that optimization is not minimization. Optimization is the result of an evaluation that carefully balances the benefits from exposure reduction (e.g., health, regulator and public goodwill, etc.) with the costs (e.g. economic, schedule, social, etc.). Thus, the best option is not necessarily the one with the lowest dose.

The importance of the ALARA concept was further stressed in DOE P 450.4A, *Integrated Safety Management Policy* (DOE, 2011), which states:

> *It is the Department's policy that work be conducted safely and efficiently and in a manner that ensures protection of workers, the public, and the environment. To achieve this Policy, effective safety requirements and goals are established; applicable national and international consensus standards are adopted; and where necessary to address unique conditions, additional standards are developed and effectively implemented. Implementing Integrated Safety Management requirements for Federal organizations are established through directives, and for contractor organizations through contract clauses.*
>
> *The Department's ultimate goal is zero accidents, work-related injuries and illnesses, regulatory violations, and reportable environmental releases. The Department expects that for all activities and phases in the lifecycle of missions (design, construction, research and development, operations, and decommissioning and decontamination), appropriate mechanisms are in place to ensure that exposures to workers, the public, and the environment to radiological and nonradiological hazards are maintained below regulatory limits. Furthermore, DOE expects that deliberate efforts are taken to keep exposures to radiation as low as reasonably achievable.*

The goals of this Handbook are:

- To provide additional information on the ALARA requirements in DOE O 458.1;
- To elaborate on the necessary elements of an ALARA process;
- To assist DOE program and field offices in understanding what is necessary and acceptable for implementing the ALARA process for DOE activities that are conducted under DOE O 458.1; and
- To aid decision makers by identifying acceptable approaches and methods for identifying and selecting the optimum radiation protection alternative from among several candidate radiation protection alternatives.

Chapter 3 addresses the DOE ALARA requirements. Chapters 4 - 6 provide information on the various levels of ALARA analysis, assumptions and other factors related to the ALARA process. Chapters 7 - 10 provide information and case studies specific to qualitative, semi-quantitative and quantitative ALARA analyses, respectively. Chapter 10 and the appendices provide additional examples of historical ALARA analyses conducted throughout the Department to further help implement the ALARA process.

Chapter 2. **PURPOSE AND APPLICABILITY**

This Handbook addresses the development and use of a process to keep radiation exposures of the public and environment, and releases of radioactive material to the environment from DOE activities as low as reasonably achievable (ALARA), that is; an ALARA process to implement and comply with DOE O 458.1, *Radiation Protection of the Public and the Environment*.

10 CFR Part 835, *Occupational Radiation Protection,* prescribes regulations for occupational dose to general employees from exposure to ionizing radiation from DOE activities. 10 CFR Part 835 also includes dose limits for members of the public in a controlled area. ALARA requirements for general employees as well as definitions of the terms “general employee,” “occupational dose,” and “controlled area” are addressed in 10 CFR Part 835, and discussed in associated 10 CFR Part 835 guidance.

The word “must” as used in this Handbook designates requirements from DOE O 458.1. The words “should” and “may” are used to denote optional program recommendations and allowable alternatives, respectively.

To achieve an adequate level of radiation protection, the degree of control, treatment, processing, remedial action, or other method limiting doses to workers and members of the general public should be determined by implementing a process that identifies and considers all factors important to decision-making. ALARA, as applied by DOE, is not a level or limit to be achieved in controlling radiation exposures or doses, but rather a process used to ensure that appropriate factors are considered in making decisions that could affect protection against radiation.

KEY TERMS

ALARA means “As Low As is Reasonably Achievable,” which is an approach to radiation protection to manage and control releases of radioactive material to the environment, and exposure to the work force and to members of the public so that the levels are as low as reasonable, taking into account societal, environmental, technical, economic, and public policy considerations. As used in DOE O 458.1, ALARA is not a specific release or dose limit but a process that has the goal of optimizing control and management of release of radioactive material to the environment and doses so that they are as far below the applicable limits of the Order as reasonably achievable. ALARA optimizes radiation protection.

ALARA Process means a graded process for evaluating alternative operations, processes, and other measures, for optimizing releases of radioactive material to the environment, and exposure to the work force and to members of the public taking into account societal, environmental, technical, economic, and public policy considerations to make a decision concerning the optimum level of public health and environmental protection. A graded approach provides the flexibility to perform qualitative or quantitative ALARA analyses. For low doses, qualitative evaluations normally will suffice.

An **ALARA Program** refers to the set of design specifications, operating procedures, techniques, monitoring and surveillance programs, records, instructions and other elements that have been used to implement the ALARA process.

Doses to the public from effluents, emissions, and residual radioactive material must be maintained as low as reasonably achievable below the primary dose limits. Under DOE O 458.1 a documented ALARA process must be implemented to optimize control and management of radiological activities so that doses to members of the public (both individual and collective) and releases to the environment are kept as low as reasonably achievable. The ALARA process must be applied to DOE activities and the design or modification of facilities that expose the public or the environment, no matter how small the dose. In all cases, the scope and detail of the ALARA analysis should be commensurate with the potential benefit of the dose reduction.

DOE O 458.1 requires that the ALARA process use a graded approach (e.g. a graded level of control and oversight) to ensure that doses to the public are low and any decisions made as a result of the process be both beneficial and cost-effective. DOE has defined the graded approach for nuclear safety management (10 CFR Part 830.3) as the process of ensuring that the level of analysis, documentation, and actions used to comply with a requirement are commensurate with:

- The relative importance to safety, safeguards, and security;
- The magnitude of any hazard involved;
- The life cycle stage of a facility;
- The programmatic mission and characteristics of a facility;
- The relative importance of radiological and non-radiological hazards; and
- Any other relevant factor.

This graded approach and these criteria generally are applicable to this Handbook, although other factors may modify how they are used. For example, a highly contentious issue may result in public concern and public policy becoming more consequential factors in the ALARA process.

This Handbook describes a graded approach for applying the ALARA process. ALARA is a self-limiting system and thus the level of analysis should be commensurate with the estimated collective dose to the exposed population; higher estimated collective doses require more rigor in the analysis. In this sense, the cost of the analysis itself should be justified. For instance, DOE recommends the monetary value of a unit of collective dose be between $1,000 and $6,000 per person-rem (see Chapter 9). For an action that might cause a collective dose at the end of the qualitative range in Figure 2-1 (e.g. 10 person-rem/yr) to be reduced to zero (0 person-rem/yr), the averted dose value would be $60,000. In many cases, the cost of a quantitative ALARA analysis (e.g. Cost-Benefit Analysis) alone may significantly exceed this value.

It is difficult to be prescriptive in setting guidelines for the level of ALARA analysis because many factors – both technical and societal in nature – can influence such an evaluation. A detailed quantitative ALARA analysis may only be necessary for major actions. DOE has therefore opted to provide flexibility in selecting the level of analysis. “Reference” dose levels have been established to help determine the level of effort required for an ALARA analysis, as illustrated in Figure 2-1. In general, if the dose to the maximally exposed individual (MEI), or the representative person of the critical group, is much less than 1 mrem (0.01 mSv) in a year and the collective dose to the exposed population is less than 10 person-rem in a year, only a qualitative[1] ALARA analysis is warranted. When doses are near the reference levels, it may be necessary to evaluate the alternatives semi-quantitatively[2]. However, if individual doses are significant compared to the primary dose limit, e.g., tens of millirem in a year, or the collective dose exceeds 100 person-rem in a year, a quantitative ALARA analysis is recommended. Section 4.2 provides more detail on determining the level of ALARA analysis.

ALARA applications to radiation protection may be reflected in decision-making among various options or alternatives such as design of a process system, performance criteria for the features or components of the system, selection of operating modes or other parameters, and other facility-specific or programmatic decisions that can affect the exposure of members of the public to radiation. The optimal decision may be reached through an ALARA process. The ALARA process should be applied to the control of routine doses and effluents, including those resulting from minor operational occurrences and anticipated off-normal operation. Although the ALARA process may be applied to accident-mitigating design features, that application is beyond the scope of this Handbook. While this Handbook includes some discussion of ALARA considerations for general employees, the 10 CFR Part 835 ALARA provisions must be incorporated into occupational ALARA considerations. Implementation of this Handbook does not constitute compliance with the ALARA requirements from 10 CFR Part 835.

[1] A *qualitative* ALARA analysis is done by describing alternatives and comparing the costs and benefits without estimating their monetary or numerical values. A simple "pros and cons" analysis is an example of a qualitative type of analysis and is described further in Chapter 8 and in the *Guidebook to Decision-Making Methods* (Baker et al., 2001).

[2] A *semi-quantitative* ALARA analysis develops alternative descriptions and estimates of the costs and benefits which can be enumerated readily, but may lack a comprehensive numerical comparison employing all factors. Although numerical criteria (some subjectively assigned) may be used to help rank alternatives in the decision process. Examples of semi-quantitative analyses are presented in Chapter 9.

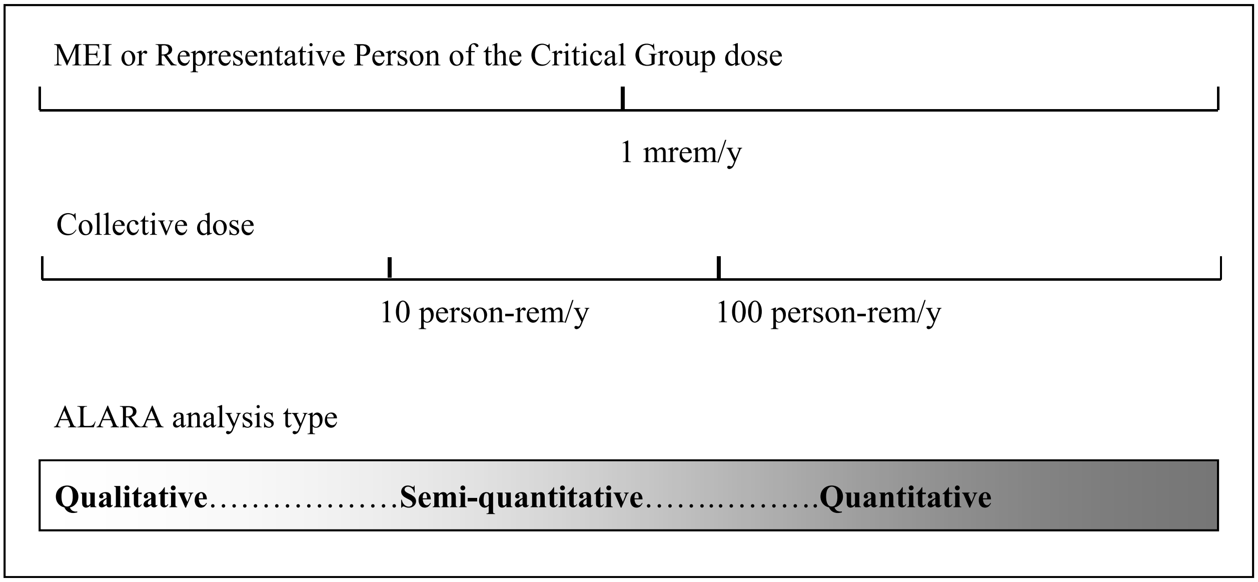

FIGURE 2-1. General Guidance for Determining the Level of ALARA Analysis Required

This Handbook:

- Identifies a number of factors that should be considered in an ALARA analysis;
- Presents a logical sequence for reviewing the factors important to decision-making; and
- References techniques that may be used to quantify some of the factors.

This Handbook also recognizes the difficulties in performing quantitative evaluations of alternative options using tools, such as cost-benefit analyses, and acknowledges that decisions inevitably involve technical and managerial judgment, regardless of the approach used. This Handbook goes beyond traditional quantitative ALARA tools such as cost-benefit analysis and optimization, recognizing the utility and efficiency of allowing different levels of detail in the ALARA process and further recognizing that other decision-making tools such as multi-attribute utility analysis may also be useful, particularly where non-quantifiable factors or attributes are concerned.

Due to the complex nature of many DOE activities, a combination of radiological and non-radiological hazards may be encountered. DOE O 458.1 and this Handbook apply only to radiation exposures of the public and releases of radioactive material to the environment. However, identification of non-radiological hazards is critical to the ALARA process, because efforts to apply the ALARA process may inadvertently increase risks from non-radiological hazards. An integrated safety management approach that optimizes protection of the public and environment from all potential hazards should be considered in the ALARA process for a given DOE activity.

> It is necessary to comply with the appropriate (individual) dose limit to any member of the public, whatever the cost. However, it is the collective dose that is used in the ALARA analysis to select a radiation protection alternative.

Chapter 3. **ALARA REQUIREMENTS IN DOE DIRECTIVES**

The principal ALARA requirements for DOE actions in protecting the public and environment are contained in DOE O 458.1, paragraph 4.d [paragraph 2.d of the Contractor Requirements Document (CRD)]. However, specific references to the application of ALARA process appear throughout DOE O 458.1, including sections on the public dose limit, temporary dose limits, airborne radioactive effluents, liquid discharges, management, storage and disposal of radioactive waste, protection of drinking water and ground water, and release and clearance of property. Related directives such as DOE O 435.1, *Radioactive Waste Management*, also contain ALARA requirements. Application of ALARA is a broad, integral part of the overall implementation of DOE public, environmental and worker protection programs, and is not a limited or niche application.

3.1 ALARA Process

In accordance with DOE O 458.1, a documented ALARA process must be implemented to control and manage releases of radioactive material to the environment and exposures of members of the public to radiation at levels as low as reasonably achievable.

> The ALARA process is an integral part of an environmental radiation protection program and should be reviewed and approved either separately or as part of other environmental protection documents such as those associated with the implementation of an Environmental Management System (EMS). The description of the ALARA process should be contained in, or summarized and referenced in, the DOE-approved plans, procedures or other documentation. The degree of formality and the level of detail contained in these documents should be commensurate with the magnitude of the radiological hazard associated with the DOE activity.

Likewise, the method for implementing the ALARA process is highly dependent on the complexity of the activity and should be commensurate with the potential radiological hazard associated with the DOE activity. For example, activities that use encapsulated radiation sources where there is essentially no likelihood of releasing source material with no potential for public or environmental exposures would only require addressing possible contamination from ruptured sources and potential external exposure. In contrast, if the activity included recovering the source material from ruptured capsules and re-encapsulation, the potential environmental exposure pathways for inhalation and ingestion would also be required in the ALARA process.

An ALARA process should be reviewed by the DOE contractor or operating organization as necessary to maintain a current and effective program, but at least every three years, to identify:

- Changes that have occurred in the facility, operations, or activities that could alter the relative importance of the releases or exposures;
- Alternatives to operations or activities that were not considered previously;
- Operational information on the performance of the selected equipment or process that could alter the decision on choice among alternatives; and
- Changes in administration of the program, such as changes in mission or contractor.

Internal assessments or audits should be conducted to evaluate the effectiveness of the ALARA process and to ensure improvements are implemented to strengthen it, if justified. This is consistent with the approach in DOE G 441.1-1C, *Radiation Protection Programs Guide for Use with Title 10, Code of Federal Regulations, Part 835, Occupational Radiation Protection* (2011).

The basis for ALARA decisions should be made available to the public. DOE encourages public participation in the process as well as coordination with appropriate external regulators that may be involved in related activities. This can be accomplished through existing site advisory groups, the National Environmental Policy Act (NEPA) process, or other public involvement programs that currently are being implemented in support of DOE actions. It is important to assure that the public understands DOE's ongoing environmental protection activities.

3.1.1 ALARA Commitment

Management commitment to ALARA is a critical element in ensuring a successful ALARA program. DOE management retains the primary responsibility and accountability for the scope and implementation of ALARA. This commitment should take the form of a formal, written policy statement from a high-level manager responsible for DOE radiological activities committing to establish and to implement the ALARA process for activities that are sources of exposures to ionizing radiation. This commitment should hold all levels of management and personnel responsible for adhering to ALARA policy.

All site personnel should know management's commitment to ALARA and appropriate personnel should be instructed on their ALARA responsibilities. Line management should demonstrate support for the ALARA program through direct communication, training, inspection of the workplace, and actions including:

- Management decisions that incorporate ALARA considerations along with cost or schedule considerations;
- Encouragement of, and praise for, employees who identify ALARA opportunities;
- Support of the ALARA Committee; and
- Publication of ALARA success stories.

Also, it is essential that the public is aware of an organization's commitment to ALARA. For example, the policy statement could be part of the public record.

Management commitment is essential to implementing a successful ALARA process.

3.1.2 Implementing ALARA

A description of how the ALARA process will be implemented, including appropriate involvement of interested parties, should identify:

- The designated organizational responsibility, authority, and structure for implementing ALARA;
- The systematic evaluation of the activities at the site to identify those activities that are responsible for the release of radioactive material and the exposures of the public and workers; and
- A procedure to analyze the operations or activities to determine whether they are being performed in a manner that will ensure that the radiological impacts are ALARA.

3.1.3 Documenting ALARA Decisions

DOE O 458.1 requires that a documented ALARA process be implemented however, as ALARA is a graded approach whose rigor and detail should be commensurate with potential benefit, documentation of the process can also be graded. In cases where no options exist to further reduce dose or dose reduction for all options are very small, minimal documentation (e.g. memorandum to file) may be adequate. Factors that should be considered and documented for any ALARA decision-making process are specified in Section 3.2.

Records requirements are contained in DOE O 458.1, paragraph 4.l (paragraph 2.l of the CRD) and include:

- Documentation of individual and collective dose to members of the public due to radiological activities. This includes documentation of site-specific information on radiation source dispersion patterns, location and demography of members of the public in the vicinity of the radiological activity and assumed default values or site-specific parameters used in calculations.
- Documentation of actions taken to implement the ALARA process identified in the Order (CRD). Examples include records of cost-benefit or other analyses, and other factors considered important to the ALARA decision-making process.
- Documentation of actions taken to implement the best available technology (BAT) selection process in regulating liquid discharges, including documentation of the analyses and factors considered to be important, including alternative processes.

ALARA evaluations and other activities and information considered in the selection of the alternative radiological protection option judged to be ALARA and in the rationale leading to the selection should be documented, to include referencing data utilized as part of NEPA or CERCLA requirements. Procedures should be established and implemented to assure that ALARA records are kept current, complete, and readily available for use. The records should be organized in such a way that appropriate sections can be located easily to demonstrate compliance with the ALARA requirements. The records should facilitate coordination and cooperation with other organizations in sharing information on analyses, performance of equipment, costs, operations, maintenance, identity, and evaluations of alternatives.

3.1.4 ALARA Training

Personnel who plan, prepare, schedule, estimate, or engineer jobs that have the potential for radiological consequences should receive appropriate training to be knowledgeable of the ALARA process. The purpose of providing training in ALARA concepts and techniques is to ensure that personnel have the necessary knowledge and skills to conduct the needed analyses and evaluations. ALARA training should provide the basics of ALARA concepts and the use of ALARA-related equipment such as containment devices, shielding, ventilation, and special tools. Topics such as radiological waste minimization, application of decontamination efforts, and basic contingency planning for mitigation of accidental spills or releases may also be appropriate. The size, frequency, and content of the ALARA training should be commensurate with the size, complexity, and hazard potential of the DOE activity (i.e., a graded approach should be applied).

Application of the ALARA process includes evaluations of:

- Exposures and doses to individuals and populations;
- Dispersions of radioactive material in the environment;
- Cost-benefit and other economic evaluations;
- Engineering evaluations of equipment performance and source determinations; and
- Applications of other disciplines.

As appropriate, such training may be integrated with other activities including ALARA-related training for 10 CFR Part 835 or DOE O 435.1. DOE has developed specialized training material in DOE HDBK 1110-2008, *ALARA Training for Technical Support Personnel* (DOE 2008b).

3.2 Factors to consider during the ALARA Process

The ALARA process evaluates and documents the societal, environmental, technological, economic, and public policy factors considered in decisions where public exposures to radiation can occur from DOE activities. At a minimum, the following factors should be considered and documented as part of the ALARA process:

- The maximum dose to an individual member of the public [termed MEI or representative person of the critical group];
- The collective dose to the exposed population;
- Doses to workers;
- Applicable alternative processes such as alternative treatments of discharge streams, operating methods, or controls;
- Doses for each alternative evaluated;
- Cost for each alternative evaluated;
- An examination of the changes in cost among alternatives; and
- Societal and environmental (positive and negative) impacts associated with alternatives.

These factors should be addressed whether the assessment is qualitative, semi-quantitative, or quantitative. If a specific factor(s) was not included in the evaluation, this should be noted and the justification documented.

No single best procedure exists for implementing the ALARA process for all DOE activities. This choice depends on the characteristics of the activity, the site, and the potential doses involved.

3.3 Compliance

DOE requires application of the ALARA process in most activities addressed in DOE O 458.1. The exception is an activity regulated by a rule containing dose or other limits based on an ALARA determination. In that case, simply complying with the dose limit constitutes ALARA. Applicable requirements are specified in DOE Orders and rules as well as those of other Federal, State, and local agencies. Requirements do not originate in guidance documents.

Demonstration of compliance with the ALARA requirements may be provided by:

- A documented current description of the site ALARA process, reviewed and approved by the appropriate DOE Program or Field Office and a statement of commitment to implement the ALARA process;
- A documented ALARA process describing procedures by which the individual ALARA evaluations and judgments will be made and the documentation of the procedures;
- A description of the training program provided to ensure staff capabilities to perform ALARA evaluations; and
- Records of all formal ALARA evaluations and decisions, including the rationale for the ALARA judgments, indicating that the ALARA process is being implemented. The records should demonstrate that sufficient information was assembled and considered to support the ALARA decisions.

An ALARA process should identify general areas to be considered in making ALARA decisions: societal, technological, economic, and public policy considerations.

> Whether the ALARA analyses are qualitative, semi-quantitative, or quantitative, it is essential to document the analyses and decision.

Chapter 4. **ALARA PROCESS ANALYSIS**

This Chapter provides additional information related to the implementation of the ALARA process and the analysis methods that may be used.

> The goal of the ALARA process is to identify, from among candidate radiation protection alternatives, the alternative that would result in the maximum total benefit, considering the protective measures and their costs. Assumptions and parameters used in the ALARA evaluation should be realistic instead of overly conservative. Overly conservative choices of parameters may bias the ALARA analysis and could result in unjustified control expenditures or, in some cases, increased risk or detriment.

The ALARA process is a management and decision-making tool designed to maximize the total benefits of the radiation protection provisions of a DOE activity that is likely to expose members of the public to ionizing radiation. The optimal radiation protection alternative can be selected from among several candidates by considering the radiation protection benefits, and, as appropriate, other benefits and detriments, along with the cost of implementing these protective measures. No single best method exists for implementing the ALARA process at all DOE activities. This choice depends on the characteristics of the activity or operation, the site, and the potential doses involved. Use of site-specific and activity- or operation-specific factors is encouraged for all ALARA analyses.

4.1 Implementation

The basic question to be answered in the implementation of the ALARA process is "*Has everything that* ***reasonably*** *can be completed to reduce the radiation doses been done?*" Although the primary goal of ALARA is radiation dose reduction, hazardous non-radioactive materials also might be components of the waste stream effluent or could be introduced by some of the optional treatments used to reduce the radiological components. Therefore, risks associated with these materials should also be factored into the ALARA process and ALARA determinations. It is important to remain informed about the overall impacts and detriments of any alternatives or decision. The release of hazardous chemicals could be treated as a "β-factor" in a cost-benefit analysis or a non-radiological factor in a multi-attribute analysis (see Section 10.1.7). Other factors such as impacts or risks to natural or cultural resources can be addressed similarly.

There are a number of methods that can be applied to gather data for the ALARA process, ranging from quantified cost-benefit analysis to multi-attribute analysis with weighting and scaling factors that can be used in both quantitative and semi-quantitative analyses. Some may be rudimentary and based upon a fundamental understanding and commitment to the ALARA principle, "common sense," or "sound judgment," rather than on formal quantitative techniques – and that may be all that is necessary or justified. Activities that involve low doses are more likely to be based on judgmental decisions. In cases where dose increments are very low compared to the dose limits, the social and public policy considerations often will be the dominant factors in arriving at the ALARA decision.

DOE's application of Best Available Technology (BAT) under DOE O 458.1 may also be seen as a form of ALARA. However, it is important to distinguish that BAT focuses on reduction of concentration or quantity of contaminants rather than dose and may lead to controls being required for releases that have no receptor and hence no dose. From a cost-benefit perspective, it may require treatment that goes beyond ALARA.

The principal difference between the ALARA process and the BAT selection is that the ALARA process balances the cost and dose reduction and attempts to identify the optimal of several alternatives, whereas the BAT selection places more importance on the source term (rather than doses). As utilized in DOE O 458.1, BAT is a regulatory process applicable only to liquid effluents, but ALARA applies to all sources of radiation exposure.

Site-specific societal values can be incorporated into the analysis through public input. Public input could be used:

- To define values for use in the ALARA balancing decision;
- For a comparative ranking of risks; and
- To provide input regarding the adequacy of the data and decision processes.

An example of incorporating societal values is the use of different food chain radiation exposure pathway models for estimating potential radiation doses to Native Americans and for ecological receptors.

Table 4-1 presents a sequence of steps that could be followed in an ALARA (or BAT) evaluation. A sensitivity analysis is worthwhile in both types of evaluations because it can provide information on the robustness of the results. A sensitivity analysis also can identify information that is important to obtain as part of the monitoring and surveillance program.

ALARA should be a flexible process, and the evaluation efforts should be proportional to the potential benefits. The boundaries between each of the steps in Table 4-1 may not always be clear-cut; some may proceed in parallel or may need to be repeated. The overall impact of the alternatives under consideration might also control the detail and level of effort assigned to individual steps. For example, if the difference in doses and costs associated with the various options is small, the cost of a detailed ALARA review may not be warranted. Similarly, if the difference in dose increments is large and the cost difference is small, or vice-versa, the choice of options could be straightforward and very detailed analyses may not be justified. However, when costs, doses, and other impacts vary significantly among options, more detailed analyses are needed.

TABLE 4-1. Implementing the ALARA Process

<u>Step 1</u>: Define the Objective and Scope of the Issue to be Analyzed. State the objectives of the project or proposal in terms that do not prejudge the means by which the objective is to be achieved. Specify the radiation protection factors to be included and other factors to be considered.
<u>Step 2</u>: Identify Radiation Protection Options. Generate several options for achieving the objective: the aim is to find options that are both practicable and environmentally acceptable. This step provides a strong incentive to consider not only obvious solutions, but also innovative alternatives. It also includes the elimination of impractical options.
<u>Step 3</u>: Evaluate the Performance of the Radiation Control Options. Analyze these options to identify the advantages and disadvantages of each option. Use quantitative and qualitative methods when appropriate. Cost (for a cost-benefit analysis) each of the options for operation, maintenance, utilities, structures, equipment, labor, and collective dose. Incorporate judgment criteria explicitly. Identify other (non-radiological) impacts and other considerations. Evaluate the impact and cost of compliance with non-radiological requirements.
<u>Step 4</u>: Screen Options. Present the results of the quantitative (or semi-quantitative) analysis of factors concisely and objectively and in a format that can highlight the advantages and disadvantages of each option. Do not combine the results of different measurements and forecasts if this would obscure information that is important to decision-making.
<u>Step 5</u>: Order and Analyze. Include consideration of all relevant factors whether treated quantitatively, semi-quantitatively, or qualitatively, together with judgment or relative weighing and the results of sensitivity analyses to select the recommended radiological optimum.
<u>Step 6</u>: Identify Optimal Alternative. Select the optimal option from the feasible options. The choice will depend upon the adequacy of the radiation protection, the weight given to the environmental impacts, the associated risks and the costs involved, and the importance of non-radiological factors.
<u>Step 7</u>: Perform Sensitivity Analysis. The robustness of the decision to choose a particular alternative can be determined by varying the more important parameters and observing how the "bottom line" results are affected. If a particular parameter is seen to be capable of substantially affecting the results, the site-specific information should be scrutinized to ensure that the value of the parameter used in the study is representative for the site.
<u>Step 8</u>: Decision. Take into account the results of optimization and any non-radiological factors and make the decision. Scrutinize closely the proposed detailed design or operating procedures to ensure that no pollution or hazards have been overlooked. It is good practice to have the scrutiny done by individuals who are independent of the original team. Decision makers should be able to demonstrate that the preferred option does not involve unacceptable consequences to the environment.
<u>Step 9</u>: Implement and Monitor. Monitor the achieved performance against the desired targets, especially those for environmental quality. Do this to establish whether the assumptions in the design are correct and to provide feedback for future development of proposals and designs. The results of the sensitivity study can provide valuable input to planning a monitoring program for the activity.
Throughout <u>Steps 1 through 9</u>: Record the bases for any choices or decisions through all of these stages: the assumptions used, the details of evaluation procedures, the reliability and origins of the data, the affiliation of those involved in the analytical work and a record of those making the decision. Record, if possible, the reasons for any departure from the recommended optimal candidate.

Under DOE O 458.1 the ALARA process must be applied to the design or modification of facilities and conduct of activities that expose the public or the environment to radiation or radioactive material. (It should be recognized that when a new facility is being considered, the ALARA evaluation process needs to be used in those cases when the selection of processes, design of the facility, and setting operating parameters and procedures needs to be consistent with10 CFR Part 835). Early consideration of alternatives allows maximum flexibility in the choice of design options. When a new DOE activity is being designed, the initial source term should be characterized and a "base case" alternative or system established. The condition that the base case needs to satisfy is that the radiation dose to the most exposed persons (workers or members of the public) must be within the appropriate dose limit. This base case system subsequently will be used as a basis for comparison of the cost- effectiveness of more sophisticated and more expensive alternative systems. The base case or some of the alternative cases may or may not be practical design candidates because of possible environmental or other impacts that may be judged to be undesirable or unacceptable, but these considerations would be evaluated at a later point in the decision-making.

When the ALARA application is for an established, ongoing activity or facility (i.e., retrofitting), the practical alternatives are likely to be more limited. Retrofitting is considerably more costly (frequently by a factor of 2 to 3, or more) than the cost of the original design features, and the alternatives generally are limited to practical modifications of existing facility structures or operational procedures. In such cases, the "no action" case (i.e., the status quo) may be used as the base case. In some situations the no action case may result in potential doses that exceed dose limits (e.g., a cleanup site), and as a result, may not be a viable alternative in the long term. However, it is helpful as a basis for comparison with other alternatives to assess risks and benefits and provide a perspective on the cost of various dose reductions.

> The ALARA process can be most effective when applied in the design of new facilities that have potential to expose workers and members of the general public to radiation or radioactive material.

4.2 Determining the Level of ALARA Analysis

As a management tool, the resources expended to implement the ALARA process should be proportional to the potential benefits to the decision process. Although some level of evaluation is required for all actions that may affect doses to the public and environment, that level may vary from a "Memorandum to File" when the choice is obvious, to a very complex cost/benefit or multi-criteria decision analysis when there are multiple options with varied impacts. To assist in determining the necessary complexity of the analysis, DOE recommends "reference" dose levels to the MEI (or representative person of the critical group) and to the exposed population to assist in determining the level of detail needed in an ALARA analysis (See Figure 2-1).

This Handbook provides the flexibility to perform qualitative, semi-quantitative, or quantitative ALARA analyses, depending on the dose expected to be received by the MEI (or representative person of the critical group) or the exposed population, and other influencing factors. The level of effort expended to estimate the initial dose level and to determine the level of ALARA analysis should be appropriate to the level of the activity. Professional judgment should be applied, and it should be considered an iterative process if the initial estimate seems too high or too low. In many cases, reasonable estimates of the radionuclide source term, site-specific meteorology, and dose screening factors should provide a reasonable dose estimate that allows the level of analysis to be determined.

Resources allocated to the ALARA evaluation process should be commensurate with their potential benefits.

4.2.1 Qualitative Analysis

A qualitative ALARA analysis may be appropriate when the estimated doses are less than the reference dose levels and, in particular, when the collective dose is estimated to be less than 10 person-rem per year and individual doses are less than 1 mrem (0.01 mSv) per year. As for all analyses, several alternatives should be considered. All appropriate attributes or criteria of the alternatives should be identified, described, and compared but without assigning any numerical criteria to them. For example, the radionuclide emission level likely would be an important attribute of candidate airborne emission control systems, and could be described as low, medium or high. The cost of the candidate systems could be described similarly. In situations where there is only one obvious reasonable action, or there are a few alternatives all resulting in insignificant dose differences and one of the alternatives is clearly the favored approach based on one important attribute (e.g., cost, schedule, public acceptance), a simple memorandum explaining the options and the rationale for selecting one of the options may be adequate to satisfy DOE ALARA requirements. In other cases where doses are below the reference levels but there are multiple options with various risks or benefits, it may be appropriate to identify and qualitatively discuss multiple attributes, how each option addressed them, and qualitatively compare the options.

4.2.2 Semi-Quantitative Analysis

A semi-quantitative ALARA analysis may be needed as the estimated doses from the alternative actions begin to approach or exceed the "reference" dose levels. Alternatives with collective doses between 10 and 100 person-rem per year are prime candidates for semi-quantitative analysis. In addition to the estimated dose the level of analysis also depends upon the complexity of the alternatives and the number and types of attributes. Semi-quantitative analysis may be necessary at lower levels if there are several attributes that are difficult to describe and compare qualitatively to show difference among alternatives. Useful tools for semi-quantitative analysis are multi-attribute analyses to rank and score attributes, with the level of analysis complexity following a sliding scale based on the estimated dose level. All significant attributes should be identified, characterized (rather than just described), weighted and scored, then compared and selected. More rigor is required to develop the attributes, their characteristics, and the relationships among attributes (e.g., uncertainty) for high-level multi-attribute analyses. The cost-benefit analyses generally will be partial analyses that are representative of the relative costs of each alternative, or surrogates may be used for dollars. For example, in a cleanup project, volume of material excavated may be assumed proportional to cost for the purpose of comparing alternative standards.

> For semi-quantitative and quantitative analyses, it is important to avoid using very similar attributes to characterize the alternatives. Duplicative attributes result in unwarranted emphasis to a given impact area, manipulating the decision making process and leading to bias. Duplication should also be avoided for qualitative analyses.

4.2.3 Quantitative Analysis

A quantitative ALARA analyses may be justified for estimated doses that are above the "reference" dose levels. For example, if alternative actions produce individual doses that could cause the public dose to exceed or approach the all sources/all pathways dose limit [100 mrem (1 mSv) per year], or an associated source-based dose constraint such as the 25 mrem (0.25 mSv) per year for waste management or property control, or if collective dose exceeds 100 person-rem per year, a quantitative evaluation likely is warranted. However, dose is not the only attribute on which to base a decision to conduct a more rigorous evaluation. If there are several viable, alternative actions and their performance with respect to the various criteria is determined to be important to the decision (e.g., overall environmental performance, worker risk, cost, resource utilization), a quantitative evaluation may be needed. Similarly, if there are a large number of non-health factors to evaluate, it may be more appropriate to perform a quantitative analysis to determine which are more important to the decision. ICRP Publication 55 (ICRP 1989) presents a number of quantitative decision-aiding techniques that can be used such as: cost-effectiveness analysis, cost-benefit analysis, multi-attribute utility analysis, and multi-criteria outranking analysis. The process of quantitatively determining the alternative with the greatest total radiation protection benefit is formally called "optimization," although all of the ALARA approaches discussed above seek the "optimal" radiation protection solution. "Optimization" should be used whenever decisions involve the implementation of a radiation protection practice that would be costly, complex, and/or involve significant dose savings (Munson 1988).

4.3 General Steps in Quantitative ALARA Analysis

Quantitative analyses require the most effort and rigor and are the primary focus of much of this Handbook. Most of the information provided for quantitative analysis can be adapted for use in semi-quantitative and even qualitative analyses.

The major steps in a quantitative ALARA analysis include the following:

- Identify and quantify the sources of radiation;
- Identify and define candidate radiation protection alternatives or systems (including waste stream treatment) that would reduce the exposure or doses;
- Quantify economic factors (cost of systems, operations, maintenance, etc.);
- Quantify exposures and doses to individuals and to populations in the vicinity of the DOE activity;
- Estimate the health risk and identify non-health detriments (or benefits); and
- Select one or more of the candidate radiation protection systems as ALARA.

The above steps are based on a cost-benefit analysis but they are generally applicable to other types of analyses, considering that cost-benefit analyses require benefits and detriments to be quantified in monetary or economic terms. The following subsections expand on these major steps of a quantitative ALARA analysis.

4.3.1 Identify and Quantify the Sources of Radiation

A logical starting point for any ALARA analysis is to identify and characterize all anticipated radiation source terms, that is, sources of ionizing radiation from DOE activities. The source evaluation should quantify all parameters germane to the estimation of potential direct exposures of the workers and members of the public and internal exposures due to inhalation, ingestion, immersion, or absorption of radioactive material released to the environs by the DOE activity.

For operational facilities, the "base case" source term used to compare with all alternative radiation protection systems is that which currently exists or a reasonable representation of the baseline source term. The data obtained from effluent sampling and/or monitoring, and environmental surveillance could be valuable when defining existing source terms from an ongoing activity and can provide exposure pathways and source data as well. The sampling, monitoring and surveillance data also may verify the adequacy of analytical models for dispersion of radioactive material in the environs and exposure pathways used to evaluate exposure conditions and dose estimates. Careful evaluations of facility design and operating conditions and measurements at a variety of locations in and around the facility or activity may reveal radiation sources and release and exposure pathways not previously identified or anticipated. Differentiation may have to be made between releases of radioactive materials as controlled airborne or liquid effluents and releases arising from pre-existing contamination (e.g., re-suspension).

For facilities that are in the design stage, the base case is a radiation protection system that will meet the dose limits for postulated dose to the maximally exposed general employee or member of the general public. Although ALARA may be applied to the prevention of non-routine or accidental releases of radioactive materials, the application of this Handbook and the requirements of DOE O 458.1 are intended to apply to routine releases of radioactive material as airborne effluents and liquid discharges from normal operation.

The ALARA process can also be used to set cleanup levels and authorized limits in the decontamination and decommissioning (D&D) of DOE facilities.

> The ALARA process should indicate how the activities and operation of the facility are analyzed systematically to identify existing and potential radiation sources and pathways for discharges or leakage of radioactive material that can be released to the environment where members of the public could be exposed.

4.3.2 Define Candidate Radiation Protection Systems

When the amount, physical characteristics, and location of the radiation sources are known, process systems can be designed to reduce the exposures of the workers and the public from the sources.

For *new* facilities, or those being designed, source characterization likely would be based on:

- Component performance data supplied by the manufacturer;
- The design engineers;
- Data from other installations that have used similar components; or
- Laboratory tests.

Source characterization also should consider life cycle costs and impacts of new facilities. The future cleanup or D&D costs should be considered as a criterion or attribute in selecting the appropriate environmental radiation protection approach for a new facility.

For *operating* facilities, the source characterization can be based on the results of survey, monitoring, and environmental surveillance data with supplemental studies or measurements, as necessary.

Assuming that the sources of radiation and potential exposures are sufficient to justify the effort, several system design and operating options that would result in a range of release or exposure conditions and costs should be identified for each radiation source. Ideally, the design options would include several process technologies, combinations of process components, and operating conditions ranging from the most rudimentary (base case) to the most technologically sophisticated system. The ALARA process will identify the most favorable of the candidate design and operating options.

The performance of the components of the radiation protection systems for reducing the exposures and associated doses should be estimated for each candidate system and option so that the modified source term, before and after treatment, can be estimated. Engineers, operators, and designers of other nuclear (and non-nuclear) facilities can provide extremely valuable data on alternative systems and components, cost, maintenance, and operating experience, particularly where the characteristics of the streams or processes are similar. Data should include system descriptions, performance and cost characteristics.

> It is essential that several candidate process or radiation protection design options be evaluated so that the ALARA process can identify the best system(s).

4.3.3 Quantify the Economic Factors (Costs)

Two primary components of the cost associated with a radiation protection system are:

- The system cost of purchasing, installing, operating, maintaining the equipment and D&D, and
- The cost of the potential health effects.

In ALARA applications, one is interested in the cost of providing various degrees of radiation protection for persons who are anticipated to be exposed to sources of radiation caused by a DOE activity, and in how these costs change with alternative systems. There also may be other costs associated with alternative systems that should be considered, such as those related to damage (due to implementing an alternative) to a natural or cultural resource, or benefits to the protection of those resources from other alternatives. These factors also may be identified as part of the other "non-health detriments" discussed in Section 4.5.2. These analyses identify the candidate system with the least total (benefit [control] + detriment) cost in a cost-benefit analysis; hence the optimum system. The same types of factors help identify the optimum system in a multi-attribute analysis, but are not quantified in monetary equivalents. It is important to recognize that cost is a metric used to compare alternatives. Alternative metrics may be used in multi-attribute analyses, but the goal is the same – to present the cost and benefits of the alternatives in common terms that can be easily compared.

4.3.4 Quantify Exposures and Doses from DOE Activities

The doses to occupationally-exposed individuals and to the MEI (or representative person of the critical group) from a DOE activity are important because there are specific dose limits established by regulation or directive that must be met if the activity causing the exposures is to be permitted. The appropriate dose limit for an individual worker or member of the general public must be met ***regardless of cost***. DOE also utilizes dose constraints for specific activities. In most cases, the constraints are treated like limits when evaluating options. If the constraint cannot be met, then the alternative is not viable. However, unlike limits, it is possible to consider an alternative that might exceed a constraint when other attributes of the ALARA analysis clearly override the benefit of meeting the constraint, as long as the dose limits are not exceeded. 10 CFR Part 835 regulates doses to workers. ALARA requirements for workers are addressed in that rule and its associated guidance.

Collective dose is used as a surrogate for the potential radiological health impact on the population exposed to the radioactive material. DOE O 458.1, consistent with the ICRP, defines collective dose (S) as the sum of the total effective dose (TED) to all persons in a specified population received in a specified period of time. ICRP 103 recognized that this definition has led people in some cases to use the collective dose incorrectly to calculate radiation-related detriments by summing radiation exposures over a wide range of doses, over very long time periods and over large geographical regions. The following aspects should be considered and critically reviewed in order to assure that the collective dose is correctly calculated and applied as an instrument for optimization:

- The radiation source geometry;
- Quantity, type and energy of radiation emissions;
- Exposure modes and pathways;
- Number of exposed individuals and population distribution;
- Age and sex of exposed persons;
- Range of individual doses;
- Location of the receptor with respect to the source location;
- Duration of exposure and dose distribution in time;
- Quantity of radioactive material released;

- Dispersion by natural forces;
- Lifestyle of the receptors; and
- Other parameters.

There are no specific dose limits in DOE O 458.1 for collective dose from a DOE activity. As will be seen, if the health-detriment or health benefit can be quantified, a cost of the detriment or benefit may be postulated for cost-benefit assessment purposes.

> It is necessary to comply with the appropriate (individual) dose limit to any member of the public, whatever the cost. However, it is the collective dose that is used in the cost-benefit analysis to select a radiation protection system.

4.3.5 Estimate Health and Non-Health Detriments and Benefits

It is important to quantify the detriment (risk) or benefit (risk reduction) because, by doing so, a value can be placed on the amount of resources that may be committed for a radiation protection system to avoid a radiation-induced serious health effect. Again, the terminology of detriment and benefits is used principally in cost-benefit analysis, but the concepts are applicable to other ALARA process evaluations such as multi-attribute utility analyses.

4.3.5.1 Health Detriments

Serious health effects, such as cancer and genetic diseases, can be induced by exposures of humans to ionizing radiation. The effects have been observed only among populations subjected to doses greater than 10 rad delivered at a high dose rate. Whether these health effects occur at lower dose rates or by chronic exposure at low dose rates has not been determined due to the problems attendant to large epidemiological studies and to incomplete knowledge of the mechanisms of radiation-induced cancer causation. For radiation protection purposes, DOE *assumes* that there is proportionality between dose and risk (the probability of radiation-induced health effects) at dose levels encountered in the workplace and in the environment. To estimate radiation-induced health effects from low dose or low dose rate exposures, DOE recommends the use of cancer risk coefficients in the supplemental disk to Federal Guidance Report #13 update supplement, *Cancer Risk Coefficients for Environmental Exposure to Radionuclides*, EPA402-R-99-001, September 1999. However, this methodology requires estimates of radionuclide intake and may be too rigorous for many ALARA assessments. For estimating health effects from TED estimates, DOE recommends a mortality value of 6×10^{-4} fatal cancers/TED (rem) and a morbidity value of 8×10^{-4} cancers/TED (rem) based on use of technical guidance developed by the Interagency Steering Committee on Radiation Standards (DOE, 2003b). There are considerable uncertainties regarding radiation-induced health risks and, in general, DOE recommends ALARA analyses use dose and its monetary equivalents for comparative analysis rather than risk.

The analyses conducted to support the ALARA process should consider all health detriments and benefits associated with the various alternatives evaluated. For example, one alternative control technology might reduce the collective dose (person-rem), by ΔS (detriment averted), but could significantly increase the risk to workers. The technology also might create a hazardous waste that could increase the public risk and present difficult disposal problems. These and similar factors need to be considered in the ALARA assessment. Reasonable measures should be taken to mitigate any additional risks caused by the technology. Due to the complex nature of many DOE activities, a combination of radiological and non-radiological hazards may be encountered. Identification of non-radiological hazards is critical to the ALARA process, because efforts to apply the ALARA process inadvertently may increase risks from non-radiological hazards. An integrated safety management approach that optimizes protection from all hazards should be considered in the ALARA process for a given DOE activity.

4.3.5.2 Non-Health Detriments

Non-health effects also can be experienced from activities that involve actual or potential exposures to radiation. Some of these effects are real and associated with environmental factors, such as temperature, noise, humidity, and other comfort considerations. Cost or other impacts and benefits may be accrued to a population other than the one receiving the exposure. It could include costs for purchasing property or other expenses to avoid litigation or demonstrations from stakeholders. Unlike the health detriment, the non-health detriment is not linearly related to dose, and might not be related to dose levels at all.

Because it is difficult to anticipate the cost of non-health detriments and the cost may not even be related to collective dose, they are difficult to include in a cost-benefit analysis and may need to be compared qualitatively. Multi-attribute analyses are useful analysis tools where non-health attributes may be important contributors to the decision-making and selection process. These techniques are particularly useful for factors that are difficult to quantify in the monetary terms that are required by a cost-benefit analysis. Multi-attribute analyses also are useful when sufficient quantitative information is not available to perform a cost-benefit analysis.

4.3.6 Select a Candidate Radiation Protection Alternative as ALARA

In some cases, adequate information will be available to permit a cost-benefit analysis to quantify elements important in the decision-making process. In other cases, the information might not be available or a quantitative cost-benefit analysis might not be practical to aid in a decision-making process involving ALARA exposures—in such cases, the decision should be based on less quantitative criteria. In these cases, other decision-making tools such as multi-attribute analyses may aid in alternative selection.

In simplest terms, the radiation protection system selected by the ALARA process is the one that results in the maximum total benefit when all significant factors – either benefits or detriments – are considered. The prime factors crucial to ALARA decision-making in a cost-benefit analysis are the cost differential between candidate radiation protection systems and the differential in collective dose. These same attributes are likely the most important ones in a multi-attribute analysis; however, the inclusion of other attributes may change their relative significance.

> In the simplest case, the optimum system is that system with the maximum total benefit. In a cost-benefit analysis this is the system with the lowest total cost – including the monetary cost assigned to the health detriment. In a multi-attribute analysis it is the highest ranked system.

Chapter 5. **EVALUATIONS AND ASSUMPTIONS**

In any type of ALARA process evaluation, there are assumptions that need to be made and commonly-used methods that should be followed. This Chapter addresses some of the areas commonly encountered for an ALARA analysis.

5.1 Cost of Radiation Protection Systems

Cost projections for candidate radiation protection systems (including treatment systems) that alter the radiation source and operating cost may be expressed in terms of annual cost or total cost over the lifetime of the facility. Calculation of total cost for a facility or process typically should include, but not be limited to:

1. The system (capital) cost:
   - Equipment (description and quantity);
   - Labor (installation and operation); and
   - Other material.
2. The annual charge on capital (to the extent that this cost is applicable to Federal agencies).
3. The operation and maintenance (O&M) cost, that is:
   - A selected fraction of total capital cost equipment and piping cost;
   - Expendable material cost;
   - Electrical or other power cost;
   - Processing cost;
   - Collection and disposal cost;
   - Contingency allowance; and
   - Transportation cost.
4. The health detriment (cost for reduction).

It is essential to assess all of the alternatives on an equitable basis. Using conservative estimates for either system cost or detriment cost in one alternative but not in another will bias comparisons and should be avoided. Therefore, it is recommended that best estimates be used in all cases and for all attributes so that comparisons will be equitable.

> Standard engineering costing methods should be used in arriving at cost estimates for the systems.

5.2 Exposures and Doses

Doses to occupationally-exposed individuals (workers) and to the MEI (or representative person of the critical group) are important because there are specific dose limits that must be met, regardless of cost, if the activity causing the exposures is to be permitted. The *primary* dose limit is based on the TED and equivalent doses with few source-specific exceptions. Per DOE O 458.1, the primary dose limit for members of the public from all exposure modes is a TED of 100 mrem (1 mSv) in a year, an equivalent dose to the lens of the eye of 1500 mrem (15 mSv) in a year, or an equivalent dose to the skin or extremities of 5000 mrem (50 mSv) in a year. Dose limits for individuals are generally selected on the basis of: 1) presumed health risk to the individual that is deemed acceptable, 2) feasibility of compliance, or 3) cost-benefit considerations.

Several other individual dose limits that are source-specific or exposure-specific have been promulgated in DOE O 458.1. These include doses from airborne effluents (section 4.f.), liquid discharges (section 4.g.), radioactive waste and spent nuclear fuel (section 4.h.), drinking and ground water (4.i.), and release and clearance of property (4.k.). Thus, there may be multiple dose limits appropriate for an individual depending, in some cases, upon the exposure mode (direct exposure, ingestion, inhalation or absorption), the receptor status (occasionally exposed worker or incidentally exposed member of the public), and the source of the exposure (fuel cycle activity, exposure media such as drinking water, airborne source, etc.).

If a DOE activity is subject to a dose limit that was based on cost-benefit considerations, and if it can be demonstrated that the dose from the activity is within that dose limit, a quantitative ALARA analysis will not be required for the part of the exposure subject to that dose limit. However, it may be worthwhile to perform a simple qualitative or semi-quantitative ALARA analysis to demonstrate that the exposures or resulting doses from that site-specific exposure mode are as low as reasonably achievable.

There are many examples where non-radiological exposure limits have considered costs in their development: EPA permissible concentrations for contaminants in the environment, pesticide residual limits in food and feed stock, mercury limits in fish, EPA and FDA limits on cancer causing agents, maximum contaminant levels for public drinking waters supplies and effluent discharges for carbon based power production, to name a few. There are several examples of radiological based exposure limits included throughout this handbook.

> The maximum dose to individuals must be quantified to verify compliance with appropriate primary and supplemental dose limits.

5.2.1 Exposure Location

The magnitude of potential doses to individuals is dependent, among other things, on location during exposure. The location of the MEI, or representative person of the critical group, will depend on criteria such as:

- The amount and characteristics of the radioactive source;
- The release mechanism (through a stack, elevated vent, building leakage);

- The site dispersal modes (wind roses, natural waterways) or environmental pathways; and
- Exposure modes (direct exposure, intake of foodstuff).

If the DOE activity can cause the release of airborne radioactive material, the location of the maximum potential exposure for that pathway is likely to be where the annual maximum time-integral of the air concentration exists. For example, the location of the highest annual average air concentration as a function of distance from the point of discharge may be determined by analytical modeling of meteorological data using joint wind-direction, wind-speed, and stability roses.

The location of maximum potential dose is not necessarily where the highest concentration occurs. While the location of the maximum time-integral of the air concentration can be determined, the location might be uninhabited and no person would be exposed. Further, it is unlikely for an individual to occupy any location for very extensive periods of time. Few people live in one location all of their lives; about two-three decades of living in one residence is more likely[3]. The doses at locations where there are homes, schools, and work locations should be evaluated. Therefore, even if people did occupy that location occasionally, adjustments for exposure duration would be necessary to estimate dose.

Distance of the MEI or representative person of the critical group, from the point of discharge of the radioactive effluents can be taken as the location of the individual's home, workplace, school, or other location where the individual remains for substantial periods of time. Doses to the MEI, or representative person of the critical group, from exposures to radioactive material in a waterway might depend on the concentration at the nearest location where access to the waterway is likely to occur.

Although it is desirable (and recommended) to evaluate doses in a realistic manner, it is possible (and permissible) for economic savings to be realized to assume (conservatively) that the exposure of an individual occurs at the site boundary in the predominant wind direction. The advantage is that it is not necessary to collect data on actual locations of individuals. In this case, potential exposure pathways should be evaluated to confirm that greater potential doses are unlikely to occur at a location beyond the site boundary. This approach is less acceptable for estimating collective dose than for individual dose because overestimating doses can produce biased results and poor decisions.

Realistic parameters should be used in estimating anticipated doses for ALARA purposes. The goal should be to ensure that the estimated doses will not substantially over- or underestimate the likely actual doses. To the extent practicable, the estimates should address anticipated doses to actual people, rather than maximum doses to hypothetical persons.

[3] A 1997 EPA survey found that about 95% of the population lives in a particular residence less than 30 years. The mean duration was about 7 years per residency.

5.2.2 Receptors

For most ALARA applications, the use of "average" or typical characteristics for evaluating potential doses to exposed populations is recommended. Irrespective of the age or gender of the persons exposed, average doses to organs or tissues, average risk coefficients, and typical values for food and drink intakes and metabolic parameters for "Reference Person" should be used.[4] ALARA evaluations should be expressed in terms of TED, the sum of the effective dose from external exposures and the committed effective dose from radionuclides taken into the body during the same exposure time interval. There may be special circumstances where age or gender issues may be important considerations and the use of "Reference Person" or other standardized assumptions may not be applicable.

This is clearly different from calculations for assessing compliance with individual dose limits or dose constraints. In such cases, the MEI (or representative person of the critical group) is likely to receive the highest dose, or the average dose to the "critical group" is calculated. This value should not be used to estimate collective dose.

> In this Handbook, the **critical group** may be considered to be individuals in the general vicinity of a DOE activity, facility, or site from which radioactive material is released or other sources of exposure occurs, which have relatively homogeneous physical and lifestyle characteristics that are likely to result in the maximum dose (and presumably the highest risk) compared to other groups in the exposed population. For example, the critical group might be infants who ingest milk from cows pastured on land in the predominant downwind direction from a facility that releases radioiodine to the atmosphere. Another critical group might be comprised of persons who ingest a substantial amount of fish taken from a local waterway downstream of a facility that releases radionuclides in liquid effluent.

5.2.3 Collective Dose

By definition, collective dose (S) is the sum of the TED to all persons in a specified population received in a specified period of time. It can also be expressed as the product of the average dose to a specified population and the number of exposed persons within that population. It is important to the decision-making process that collective dose estimates be representative so that comparisons of alternatives can be conducted without bias. As with alternative cost estimates, collective dose estimates in quantitative ALARA assessments should be best estimates.

Although the use of conservative dose estimates may be acceptable for screening assessments to determine if quantitative ALARA assessments are needed, average or representative dose estimates are needed for actual optimization assessments. The problem, therefore, is determining the average dose(s) and the number of persons that receive the dose.

[4] It is noted that DOE uses the linear dose to risk assumption and average parametric assumptions for planning purposes and for evaluating potential exposure for use in the ALARA process and other environmental evaluations. However, these assumptions may not be applicable or appropriate when assessing the risks from actual exposures or the effects of exposures to accidental releases or conducting scientific studies (e.g., epidemiology).

To illustrate one method for estimating S, consider the release of radioactive material to the atmosphere. Various analytical models, generally in the form of diffusion equations, may be used to estimate the dispersion of the material at various distances from the source. Potential exposure conditions, e.g., integrated air concentration, can be evaluated as a function of distance and direction from the source. The population distribution of persons at the same distances and directions need to be determined. Within each compass direction-sector, a series of radial segments (of increasing distance from the release point, as $X_i \pm \Delta X$, or ΔR_i) can be defined and representative (average) doses estimated for the centerline of the radial increment. The potential dose at distance X_i can be taken as the average dose, (H_i) for all persons, (N), located within a given radial segment ΔR_i defined by $X_i \pm \Delta X$. Thus, the incremental collective dose (ΔS) is expressed as: N x H_i.

Similarly, additional incremental S values are estimated for all radial segments in that quadrant out to a distance of 50 miles (80 km) from the point of release or 50 miles beyond the site boundary when integration of doses beyond this point does not significantly affect data quality objectives. This process is repeated in all other sectors, each corresponding to one of the 16 compass points by which wind direction and wind speed are characterized in a wind rose. Site-specific meteorological data also combine atmospheric stability measurements with wind speed and direction to form a joint frequency file. The sum total of the incremental S values from all sectors is the collective dose for the release. Figure 5-1 provides a context for applying these concepts.

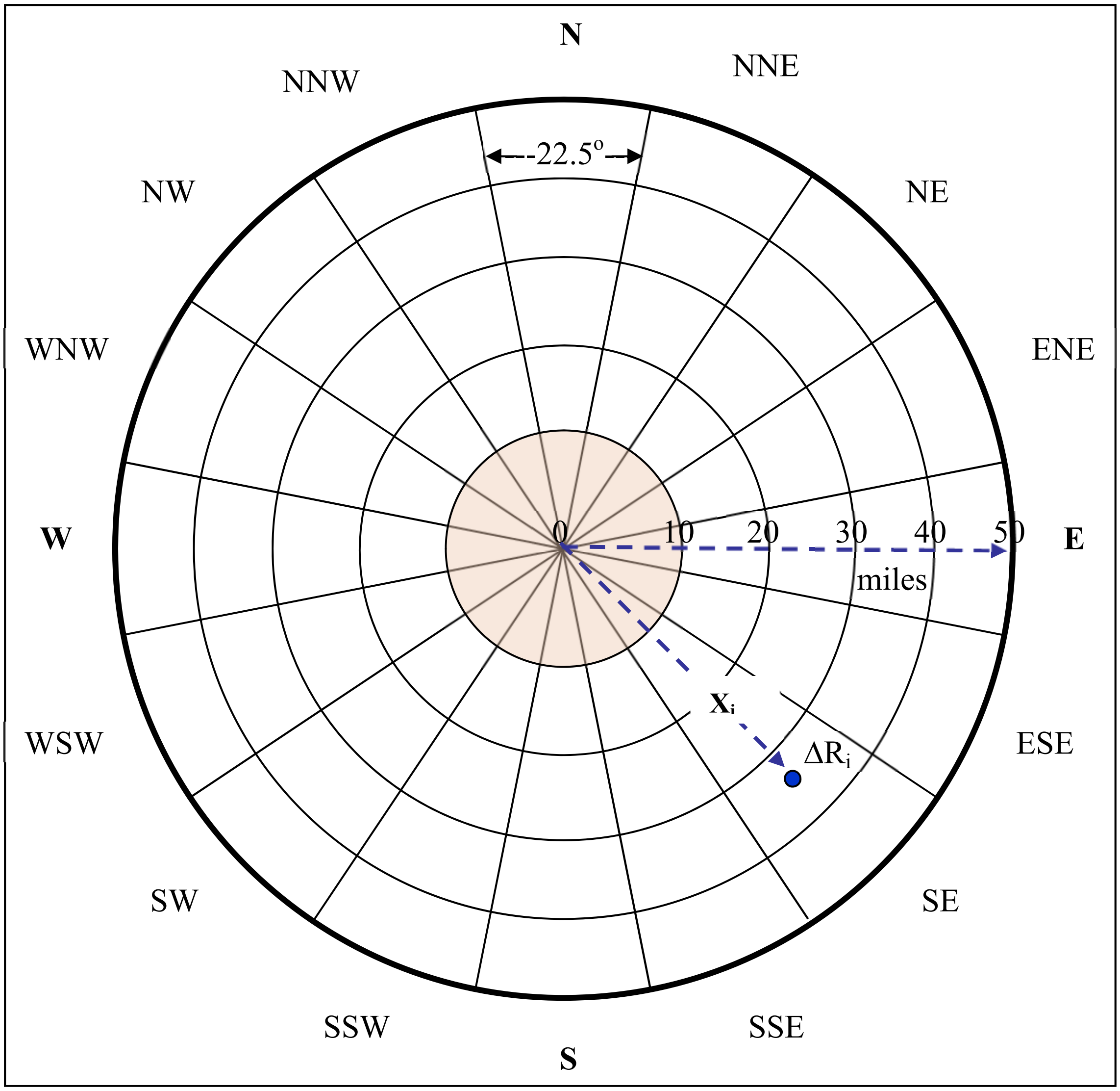

FIGURE 5-1. Concepts in Estimating Collective Dose from Airborne Radioactive Material Releases

Figure 5-1 shows the release point, 0, surrounded by 16 equal sectors of 22.5 degrees, each centered on the points of the compass corresponding to a wind direction. Each compass sector is divided into radial segments, each designated as ΔR_i where i defines the sector and distance X_i from the release point. The radial increments selected at various distances in a sector should be relatively small at locations where the concentration is decreasing rapidly with distance and larger at locations where the concentration is decreasing more slowly. This is necessary because the approximation is made that the average dose to all persons in the radial segment will be the dose calculated for the mid-point of the segment. For example, the radial increments might be no more than a mile apart out to 10 miles (16 km) and no more than 10 miles apart out to 50 miles (80 km). The actual division of sectors into radial segments depends on the site; many DOE sites are large and have unoccupied buffer areas between release points and the site boundary, so small radial segments near the release point are not necessary. When the release includes short-lived material, adjustments for decay en route may be necessary.

The collective dose associated with the use of each alternative radiation protection system is needed for any semi-quantitative or quantitative ALARA analysis. Unless the characteristics (other than magnitude) of the source term are altered by the various systems, the collective dose will be proportional to the source term and can be determined readily by using ratios.[5] Deposition of the airborne source on ground-level surfaces may be estimated using similar analytical models and estimated deposition velocities.

When evaluating collective doses for release or clearance of property, defining the representative receptor is difficult. In comparing alternative actions collective dose estimates should consider the expected or likely use of the property. Where data are available for key parameters, models may use probabilistic assessment techniques to establish the average or representative dose for computing the collective doses. However, these dose estimates may not be acceptable for demonstrating compliance with the individual dose limits that require evaluations of MEIs as critical groups. When representative data are not available, it may be necessary to use generic values. However, overly conservative parameter selections will bias the ALARA analysis.

The collective dose to the exposed population is the measure used to evaluate the potential risk of serious radiation-induced health effects to the public and to identify the optimum radiation protection system among several alternatives. Actual and projected population distributions in the vicinity of the DOE activity or site are needed for this estimate. For practical reasons, such as availability of data, relatively small source term, or limitations of dispersion data, the availability of the population distribution should be limited to a distance of 50 miles (80 km) from the point of an atmospheric release unless integration of doses beyond this distance is suspected to be significant. Analytical models may be used for evaluating atmospheric releases and may assume sector-averaging and radial increments with the dose calculated at the center of the radial sectors and applied to the number of persons in that area, as discussed previously.

For releases of radioactive materials to waterways, the method of release, such as through rakes or conduits, will determine the initial dispersal conditions. Releases may be evaluated using readily available analytical models, data on water usage, and the population data for activities involving the waterway and shoreline. The location of wells, water intakes for water processing plants, fishing, swimming, boating, shoreline, and other activities will be important parameters. In waterways, the dispersion is generally much more limited than releases to the atmosphere and evaluations of collective dose may require summations out to greater distances than for atmospheric releases. For example, discharges to a river may have few and very limited pathways of exposure within 50 miles (80 km) of the site. However, at some greater distance, such as 70 miles (110 km), a major drinking water system may extract water from the river. Potential collective doses associated with releases that might affect the system may be the major detriment associated with the alternative control systems. Therefore, unlike atmospheric releases where collective doses beyond 50 miles are typically not essential or significant to ALARA decisions, in this example, potential receptors 70 miles from the site are likely to be important to

[5] Examples of situations where collective dose may not be proportional to source term include control systems that selectively affect certain radionuclides. For example, a containment facility may be used to delay releases for a period of time sufficient to significantly deplete (through decay) short-lived radionuclides. Such a control system may also increase worker dose while reducing public dose. In this example both public and worker doses must be assessed.

the decision-making process. Although in most instances such situations are not expected to occur when evaluating releases to the air, the 50-mile practical geography-based truncation of collective dose should be used cautiously. The truncation of collective dose calculations should occur only when there is a reasonable expectation that the additional calculations will not provide information important to the ALARA decision.

To summarize, there is essentially no *de minimis* for the application of the ALARA process. Theoretically, collective doses over all time and space may be considered in applying this decision-making tool. However, given that the ALARA process is used to help optimize benefit and make good decisions by balancing many factors such as dose reduction, economics and social factors, collective dose calculations should be constrained by practical considerations. Extending dose calculations inappropriately to include very long time periods, very large areas or very low individual doses could bias the data and analysis and is as likely to result in a poor decision as in a good decision. For example, integrating doses to infinity could produce results that diminish protection of workers but, given the uncertainty in the long-term projection, tend to provide little additional benefit to the non-worker populations. Therefore, quantitative ALARA analyses should only be conducted within periods or spaces where the collective dose data and differences between alternatives are meaningful. Temporal and geographical boundaries should be selected with care to minimize bias in results and uncertainty between alternatives. It is key to assess each alternative in a consistent, representative and comparable manner.

With this in mind, as noted in the previous discussion:

- Integration times for quantitative comparisons should be limited to time periods for which reasonable projections and comparisons can be made. For operational activities it is generally the expected life of the facility or operation. For cleanup and waste management it is typically a period up to a few hundred years but no more than 1,000 years. In special circumstances, such as deep geologic disposal, quantitative analyses beyond 1,000 years may be useful, but in most situations, analyses and data relating to such long periods should be assessed qualitatively, not quantitatively.
- As a general rule, collective doses to populations need only be assessed to 50 miles (80 km) from the site boundary. There may be special circumstances where larger distances may be used (e.g., a large population is located just beyond the 50-mile radius or the dispersion is sufficiently limited that larger distances can contribute collective dose that will be significant to the analyses).
- Although DOE does not recommend dose-based value for truncating collective doses, specific analyses may truncate calculations when it is determined that the continued integration will be of little or no use in the comparison of alternative controls. It is expected that any such truncation will be at doses well below 1 mrem (0.01 mSv) in a year given that the median maximum individual dose associated with releases from DOE facilities is below 0.1 mrem (0.001 mSv) in a year.
- The ALARA process must be applied and documented for all DOE radiological activities. However, DOE supports a graded approach to the process. A process for assessing the maximum resources appropriate for an ALARA assessment is discussed in the section on Resource Allocation in Chapter 7. As a general rule, quantitative assessments will not be necessary if potential individual doses from all alternatives

assessed are less than 1 mrem (0.01 mSv) in a year and collective doses are less than 10 person-rem. Quantitative comparisons of alternatives should always be considered when individual dose may exceed tens of mrem in a year and collective doses exceed 100 person-rem.

All of the above criteria constitute guidance, not rules. The goal of any ALARA analysis is to produce data that will be useful in supporting a good decision that fairly assesses the benefits and costs associated with the alternatives under consideration. Therefore, care should be taken to treat analyses of the alternatives equally and not compare conservative estimates for one alternative to realistic estimates for another. Similarly, varied uncertainties in data from different alternatives should be identified and to the extent possible, eliminated or, at least, be stated clearly.

Chapter 6. **OTHER FACTORS AND ISSUES RELATED TO THE ALARA PROCESS**

This Chapter provides information to aid in optimizing resource allocations for radiation protection and to systemize and clarify "good ALARA practices." ALARA applications are broad, ranging from day-to-day "routine" operations to those related to the design or modification of major facilities. The information in this Chapter can help determine how much analysis is necessary for the ALARA evaluations.

DOE routine radiological activities are subject to the ALARA process. However, DOE O 458.1 requires that the ALARA process use a graded approach. The ALARA process should be commensurate with the complexity and hazard of the DOE activity. This Handbook provides practical benchmarks and criteria for ensuring that the level of effort associated with ALARA analyses is effective.

6.1 Resource Allocation

To scope the effort necessary to comply with the ALARA requirements of DOE O 458.1, one may start by estimating the maximum amount of resources that can be justified for reductions of the dose. This can eliminate considerations of options that would exceed that amount. A suggested procedure would be:

1. Estimate the source term that would cause exposures of the public;
2. Estimate the potential S value (person-rem); and
3. Multiply S by the value of α (e.g., $6,000/person-rem).[6]

The resulting value, S x $6,000, is the *maximum* amount of resources that could be justified for health concerns because there is no process or system that can eliminate *all* exposures. If the collective dose is from annual exposure, the S x $6,000 value is the maximum cost. If the collective dose is over the lifetime of the activity, the S x $6,000 value is the maximum justifiable *total* cost associated with public dose. If no process or system can be identified that could be purchased, installed, operated, and maintained within this cost constraint, no further ALARA effort is needed other than to document the conclusion as part of the record. Such a finding does not foreclose on quantitative assessments and general good management practices that may decrease doses or potential doses. Nor does it eliminate the need to consider "non dose" factors that may indicate a need for quantitative review irrespective of the dose concerns.

6.2 Uncertainties

A second basis for defining the scope of the ALARA applications is the uncertainty in the estimations of collective dose, even when using the best available models for making such estimates. Evaluations of collective dose generally involve estimating a radiation source term, estimating the dispersion patterns, characterizing exposure conditions, and summing the postulated resultant doses to members of the general public over all locations and times where

[6] DOE recommends a range of $1,000 to $6,000 per person-rem be considered as possible monetary equivalents. Depending on circumstances, it may be appropriate to use a range or the $6,000 value for such screening assessments.

and when the exposures occur. It is instructive to briefly review some of the factors that contribute to uncertainties that are germane *de minimis*[7] considerations; when uncertainties are extremely large relative to the value needed to quantify exposures and doses, it is not productive to continue the evaluation exercise.

6.2.1 Source Terms

It is unusual to know, exactly, the identity, quantity, and physical/chemical characteristics of the radioactive source term that is the cause of exposures of the public. Sampling, monitoring, and environmental surveillance can provide a reasonable database for reasonably characterizing the sources if an effort has been made to do so. Sampling, collection, and analyses all have limitations and introduce their own uncertainties. In many cases, the source term can only be estimated on the basis of fragmentary information from operating experience or is completely based on speculation. Thus, the source terms are subject to considerable uncertainty.

6.2.2 Dispersion Patterns

When radioactive material is released to the environment to be dispersed by natural forces, the concentrations generally decrease without limit until the radioactive material can no longer be measured. The ultimate fate of the material can be postulated and analytical models can be found or developed in an attempt to describe the dynamics of the dispersion between the release and its ultimate fate. There are substantial uncertainties every step of the way. The collective dose is calculated using the estimated environmental concentrations at the locations where people reside. This calculation depends on demographic information, which can be highly uncertain.

6.2.3 Time Variations

Essentially all of the parameters that determine exposure or dose vary with time. For example, source terms depend on equipment performance; dispersion patterns are affected by daily, monthly, seasonal, annual, and geologic fluctuations; and population numbers, locations, and lifestyles that affect exposure pathways and modes vary with time.

6.2.4 Release to the Atmosphere

Consider a ground-level release of airborne material. As distance from the source increases, the dose rate generally decreases and one should decide how far to extend the dose estimate as some sources are dispersed widely, perhaps thousands of miles, or worldwide. Due to the inability of analytical models to precisely predict the dispersion pattern, or any of the other exposure parameters necessary for collective dose estimates, at distances beyond a few tens of miles, extreme caution should be exercised by the user. Further, the characteristics of the source term and the inability to predict its physical fate due, for example, to deposition or re-entrainment, are confounding factors in estimating collective dose. In view of the many uncertainties such as those discussed above, it does not appear rational to attempt to predict doses beyond a modest

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[7] *De minimis* refers to an impact or effect that is so small that it is insignificant and can be ignored in the decision-making process.

distance of 50 miles (80 km) from the DOE site boundary. In most instances, collective dose integrated for distance over 50 miles (80 km) provides minimal additional information necessary for the decision process and, therefore, truncation of the dose calculations at 50 miles is usually appropriate.

Several DOE sites are very large – in some cases 10 or more miles from the release point to the site boundary. When several release points are present and they are all located at a considerable distance within the site boundary, they may be treated as a single point of release for purposes of calculating collective dose. However, the actual release points should be used where doses to individuals are evaluated to verify compliance with appropriate limits.

DOE has no *de minimis* level on individual doses in the calculation of collective dose. However, the integration may be truncated when it is unlikely to significantly affect the decision process. In most instances, this is expected to occur when individual doses are a small fraction of 1 mrem in a year.

6.2.5 Release to Surface Waterways

Releases to natural waterways generally undergo more limited dispersion than releases to the atmosphere. In both cases, dispersion is due to mixing by eddy currents, but natural waterways have much more finite dimensions than the atmosphere. This restricts the freedom for further mixing. Consequently, estimates of collective doses from releases to waterways may require including dose contributions beyond those associated with releases to the atmosphere. Further, if the waterway is a drinking water supply, many persons may be exposed. In this event, the 50-mile (80 km) distance constraint for atmospheric releases is not necessarily for releases to waterways.

For smaller waterways, such as creeks, rivers, or ponds, the concentration becomes uniform over cross-sections of the waterway in a relatively short distance and decreases with distance only as further dilution from other water sources becomes available – generally slowly. In this case, the integration of doses may be required to be extended until the next collective dose increment to be added is less than about 1% of the total to that point.

For larger waterways, such as large lakes, bays or oceans, the dimensions are generally greater and the water has fewer dimensional constraints, and the concentration is likely to decrease at a greater rate than is the case in smaller waterways. There could be less need for calculating dose contributions at the greater distances if the concentrations in the larger bodies of water are less than those in the smaller waterways. Site-specific conditions should be used to demonstrate that the collective dose has been adequately determined. The site of the receptor population is extremely important in these determinations. For example, a 0.1 mrem (0.001 mSv) per year dose 90 miles (145 km) downstream at a water treatment system serving a large population could be the most significant source of potential collective dose.

6.2.6 Releases to Ground Water

Releases to the subsurface water, which typically undergoes less dispersion than releases to surface water, may or may not impact ground water quality, depending upon a number of factors which all contribute to overall uncertainty. These factors include:

- Depth of the aquifer or water table;
- Force that drives the released material toward the aquifer or water table (infiltrating water);
- Pathways in the subsurface that include physical barriers; and
- Chemical processes that enhance or retard migration.

If factors obtained at a particular site suggest that ground water will be impacted by a release, then additional factors related to the saturated zone become significant in determining the ultimate fate of the released material, and also contribute to overall uncertainty.

Such additional factors include:

- Transmissive properties of the hydrogeologic unit, including the hydraulic gradient, the size and dimensions of the unit, and soil particle distribution;
- Geochemical processes that can vary significantly from one point to another in the same ground water unit, and can vary significantly over time; and
- Chemical and physical properties of the released material.

Further, understanding the current physical conditions of the subsurface is limited as a result of the high costs of subsurface investigations. While "at surface" and "above surface" conditions can be observed directly, "subsurface" conditions cannot. Generally, data from soil core samples, monitoring wells, and geophysical techniques are collected from a small number of observation points, and extrapolated to a much larger subsurface area, or to future time periods. Extrapolation, based on models and inference, adds uncertainty, due to the lack of uniformity in the subsurface (even considering small-scale investigations) and to the relatively long time periods needed to validate modeling analyses and predictions.

One should also consider the uncertainty associated with long-term unknowns. Travel time of a conservative (that is, non-degrading) species in the ground water typically can be measured in tens of meters per year. At this rate of migration, human activities many generations into the future, as well as long-term geologic phenomena, can contribute further to uncertainty.

Conceptual models of a site's subsurface conditions should be designed to identify sources of uncertainty, and to include each source in any analysis performed – if only in a qualitative sense. Short-term (decades to centuries long) predictions of the fate of releases to the subsurface should be matched with ongoing monitoring of actual site conditions to reduce uncertainty, and to continually validate long-term predictions.

6.3 Exposures within Facilities

Reduction in releases of radioactive material into the environment may be associated with increased amounts retained within the facility. This could lead to increases in the dose to both individual workers and the collective occupational dose. The detriment cost associated with these doses should be considered and the benefit due to the reduction in public dose should be reduced by this amount.

6.4 Exposure Time

Among the more difficult issues to evaluate are those that deal with very low levels of exposure from man-made sources in the environment, and result in individual and collective doses that are a small fraction of those from naturally occurring sources. In some activities, widespread, chronic, very low dose levels might be delivered over very long time intervals (such as several generations) to many people over a very large geographical area.

The dose from radiation sources depends on the dose rate and the duration of exposure. Possible duration of exposures to members of the public to radiation from some DOE activities could range from the duration of a cloud passage to a receptor's lifetime. Estimates of the time-integrated air concentration and doses from airborne radioactive material in the cloud can be evaluated using available meteorological models describing atmospheric dispersion in the lower atmosphere for finite size clouds and for clouds of semi-infinite dimensions. Such calculations also can be used to estimate the intake of radioactive material by inhalation during cloud passage.

In estimating the doses from finite exposure durations, the annual intake of radionuclides by inhalation or ingestion should be determined and appropriate dose coefficients used to estimate the annual (committed) dose and summed over the years of exposure. The average lifetime is about 70 years. However, it is highly unlikely that an individual would be exposed to one source for more than 20-30 years, because people usually do not live in one location more than 30 years.

Most dose coefficients are based on 50-year time-integrals (dose commitments) after the intake. These factors are widely accepted and appropriate for DOE use regardless of the lifetime or period of exposure used.

Another time-interval to consider is the time over which the public could be exposed. In some cases, chronic exposures presumably could occur over many years – perhaps several hundreds and possibly several thousands of years. Durations of these exposures are generally associated with applications involving very long-lived radionuclide materials that are assumed to be released to the biosphere at some point. The scenario usually ties the assumption of a release mechanism and a fraction of the existing inventory of material into a medium such as the water supply, and chronic exposure of the public. The results of such evaluations usually assume that a large number of people will receive relatively low doses for many generations. Such projections deserve critical examination to verify their credibility. Judgments on the acceptability of such doses usually are based on the dose to individuals, rather than on the collective dose, but the societal impact is related to collective rather than individual dose. The dose estimate can require the summation of annual dose over a lifetime and the total exposure is assumed to continue over many generations. Further, the population density and distribution can be expected to differ substantially as compared to current distributions. Lifestyles, which determine exposure modes, also can be expected to change markedly over such a time span.

For purposes of comparing ALARA alternatives for operational systems, the lifetime of the facility generally is a basis for truncating collective dose estimates, temporally. However, where cleanup, restoration, and waste management activities are necessary, the time frame of interest can be much longer. Where radionuclides have relatively short half-lives, decay over a few half-lives may be sufficient to determine the collective dose. For longer-lived radionuclides, integration times may be determined by the uncertainties in scenarios and due to the physical parameters affecting dose rates. These uncertainties make it difficult to determine and quantitatively assess the difference in alternatives beyond a few hundred years because the differences are based largely on assumptions rather than fact. Therefore, it is only appropriate to do quantitative comparisons to a few hundred years, or less.[8] Although evaluating doses for periods of up to 1,000 years may provide useful information, periods beyond 1,000 years should not be used in quantitative ALARA assessments.

Due to the uncertainties and difficulty in quantifying these time-related factors, it is critical that knowledgeable persons are responsible for making ALARA judgments. As an example, the time and duration of exposures to the affected individuals or population and the likelihood or probability of occurrence of the exposure scenarios evaluated in the analyses should be considered and appropriately balanced when the alternatives are weighed. It may be appropriate for instance, to give more weight to likely near-term exposures than to plausible but unlikely future exposures. In general, it is reasonable to assign lower values to doses that are increasingly uncertain than to those that are not. Similarly, equal collective doses resulting from individual doses that are a significant fraction of the dose limit may be considered more important than collective doses resulting from individual doses that are very small compared to the dose limit. This is recommended because the linear non-threshold dose-risk assumption is generally believed to be conservative.

> The product of a very small annual dose to a very large number of people, over a very large area and over a very long period of time may aggregate information inappropriately and could be misleading when selecting protective actions.

6.5 Discounting Cost

One of the more controversial time-integral issues is associated with discounting cost when the expenditure is present and the health detriment that is being reduced is several hundreds or thousands of years in the future. From strictly an economics point of view, it is rational to discount cost projections based on postulated health effects centuries and eons in the future. Assuming all conservative assumptions in quantifying potential health effects are factual, if any finite discounting is applied, the present worth would be a small, even infinitesimal, fraction of

[8] Administrator of the Office of Information and Regulatory Affairs of the Office of Management and Budget, January 11, 1996, *Regulatory Planning and Review – Economic Analysis of Federal Regulations Under Executive Order 12866.*

the cost of the future detriment. Because of this, and the extreme uncertainties associated with very long projections of dose which limits the value in decision making, DOE recommends limiting quantitative assessments of collective dose to support ALARA efforts to a few hundred years. This is one method of weighting present collective doses greater than those that occur in the future. Conventional discounting is not recommended for analyses hundreds of years into the future (NAPA, 1997). However, without discounting, analyses of detriments over long periods typically are biased in favor of future generations at the expense of the present generation.

Although justifiable from economic considerations, the issue of discounting (like many other factors) is a policy consideration, and currently no discounting is likely to be considered.

6.6 Perspectives

A perspective of the dose analysis should be provided. It is often useful to compare estimated collective dose values from DOE activities with the collective dose to the same exposed population from natural (background) radiation sources. One such comparison would be the time required for the exposed population to receive a comparable collective dose from natural background radiation. Similarly, risks to populations can be compared to the normal incidence of cancers (fatal and non-fatal to the same population during the same exposure time). For example, about one-third of the population will contract cancer in their lifetime, and about half of those will be fatal. There are other comparisons that also can add perspective.

6.7 Other Factors and Criteria

In many cases, particularly where multiple contaminants in multimedia situations occur, DOE ALARA requirements must be applied along with other criteria and requirements. The ALARA process is sufficiently flexible to incorporate such criteria into the process and in many cases, these factors or criteria are already parts of the process.

For example, under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) regulations (40 CFR 300.430), selection of remedial actions must consider the criteria shown in Table 6-1.

As noted above, all of these criteria are, or readily can be, addressed as part of the ALARA process and the CERCLA requirements to document that consideration of these factors is consistent with the ALARA documentation requirements. Although some of the CERCLA criteria may not be easily quantified through a monetary equivalent in the cost-benefit analysis, they all can be addressed with multi-attribute analysis approaches. Such approaches would weight each criterion and then score the alternatives for each criterion. The sum of these scores may be used to rank the alternatives.

TABLE 6-1. CERCLA Criteria That Can Be Addressed Using the ALARA Process

Threshold Criteria

Compliance with Applicable or Relevant and Appropriate Requirements (ARARs) – Addresses whether a remedy will meet the applicable or relevant and appropriate Federal and State standards or whether a waiver is justified.

Overall protection of human health and the environment – Addresses whether a remedy provides adequate protection of human health and the environment and discusses how risks are eliminated, reduced or controlled through treatment, engineered controls or institutional controls.

Both of these criteria are addressed in the ALARA process through the consideration of dose constraints and selection of alternatives that reduce doses (risks) to as low as reasonably achievable. The ALARA process may be useful in assessing the impact of specific ARARs with regard to implementable alternatives in cleanups under CERCLA.

Primary Balancing Criteria

Short-term effectiveness – Addresses the period of time needed to achieve and to determine any adverse impacts on human health and the environment that may be posed during the construction and implementation period, until remedial action objectives are achieved.

Long-term effectiveness and permanence – Refers to expected residual risk and ability of a remedy to maintain reliable protection of human health and the environment over time.

Reduction of toxicity, mobility, or volume through treatment – Refers to the performance of treatment technologies.

Implementability – Refers to the technical and administrative feasibility of a remedy including the availability of materials and services to implement the alternative remedy.

Cost – Includes estimated capital cost, annual operation and maintenance costs, and the net present value of capital and operational and maintenance costs.

All of the primary balancing criteria are key factors in ALARA process assessments. Although the reduction of toxicity, mobility, or volume criterion is not addressed in detail, processes or techniques such as these that can reduce migration and possibly dose should be considered and addressed in the selection of alternatives.

Modifying Criteria

State acceptance – Indicates whether the State concurs with, opposes, or has no comment on the preferred alternative, and State comments on ARARs or proposed waivers.

Community acceptance – Summarizes the public's response to the alternatives.

As noted in this document, the analysis of the ALARA process factors requires judgment and as a result, input from interested groups (e.g., States, communities, Site Advisory Boards, unions, etc.) may be important when considering and evaluating the ALARA factors. The impacts of such input are discussed in some of the examples presented in the appendices of this Handbook for both CERCLA and non-CERCLA-related projects.

Chapter 7. **QUALITATIVE ALARA ANALYSIS**

As previously expressed in Chapter 1, the goal of the ALARA process is to identify, from among candidate radiation protection alternatives, the alternative that would result in the maximum total benefit, considering the protective measures and their costs. Resources allocated to the ALARA evaluation process should be commensurate with their potential benefits. As illustrated in Figure 2-1, DOE recommends reference dose limits to the MEI (or representative person of the critical group) and to the exposed population to assist in determining the level of detail needed in an ALARA analysis.

Qualitative analysis typically uses words to describe the magnitude of potential consequences and the likelihood that those consequences will occur. Scales or matrices are useful tools that can be adapted to suit the circumstances of the analysis. This type analysis is useful when reliable data for a more quantitative analysis is not available or necessary.

A qualitative ALARA analysis may be appropriate when the estimated doses are less than the reference dose levels and, in particular, when the collective dose is estimated to be less than 10 person-rem per year and individual doses are less than 1 mrem (0.01 mSv) per year.

7.1 Environmental Restoration Case Study

This case study is an example of using a Qualitative ALARA analysis for a small environmental restoration project to show that a complex analysis need not be performed to arrive at an optimum conclusion. This case study examined the options of removal of contaminated soil in a Radiological Materials Management Area (RMMA) to satisfy an industry land-use scenario and a residential land-use scenario.

Site Description and History

The RMMA is located immediately surrounding the outfall of an old industrial building and the former location of a trailer used for industrial operations. The industrial building was constructed in the late 1950s for explosive compounds synthesis and had also been used for animal experiments. A machine shop was opened in the mid-1960s and may have discharged solvents and acids to floor drains. There is currently no activity in the building and all floor drains had been sealed at some point in the past. The drains discharge to a central drain line east of the building to a surface outfall near the bottom of a small ravine, which is a tributary of a nearby stream. A thick mat of dead vegetation has built up around the discharge point. The area of the site is approximately 1000 m^2 estimated to be 15-45 meters above the regional water table.

Site Status

A final status survey was conducted in accordance with Multi-Agency Radiological Survey and Site Investigation Manual (MARSSIM) guidelines. Surface radiation surveys did not detect any anomalies above background at the site. Subsequent soil sampling found one slightly elevated U-235 result but otherwise passed the MARSSIM statistical tests.

Dose Assessments

A dose assessment, using the Residual Radiation (RESRAD) computer code, was performed assuming both an industrial (most likely) and residential (assumes loss of active control measures) land-use scenarios. The assessment assumes that the only contamination will come from the U-235 concentration within the top 0.15 m of soil. As a conservative approach, this U-235 concentration was averaged over the entire site.

The RESRAD dose assessment resulted in an annual TED to an MEI of 0.08 mrem (8.0 E-4 mSv) per year and 0.18 mrem (0.0018 mSv) per year for the industrial land-use and residential land-use scenario, respectively. Both values are much less than the numerical EPA guidance of 15 mrem (0.15 mSv) per year.

ALARA Analysis for the Site

Since only one slightly contaminated area of soil was found at the site, the ALARA cost analysis addresses only the expense of removing the soil and treating it as radioactive waste versus leaving it on the site. The disposal cost for 150 m^3 of radioactive waste at this concentration would be approximately $108,000. Assuming an unlikely residential land-use scenario, where 0.18 mrem (1.8 E-3 mSv) per year is avoided by each of the projected 1 site resident (8 residents/acre * 0.04 acre) for each of the next 50 years, the projected cost per person-rem avoided would be $12 million ($108,000/(0.00018 rem/yr * 50yr * 1 person). By comparison, the cost to simply leave the soil untouched on-site would be $0. Therefore, further remedial actions or waste disposal expenses to reduce the already minimal radiation doses at this site are not reasonably justified.

7.2 Volumetric Release of Sediment for Off-Site Landfill Disposal

This qualitative ALARA analysis was prepared in 1998 to evaluate the potential disposal of approximately 9 m^3 (12 yd^3) of sediments containing polychlorinated biphenyls (PCBs) and low levels of residual radioactive materials in accordance with DOE O 5400.5 and associated guidance.

Site Description and History

Sediments from a DOE facility containing PCBs at levels regulated under the Toxic Substances Control Act of 1976 (TSCA). Levels ranged from 52 to 450 ppm as compared to the TSCA criterion of 50 ppm. In addition, the sediments contained low levels of residual uranium at a maximum measured concentration of approximately 8 pCi/g.

At the time of this evaluation, DOE requirements for release of real property were specified in Chapter IV of DOE O 5400.5. These requirements include: an evaluation to ensure that potential radiation doses to the public would not exceed 25 mrem (0.25 mSv) per yr with a goal of a few mrem per yr, in accordance with DOE's requirements to reduce radiation exposures to ALARA; an evaluation of compliance with groundwater protection requirements; reasonable assurance that the proposed disposal is not likely to result in a future requirements for remediation of the landfill; and assurance that the materials proposed for disposal are acceptable to the owner/operator of the facility and regulators.

Disposal Alternatives

Two primary disposal alternatives were available for this waste stream, an off-site, DOE-owned TSCA Incinerator or an off-site, commercial TSCA-permitted disposal facility. Utilization of the DOE-owned TSCA Incinerator would also require removed sediments be stored for an indefinite period of time until the then-current waste backlog be processed. In contrast, the commercial facility could provide permanent disposal of this waste immediately upon its generation.

Dose Assessment

In accordance with DOE O 5400.5, dose assessments were conducted to determine:

- Reasonable maximum worker dose during disposal
- Reasonable maximum worker dose following disposal
- Collective dose to facility workers
- Long-term residential dose via ground water protection
- Long-term remediation of disposal site

Reasonable Maximum Worker Dose during Disposal

Disposal workers were considered to be at greatest risk of exposure to radioactive materials during the disposal of the proposed waste stream. Three components of this work scope were identified as potential exposure periods:

1. Waste Transportation – Personnel involved in loading materials into trucks at the DOE site and driving loaded trucks to the disposal facility.
2. Waste Receiving – Personnel involved in receiving waste at the disposal facility, including inspection of the waste manifest, weighing the trucks, sampling and analysis of waste, and transferring the load to a staging area to await disposal.
3. Waste Disposal – Personnel involved in placement of waste in the disposal cell, including transfer from staging area, placement in the disposal cell, and placement of cover material as required by facility operating procedures.

Estimated exposure times and characteristics for activities conducted by each of these hypothetical worker categories were derived in consideration of the specific characteristics of the waste stream. All parameter values and assumptions were also selected to be conservative. These parameters were combined with external dose factors developed for each scenario and appropriate internal dose conversion factors for inhalation and ingestion to estimate potential dose to each worker category.

In all cases, the estimated annual dose to a hypothetical worker was less than 0.0003 mrem (3.0 E-6 mSv), which is more than five orders of magnitude below the primary DOE dose limit of 100 mrem per yr and far below the limit of 25 mrem (0.25 mSv) per yr specified for release of materials for disposal at an off-site landfill.

Reasonable Maximum Worker Dose following Disposal

A hypothetical future worker employed full-time at the landfill facility following closure for site maintenance and surveillance was the basis of this dose assessment. The hypothetical future worker was assumed to spend 8 hours per day at the disposal facility for 250 hours per year in a position directly above the waste. This scenario and resulting dose estimate also represented a disposal worker involved in the placement of subsequent waste materials into the disposal cell during the active operating period of the facility.

Under these conservative assumptions, the predicted dose to the future worker was 1×10^{-10} mrem (1×10^{-12} mSv) per year. In the event that a building was constructed over the disposal cell cover system, the potential concentration of radon decay products in indoor air was estimated at less than 2×10^{-7} working level, five orders of magnitude below the applicable limit of 0.02 working level. As indicated by these calculated levels, most potential exposure pathways are significantly restricted or eliminated due to the engineering of the disposal cell. Only external radiation, radon mitigation through the cap and cover system, and exposure to radiation in leachate would be active exposure pathways. Radionuclides of concern in this scenario are relative insoluble and immobile and not expected to be readily leached from the disposal material. As long as the cap and cover system retains its integrity, radiation exposures to any future receptor would be negligible for any future land use.

Collective dose to facility workers

The following categories of workers, with varying potential for exposure to residual radioactive materials, were considered in this analysis:

1. Facility Worker/High-Exposure – Hypothetical worker population of 40 persons with high potential for exposure to waste or residual materials.
2. Facility Worker/Medium-Exposure – Hypothetical worker population of 60 persons with moderate potential for exposure to waste or residual materials.
3. Facility Worker/Low-Exposure – Hypothetical worker population of 80 persons with low potential for exposure to waste or residual materials (e.g. clerical workers).

Dose assessment for this analysis utilized methodology and assumptions developed within the Complex for evaluating potential collective exposures at generic hazardous waste disposal facilities. Using these default parameters, the collective worker dose is estimated at approximately 2×10^{-5} person-rem during the active disposal operation for this waste stream.

Similar methods and parameters were applied to estimate potential dose to the off-site public. The collective dose to this population would be negligibly small, due to the small volume and low radionuclide concentrations in the waste and the non-energetic dispersion mechanisms. Following placement in the disposal facility, there would be no plausible pathway for off-site exposures to the public.

Long-term residential dose via ground water protection

For the selected facility, no breakthrough of contaminated groundwater was predicted during the 1,000-year period of analysis. Therefore, no impacts to groundwater were predicted. Even in the unlikely event that all design features and post-closure care requirements for the facility fail, no significant impacts to groundwater would be predicted due to the small volume of the waste stream and the very low concentrations of residual radioactive materials.

Long-term remediation of disposal site

Since the selected facility is permitted under RCRA and TSCA, closure and post-closure requirements are specified to control, minimize or eliminate the potential for future remediation at the site. The facility has a closure plan and perpetual fund established for future maintenance, monitoring and control of the site, to ensure care is provided. This will ensure that the facility will not be subject to future remediation under DOE Orders or other applicable requirements as a result of the disposal of this waste stream.

ALARA Analysis for the Sediment

Disposal of the materials at a commercial disposal facility was estimated to cost approximately $14,000 (including transportation and disposal) while disposal at the DOE-owned facility was estimated at $554,000 (not including interim storage costs). The results of this analysis clearly indicated that the disposal of these materials at the commercial facility would be protective of human health and the environment, while providing significant cost savings (approximately $540,000) and immediate disposal capacity for this waste. Evaluating the information readily available, a qualitative decision to select the commercial disposal option was made without having to perform a full quantitative ALARA analysis – further saving time and money.

7.3 Pros and Cons Analysis

A Pros and Cons Analysis is another example of a qualitative comparison method. As the name implies, positive and negative results are identified about each alternative. It requires no mathematical skill and can be implemented rapidly. Lists of the pros and cons, likely based on input from subject matter experts, are compared to one another for each alternative. The alternative with the strongest pros and weakest cons is preferred. A Pros and Cons Analysis is suitable for simple decisions with few alternatives and few discriminating criteria of approximately equal value. The following case study provides a simple example of this type analysis.

Problem

You must ensure the dose rate in a public area adjacent to a DOE facility is consistent with DOE guidelines.

Approach to the problem

To ensure public dose limits are consistent with DOE guidelines, you must determine the dose rates in the area adjacent to a DOE facility during routine facility operations. There are a number of options available to determine the dose rates using resources commonly available at a DOE site. Three suggested options include:

1. Placing Thermoluminescent Dosimeters (TLDs) or Electronic Personnel Dosimeters (EPDs) in common area for 30 days to determine average dose rate in adjacent area;
2. Perform a survey using direct-reading radiation detectors to map the dose rate in the adjacent area; or
3. Use of a modeling code (e.g., Microshield) to estimate the dose rate at any point in the adjacent area.

Applying the Pros and Cons Analysis

You assemble a group of subject matter experts to provide comments on each alternative. Table 7-1 lists the generated Pros/Cons for each alternative:

TABLE 7-1. Pros and Cons

TLDs/EPDs	
Pro	Con
Easy to perform	Delayed results (TLDs)
Minimum time to employ	Tampering of TLDs/EPDs
DOECAP accredited	Environmental Issues (e.g. weathering)
Longer dwell time	

Instrumentation	
Pro	Con
Easy to perform	Can be time intensive
Immediate results	Snap-shot in time
Calibrated equipment	

Modeling	
Pro	Con
Immediate results	Can be complex
	Model uncertainty
	Subjective

Although all three options will provide the required information, a simple comparison of the Pros and Cons for each as they pertain to the particular circumstance will identify the best option to employ.

Chapter 8. **SEMI-QUANTITATIVE ALARA ANALYSIS**

A semi-quantitative analysis is an approach that blends attributes of both qualitative and quantitative approaches. Where quantitative analyses can be both exhaustive and detailed, and typically performed by an outside third party, qualitative approaches lack the accuracy and transparency but usually result in high stakeholder buy-in as the level of involvement in the analysis is greater. A semi-quantitative approach is a mixture of the two.

A semi-quantitative analysis attempts to match the thoroughness of a quantitative analysis with some of the simplicity of performing a qualitative analysis. The process is less costly and time-consuming than a quantitative analysis but the primary objectives are achievable at only a moderate loss in detail.

A semi-quantitative ALARA analysis may be needed as the estimated doses from the alternative actions begin to approach or exceed the “reference” dose levels (i.e., collective doses between 10 and 100 person-rem per year) as illustrated in Figure 2-1. In addition to these dose levels, a semi-quantitative ALARA analysis, as compared to a quantitative ALARA analysis, is more appropriate when the number, types and complexities of alternative actions are not as substantive.

Five case studies are presented to explain the basis for derived standards applied to specific cleanups. The case study discussions are intended to provide examples of the impacts of cleanup criteria on waste volume, costs, and dose/risk avoided. These examples demonstrate various semi-quantitative evaluation processes used to satisfy ALARA process requirements when selecting Authorized Limits. The benefits or limitations to the approaches also are discussed. The comparisons also demonstrate that some knowledge of projected collective dose is important to the decision-making process.

8.1 Case Study #1: Colonie, New York

Authorized limits for this case study were initially developed qualitatively, and post-activity analysis indicates the acceptability of the approach used. This case study demonstrates the importance of realistic assumptions in evaluating the benefits and assessing expected outcome.

Site

This site was a formerly-licensed (State and U.S. Nuclear Regulatory Commission (NRC)) facility that processed uranium largely for Department of Defense use. The facility operated for some period without functional stack controls. The State ultimately closed the facility, and Congress directed DOE to remediate the plant and residential properties around the plant. Vicinity properties have been remediated. This discussion deals primarily with the vicinity properties remediated in the late 1980s.

Basis for Standard

The cleanup standard or authorized limit used for cleanups at Colonie, New York, was 35 pCi/g for depleted uranium (U-238). This standard was derived using a process similar to that contained in DOE Order 5400.5, the predecessor to DOE O 458.1. DOE conducted dose assessments that assumed a residential farmer scenario (a resident gets a significant fraction of food supplied from a home garden) and determined that a 120 pCi/g concentration of depleted uranium could result in a dose of 100 mrem (1 mSv) in a year. Based on a cost evaluation and through meetings with New York State and EPA officials, 35 pCi/g was determined to be an appropriate ALARA-based limit. At the time of the cost analysis, only 12 properties were known to be contaminated and the incremental cost between 35 pCi/g and other alternatives was on the order of a few thousand dollars per property. Therefore, the incremental costs were considered not to be significant. The supporting analysis was qualitative and included no systematic assessment of collective dose or waste volume-cost relationships. The standard ensured that maximum doses to residents would be less than 25 mrem (0.25 mSv) in a year assuming the contamination was uniformly spread over the property. For the most part, actual contamination was concentrated in areas such as near drain spouts, drip lines or run-off areas from pavement. Localized concentrations in these small areas exceed 100 pCi/g. Over 50 properties were cleaned up and many had only small areas of contamination.

Results

The final cleanup reduced maximum uranium concentrations on the properties to levels between 1.5 and 24 pCi/g. Post-remedial action dose assessments, conducted on the first 47 properties, indicated that the average maximum dose was 1 mrem (0.01 mSv) in a year (an average of the doses to the MEI from each of the properties evaluated). The maximum dose for any single property was 3.3 mrem (3.3 E-2 mSv) in a year. This dose is less than 15% of the dose used to select the authorized limits for uranium at this site.[9]

These dose estimates are generally conservative in that they are calculated assuming dose over the entire time period was equivalent to the dose at the time of maximum dose rate, and assume a significant portion of the resident's diet is obtained from home gardening. In fact, the food grown may exceed the quantity that can be produced on the lots, although this is a minor contributor to dose, assuming a reasonably conservative mass loading factor used for inhalation (a major contributor to dose), likely overestimation of dose, and assuming that the residential scenario applied for all dose estimates, despite the fact that some properties were commercial or open areas. Doses from U-234 were not estimated; however, the site was contaminated with depleted uranium that is primarily U-238 and the contribution to dose from U-234 is expected to be low. Likewise, Ra-226 will eventually result from ingrowth; however, over the 1,000-year period evaluated, the contribution is insignificant.

Table 8-1 presents a summary of the pre-remedial action doses, the post-remedial action doses, and the dose reduction resulting from the remedial action (Figure 8-1 presents pre- and post-remedial action doses by property). Pre-remedial action doses for these properties ranged from about 1 mrem (0.01 mSv) per year to less than 15 mrem (0.15 mSv) per year. In other words, although the generic dose assessment used to develop the standard assumed that the potential

[9] This is not an uncommon situation – due to the field application of the ALARA principles and the precautions taken to account for uncertainties in field radioanalytical methods and excavation techniques, post-remedial levels actually achieved routinely surpass the authorized limit. However, this decrease cannot be predicted in advance and efforts to lower pre-remedial action limits to account for this phenomenon will likely cause significant increases in waste volume, costs and impact schedules.

dose on the contaminated properties could be as high as 25 mrem (0.25 mSv) in a year, given the actual use of the properties, the distribution of radionuclides, and the site-specific parameters, none of the 47 properties studied were likely to approach that dose even prior to remedial action.[10]

Annual individual risk of cancer, given residential use of the subject property, was reduced from $2x10^{-6}$ to $5x10^{-7}$. Assuming individuals spend 30 years at a property (EPA data suggest that most individuals spend, on average, seven years at a given property and 95% of the population spends less than 30 years at a given property), the lifetime incremental risk of fatal cancer was reduced from $6x10^{-5}$ to $1x10^{-5}$ (6 in 100,000 to 1 in 100,000).

Assuming an average of four persons per household, collective doses for pre-remedial action conditions, post-remedial action conditions, and collective dose avoided by the action were estimated for 1 year, 50 years, and 200 years. Table 8-1 presents these doses. The estimated collective dose avoided over the 200-year period was 30 person-rem. At a cost of about $200,000 for vicinity property cleanup, this equates to about $6,700 per person-rem avoided, which is consistent with the upper end of the DOE recommended range of values for the monetary values for collective dose. The total number of health effects avoided, over a 200-year period, by these remedial actions is calculated to be 0.02 (this is effectively no cancers). The estimated cost per health effect averted for the project is about $10,000,000.

Authorized limits used for this remedial action were established at a concentration that provides assurance that doses would be less than 25 mrem (0.25 mSv) in a year. However, in this situation, it was developed using the worse plausible use scenario as the expected use scenario. Data from this site also demonstrate the importance of using dose estimates that are as realistic as possible in developing authorized limits. The results of modeling pre- and post-remedial action doses shows that the most conservative scenario and qualitative analysis used to derive the 25 mrem (0.25 mSv) per year-based authorized limits significantly overestimated actual doses.

TABLE 8-1. Colonie, New York, Summary of Dose, Collective Dose, and Risk Averted

	Pre-Cleanup	**Post-Clean**	**Reduction (Risk or Dose Averted)**	
Average Maximum Individual Dose	4.2 mrem/y	1.0 mrem/y	3.2 mrem/y	
Hypothetical Annual Risk (cancer)	2 in 1,000,000	5 in 10,000,000	2 in 1,000,000	
Hypothetical Lifetime Risk (30 yrs exposure)	6 in 100,000	1 in 100,000	5 in 100,000	
Collective Integration time	**Person-rem**	**Person-rem**	**Person-rem**	**Hypothetical Cancers Averted**
Annual	0.2	0.05	0.2	0.00008
50 year period	10	2	8	0.004
200 year period	40	10	30	0.02

[10] Conservative assumptions routinely result in over-estimates of dose. Generic modeling conducted (in the early 1980s) to develop dose-based authorized limits for remediation of this site produced doses that were greater than those that were more firmly based on more site-specific data.

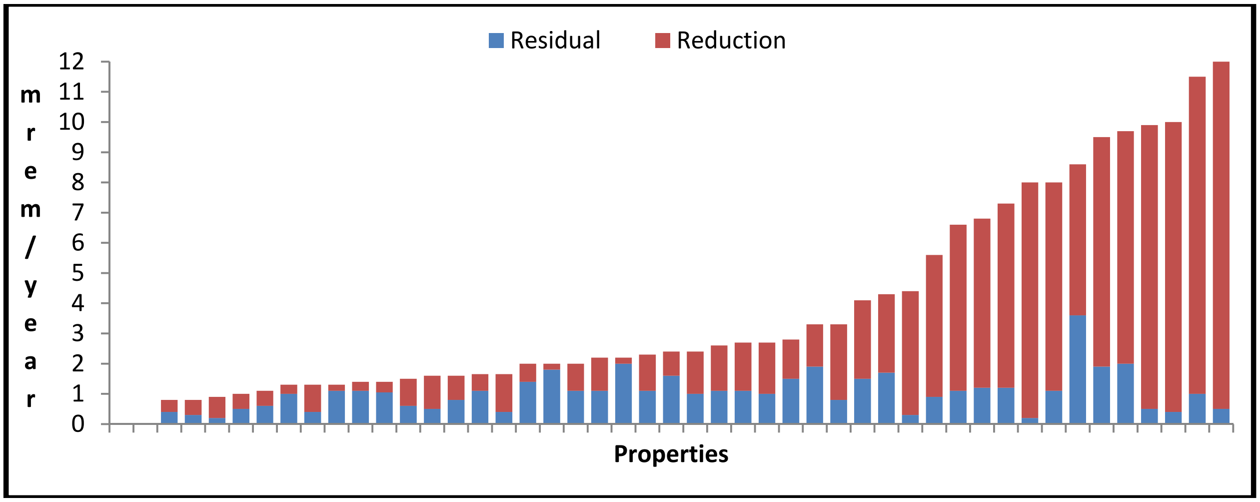

FIGURE 8-1. Estimated Doses (Total Pre-cleanup, Residual and Reduction) by Property

8.2 Case Study #2: Elza Gate Site, Tennessee

This is an example of applying the ALARA process to a small area with modest soil contamination. Authorized Limits for uranium were established based on a semi-quantitative evaluation using waste volume as a surrogate for costs. The selection of the ALARA-based authorized limit was made on the basis of cost-effectiveness rather than cost-benefit. The analysis also suggests that Authorized Limits developed separately for various radionuclides, when used together, likely will result in more dose reduction than projected.

Site

This site was a former storage site for waste and contaminated material. It was remediated and released to standards in effect in the 1970s. The property is now an industrial park that includes about 20 acres. The primary radionuclides of concern were Ra-226, Th-230, and U-238. The 5 pCi/g surface and 15 pCi/g subsurface criteria were used for Ra-226 and Th-230 based on a qualitative ALARA assessment because levels were not unlike the Uranium Mill Tailings Remedial Action (UMTRA) vicinity properties. A standard for uranium was derived using the DOE ALARA process.

Basis for Uranium Standard

The authorized limits for cleanup at Elza Gate were 35 pCi/g for U-238 and 5 pCi/g surface and 15 pci/g subsurface for the combined activities of Ra-226 and Th-230 isotopes. The uranium standard was developed independent of the radium[11] standard. A dose assessment was completed for several scenarios, and a uranium concentration that would meet a dose limit of

[11] The radium/thorium and uranium standards are not truly independent of each other. Selection of a lower or higher radium standard, for example, could impact the residual uranium levels and vice versa. In many cases, the standard development process deals with all radionuclides at once. However, because radium is treated separately in DOE standards (as low as reasonably achievable below the concentration limit) and all other radionuclides are dose-based (plus ALARA requirements), development is typically done separately and dose analyses integrate the doses later.

100 mrem (1.0 mSv) in a year was calculated for each. The results are presented in Table 8-2. It was conservatively assumed that residual dose associated with cleanups to lower concentrations would be linearly related. This assumption ignores the benefits associated with additional clean fill necessary to replace the contaminated soil that was removed.

Analysis of the relationship of the authorized limit (soil concentration of U-238) to volume of waste (a surrogate for cost) was completed (see Figure 8-2). This shows costs began to increase dramatically between concentrations of 30 and 40 pCi/g U-238. The estimated individual dose in this concentration range for the likely-use of the site was about 4 mrem (0.04 mSv) in a year, which conforms with DOE guidance to remain well below the DOE constraint of 25 mrem (0.25 mSv) in a year. The worst-case future use scenario dose was about 15 mrem (0.15 mSv) in a year, well below the 100 mrem (1.0 mSv) in a year dose limit for all sources. A cleanup standard Authorized Limit of 35 pCi/g was selected for U-238 (about 70 pCi/g total uranium).

TABLE 8-2. Uranium Concentrations representing 100 mrem/yr for Several Scenarios and Uranium Concentrations

Industrial use (current and likely use) (if U-238 used as an indicator for measurement)	- 1800 pCi/g (Uranium) - 880 pCi/g (U-238)
Recreational use (U-238 as indicator)	- 4000 pCi/g (Uranium) - 2000 pCi/g (U-238)
Residential use[12] (worst-case use) (U-238 as indicator)	- 470 pCi/g (Uranium) - 230 pCi/g (U-238)

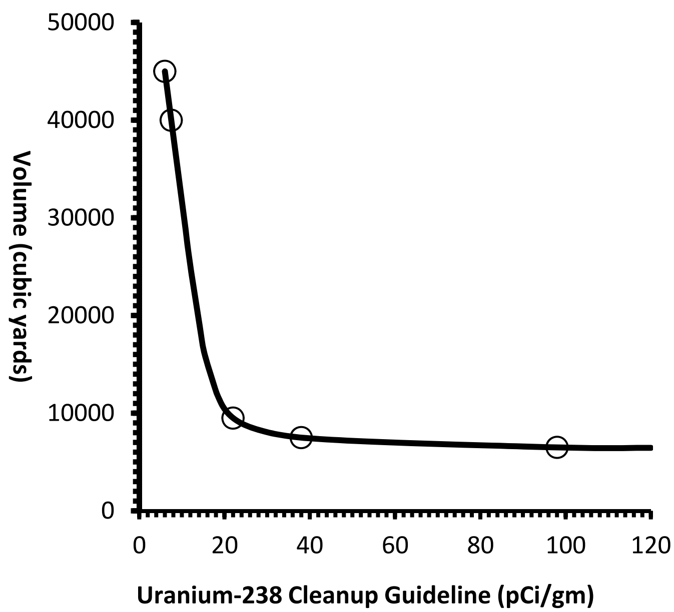

FIGURE 8-2. Elza Gate: Waste Volume vs. Uranium Concentration

[12] Another residential scenario that was evaluated was rejected because the groundwater pathway was inappropriate [that is, inappropriate assumptions and parameters]. Even for the residential scenario results that were reported here, unrealistic assumptions were used for water use – it was assumed that an on-site pond provided drinking water and irrigation water despite the fact that the site is adjacent to a river and has a relatively steep slope.

Results

Table 8-3 presents pre- and post-remedial action concentrations (in pCi/g). Post-remedial action doses were estimated for the site using the Net Average residual concentrations of the above radionuclides and estimating U-234 &U-235 (and decay products) as a standard ratio to U-238.

TABLE 8-3. Elza Gate, Tennessee, Site Pre- and Post-remedial Action Concentrations

Pre-remedial Action Concentrations			
Radionuclide	**Measured (pCi/g)**	**Average Background (pCi/g)**	**Average Net (pCi/g)**
U-238*	146	1.0	145
Ra-226	8.9	1.3	7.6
Th-232	1.9	1.5	N/A
Th-230	59	1.0	58
Post-remedial Action Concentrations			
Radionuclide	**Measured (pCi/g)**	**Average Background (pCi/g)**	**Average Net (pCi/g)**
U-238*	5.9	1.0	4.9
Ra-226	1.0	1.3	N/A
Th-232	1.3	1.5	N/A
Th-230	2.5	1.0	1.5

* U-235 and U-234 were estimated on the basis of U-238 concentrations.

The most likely use for this site will be industrial. Estimated dose for the maximum individual is shown in Table 8-4 and estimated dose for the individual risk is shown in Table 8-5.

TABLE 8-4. Estimated Dose for the Maximum Individual

Post-remedial Use	Maximum Individual Dose	Notes
Industrial	1.5 mrem/yr	less than 40% of the modeled dose[13] Most likely use
Recreational	<1 mrem/yr	
Residential farmer	12 mrem/yr	using an on-site pond for drinking water and irrigation[14]

TABLE 8-5. Estimated Dose for Individual Risk

Post-remedial Use	Potential Risk Factor	Notes
Industrial	7.5×10^{-7}	Annually
Industrial	2×10^{-5} (2 in 100,000)	Lifetime, assuming 25 years working at the site
Residential farmer	2×10^{-4} (2 in 10,000)	Lifetime

[13] Due to in-field ALARA applications and the uncertainties in radioanalytical methods and excavation techniques, post-remedial levels achieved routinely surpass the authorized limit for a site. However, because this reduction is highly dependent on field conditions, it cannot be predicted and pre-remedial action designation of this reduction as a specific goal would be likely to significantly increase volumes of waste.
[14] An extremely unlikely assumption due to the slope and proximity to river.

Assuming a 20-acre industrial site could maintain a work force of 150 persons, the collective dose and estimated number of associated cancers for 1, 25, 50, and 200 years for continued use of the site under pre- and post-remedial action conditions were estimated and are presented in Table 8-6.

TABLE 8-6. Elza Gate Site, Tennessee, Pre- and Post-remedial Action Conditions for Industrial Scenario

INDUSTRIAL SCENARIO ANALYSIS				
Years Integrated Pre-remedial Action	**Collective Dose (person-rem)**	**Estimated Cancers (fatal)**		
1	11	0.006		
25	290	0.2		
50	590	0.3		
200	2340	1.2		
Years Integrated Post-remedial Action	**Collective Dose (person-rem)**	**Estimated Cancers (fatal)**	**Collective Dose Averted (person-rem)**	**Cancers Averted**
1	0.2	0.0001	11	0.006
25	5	0.003	285	0.2
50	10	0.006	580	0.3
200	40	0.02	2300	1.2

Based on current use of the site (industrial/commercial) and assuming pre-remedial radiological conditions, dose to the reasonable MEI at the site was estimated to be about 78 mrem (0.78 mSv) in a year. An individual working at the facility and receiving this dose for 25 years would incur a potential incremental lifetime individual risk of about 1 in 1000 (about $1x10^{-3}$). It is highly unlikely that any individual would actually receive this dose for 25 years. Similarly, given the spotty and localized nature of the contaminant, it is highly unlikely, if not impossible, that a large number of the employees would be exposed to this dose; however, for the purposes of assessing collective dose, it was assumed that all 150 workers were exposed to this dose.

The total cost of this remedial action was about $5,000,000. The cost per person-rem averted for this project is $2,200 ($5,000,000/2340 person-rem) for 200 years of operation and $18,000 ($5,000,000/290 person-rem) for the 25-year period. This equates to about $4,200,000 per potential cancer averted ($5,000,000/1.2 fatal cancers) over the 200 year integration period. This assessment ignores risks associated with worker dose and fatal accidents that would be expected to be less than 1. There were no fatal accidents on this project.

To illustrate the relationship between dose criteria and cost/benefit, consider Figure 8-2 that shows waste volume to uranium concentration relationships. It is apparent that increasing the uranium limit from 35 to 80 pCi/g would have decreased waste volume by less than 10% and would result in little cost savings. However, decreasing the authorized limit from 35 to 20 pCi/g would produce a 2.4 times increase in volume of the waste and a corresponding increase in costs. The collective dose reduction for this additional remedial action would be on the order of 17 person-rems over 200 years. This incremental action would have resulted in a cost per person-rem avoided on the order of $400,000 per person-rem (about $800,000,000 per fatal cancer averted) compared to the $2,200 per person-rem for the entire project. This indicates that more extensive remedial actions would not be reasonable.

8.3 Case Study #3: Maywood, New Jersey

This case study represents a reasonable semi-quantitative assessment, although data to support volume estimates for the lower concentration alternatives were limited, producing significant uncertainty in the cost estimates at these levels. In addition to this semi-quantitative analysis, which used conservative but reasonable scenarios for exposure under all conditions, the results of a second analysis which used reasonable assumptions for the no-action option and worst-case exposure assumptions for cleanup alternatives are discussed. This comparison demonstrates the importance of using best-estimate scenarios for semi-quantitative evaluations. Mixing reasonable and worse-case assumptions can bias the results.

Site

This site includes a former thorium processing site and vicinity properties that contain residual radioactive material derived from the site. The site processed thorium and rare earth ores primarily for commercial uses. Many of the most contaminated properties have been remediated. This discussion addresses remedial action at the remainder of the vicinity properties and the site proper. Details on previous vicinity property cleanup are contained in the DOE certification docket for the Maywood remedial actions.

The primary contaminant of concern is Th-232. Radionuclides present in lesser amounts include U-238, U-234 and Ra-226. The site is located in an industrial area and the vicinity properties include primarily neighboring residences. The site has since been remediated by DOE, transferred to the Army Corp of Engineers, and is on the CERCLA national priority list (NPL).

Basis for Standards

The cleanup criterion used for the action was the DOE Order 5400.5 guidelines for radium and thorium, that is to reduce the concentrations to levels at or below 5 pCi/g for the surface and 15 pCi/g for the subsurface radionuclides based on the ALARA process. At the time of the analysis, the project was in the “feasibility study” phase and DOE was working with EPA to develop the final remediation goals. Table 8-7 provides project costs, doses, and collective doses integrated over 200 years associated with no action and various cleanup goals (all of the alternatives except no action assume that post-remedial action concentrations on the soil surface are 5 pCi/g with the ratio of Th-232 and its progeny being four times the concentration of Ra-226 and its progeny). On the basis of these data, cost per dose and cost per cancer averted can be estimated.

As indicated in Table 8-7, the baseline costs for this project (indicated as the “No Action” alternative), cost $16M. Decontamination of these properties to 30 pCi/g will reduce collective doses by 11,000 person-rem at an additional cost of $61M (total of $77M). The incremental reduction to 15 pCi/g will avert an additional 440 person-rem and cost an additional $61M (total of $138M). Remediating to 5 pCi/g will avert an additional 280 person-rem in addition to that averted by the 15 pCi/g limit and cost between $30M and $120M[15] additional (total between $168M and $258M). The incremental costs per person-rem avoided under each alternative

[15] The cost of the 5 pCi/g alternative is uncertain because measurement on these radionuclides is sufficiently near to background that the actual volume of waste to be removed cannot be adequately defined with normal survey data.

cleanup level are $5,500, $140,000 and $110,000 to $430,000 for the 30 pCi/g, 15 pCi/g and 5 pCi/g cleanup alternatives. (See Table 8-7.) This equates to about $9M per hypothetical fatal cancer avoided at the 30 pCi/g level, $230M per hypothetical cancer averted for the 30 to 15 pCi/g increment, and between $180M and $270M for 15 to 5 pCi/g increment.

TABLE 8-7. Predicted Costs, Radiation Doses, and Collective Doses for Various Criteria at Maywood, New Jersey

Alternative Remedial Action Criteria	Total Project Cost[a]($M)	Residual Dose to Exposed Individual (mrem/yr)	Residual Collective Dose (person- rem) for 200 years[b]	Remediation Worker Collective Dose (person- rem)
No action	16	12-2800	12,000	—
30 pCi/g	77	3.6 (Res[c]) 8.2 (Com[d])	880	18
15 pCi/g	138	1.8 (Res) 4.1 (com)	440	24
5 pCi/g	168 to 258	0.6 (Res) 1.4 (Com)	160	30

a. Detailed cost analysis is presented in the Feasibility Study for the No-Action alternative and Phased Action with 15 pCi/g subsurface criterion. The costs for 20 pCi/g and 5 pCi/g alternatives were scaled with the estimated change in waste volume. The waste volume for the 30 pCi/g criterion was estimated to be 56% of the waste from the 15 pCi/g alternative. The 5 pCi/g alternative was estimated to increase waste volume by 20 to 30%. The No Action alternative assumes continued environmental monitoring ($480,000 per year) and 5-year remedy reviews ($200,000 each) for 30 years.

b. An integration period of 200 years is assumed in the estimate of collective dose from exposure to residual radioactive material (evaluations beyond this time would require assessments of waste disposal alternatives and associated collective doses); implementation times for remedial action workers were assumed to be 9, 12, and 15 years for the 36, 15, and 5 pCi/g alternatives, respectively.

c. Estimated for expected conditions following remediation at residual properties (current use).

d. Estimated for expected conditions following remediation at commercial/industrial properties (current use).

As in the other examples, risks associated with the remedial actions had not been taken into account in the results stated above. Table 8-8 presents the risks of fatal accidents for remediation workers due to the transport of the waste as well as the risk averted in the analysis above. The incremental worker accident risk increases as expected with greater remediation volumes. The transportation related risks are insignificant at the 30 pCi/g criteria and lowering the criteria is shown to only result in minimal incremental increases to this risk. Depending on the volume of wastes resulting from the last increment (15 pCi/g to 5 pCi/g), the impact of the transportation and worker risks could range from that of reducing the benefits (0.14 cancers averted over the 200 years) by only a few percent to that of generating more risk than is averted by the incremental cleanup level.

TABLE 8-8. Comparison of Risk Averted to Worker and Transportation Risk at Maywood, New Jersey

Remedial Action Criteria	Incremental Transportation Accident Risk[a] (fatalities)	Incremental Remediation Worker Accident Risk (fatalities)	Incremental Excess Fatal Cancers due to Remediation Worker Exposure[b]	Incremental Cancers Averted by Remedial Action to Criteria
No action	—	—	—	—
30 pCi/g	0.004 rail 0.1 truck	0.005	0.009	5.5
15 pCi/g	0.002 rail <0.1 truck	0.009	0.003	0.22
5 pCi/g	0.002-0.003 rail <0.2 truck	0.001 — 0.01	0.003	0.14

a. Transportation risks include the risks associated with transport of the waste from the site to a commercial disposal site by rail, and transportation of borrow soil from an off-site borrow area to the site. (Risk associated with disposal or management of the waste at the disposal site are not included.) Both waste volume and borrow soil volume requirements are assumed to be proportional to the estimates of soil requiring excavation under each criterion.

b. Fatal Cancers were estimated by multiplying the collective dose (person-rem) by a risk factor of 500 cancers per million person-rem. a factor of 600 cancers per one million person-rem was used for members of the public (that is, residential use scenarios).

The data above are based on the Department's assessment of the site and environs "expected conditions." It considers likely use of the properties and takes credit for soil cover and shielding. In the Department's negotiations with EPA to establish cleanup criteria for this phase of the Maywood project, EPA proposed that the analysis be conducted for the worst-case scenario and giving no credit for soil cover. Table 8-9 presents the average individual dose for residential and industrial/commercial uses and residual and averted collective doses for the worst-case scenario.

The 30 pCi/g alternative was not assessed for the EPA scenario. For the EPA scenario, the cost per person-rem for the 15 pCi/g alternative was estimated to be between \$24,000 and \$55,000 per person-rem averted. This equates to between \$41,000,000 and \$92,000,000 per hypothetical cancer avoided.) Similar estimates for the 15 pCi/g to 5 pCi/g increment indicated that this additional cleanup would cost between \$5,000 and \$26,000 per person-rem averted (between \$7,500,000 and \$43,000,000 per hypothetical risk of fatal cancers). The decrease in the cost for collective dose (for health effects) between the 15 pCi/g criteria and the incremental reduction to 5 pCi/g may be an artifact of the assumptions. Under the scenarios used in the EPA estimates, material that was buried and not available to expose the public under the "No Action" alternative was assumed to be at the surface in the 15 pCi/g scenario despite the fact that it would be covered in that scenario as well. This artificially reduces the effectiveness of the first increment (that is, it compares a realistic no-action alternative scenario to a conservative scenario for the remedial action). It is extremely difficult to compare alternatives under such conditions and demonstrates the importance of using scenarios that are similar for all alternatives.

TABLE 8-9. Predicted Post-cleanup Dose, Collective Dose, and Collective Dose Averted by Criteria (Worst-case Exposure Assumptions for Cleanup Alternatives)

Remedial Action Criteria	Residual Individual Dose (mrem/year)	Residual Collective Dose (person-rem)	Collective Dose Averted (hypothetical Cancers averted)
15 pCi/g	122 (Res[a]) 66 (Com[b]) 189 (Future[c])	9,800 7,000[d]	2,200 person-rem 5,000 person-rem (1.1 cancers) (2.5 cancers)
5 pCi/g	40 (Res) 22 (Com) 61 (Future)	3,200 2,400	8,200 person-rem 4,600 person-rem (4.1 cancers) (2.3 cancers)

a. Estimate for worst-case conditions following remediation of residential properties.

b. Estimate for worst-case conditions following remediation of commercial/industrial properties, assuming continued commercial/industrial use.

c. Estimate for worst-case conditions following remediation of commercial/industrial properties, assuming residential use.

d. Assumes all properties are residual in the future.

In any case, the comparison of these two analyses (expected scenario analysis and worst-case analysis) demonstrates the need to clearly define the process for selecting comparable scenarios. Although in both analyses the cost per dose or health effect averted is relatively high, the use of one or the other of these analyses could very easily result in the selection of different cleanup criteria.

It is critical that risk or dose assessments used in these types of comparisons represent the best estimates of expected risk that can be calculated. Bounding assessments can be of value when considering the uncertainty of best estimates. Although, if time and resources permit, a probabilistic risk assessment would be preferable for estimating uncertainty, because bounding estimates developed to quantify 95th percentile risks can significantly overestimate the risks. In general, worst-case scenarios should only be applied for screening purposes, and never in relative risk comparisons. They are prone to biasing the results in a manner that is not readily detectable and are difficult to compare to competing non-health risks or actuarial risks that are normally “best estimates.”

This example also illustrates another important factor related to the need to define the process for selecting the comparative scenarios and evaluating the alternatives. Under the expected use scenario (as defined in the DOE analysis) all remediation criteria alternatives (30 pCi/g, 15 pCi/g, and 5 pCi/g) achieve the dose limit and constraints, and the 5 pCi/g criteria achieves the goal of a few mrem per year, or less, (although at great cost per person-rem averted). However, in the conservative assumptions (See Table 8-9), none of the alternatives are projected to achieve the “few mrem/y” goal. The waste volume data for the 5 pCi/g criteria are very uncertain because of the difficulty in adequately characterizing radium and thorium at these low concentrations. If the concentration limit was reduced by one third or one fourth to ensure compliance with a 15 mrem (0.15 mSv) per year limit (under the worst-case scenario) survey costs and remedial action costs would be further increased, not only as a function of waste volume, but also as a result of added survey costs, extensions of schedules to await verification of compliance from laboratory analyses, and possibly extra excavation to ensure compliance.

Although not considered in these analyses, it is not clear that some of these factors would not affect the cleanup costs under the 5 pCi/g criteria. This scenario illustrates the importance of communicating the results of an ALARA analysis with responsible parties (e.g. EPA) in determining final remediation goals.

8.4 Case Study #4: Ventron, Massachusetts

This case study represents another situation employing a semi-quantitative approach. However, it is a situation where a land use scenario other than industrial/commercial or suburban residential is the likely use. This is a good example of unrealistic and conservative exposure scenarios and assumptions used in many guidelines development efforts. The Ventron Site is a 3-acre site in a heavily developed area that directly abuts Massachusetts Bay (actually the mouth of the Danvers River) on two sides. The resident-farmer scenario was still evaluated assuming 100% of the milk/meat/fish and 50% of the produce was produced on site. These are extremely conservative assumptions.

Site

The former Metal Hydrides site in Beverly, Massachusetts, processed uranium compounds and scrap to produce uranium for the Manhattan Engineering District (MED) and Atomic Energy Commission (AEC). Operations contaminated portions of the buildings and grounds on site plus some of the properties around the site. The 3-acre site presently is used for industrial applications.

Basis for Standard

The authorized limit for cleanup of this site was developed consistent with DOE 5400.5 requirements and guidance. An assessment of potential doses was completed for industrial use, recreational use, and the resident farmer scenario. The analysis indicated that the 100 mrem (1.0 mSv) in a year dose limit would not be exceeded if total uranium concentrations were less than 1,800 pCi/g, 3,100 pCi/g, and 480 pCi/g for the industrial, recreational, and farmer scenarios, respectively.

To select an authorized limit that was as far below the derived 100 mrem (1.0 mSv) in a year equivalent concentration guideline values as is reasonably achievable, an analysis of the relationship between concentration and waste volume (a surrogate for cost) was performed. This analysis indicated that waste volumes (and costs) generally were constant to about 60 pCi/g of U-238 (120 pCi/g total uranium). On this basis, an authorized limit of 100 pCi/g total uranium (about 48 pCi/g U-238 and U-234, and 4 pCi/g U-235) was approved. This limit would ensure that doses under the expected use of the property would be less than 5.5 mrem (5.5 E-2 mSv) in a year to the MEI or representative person of the critical group. Lifetime risk of a fatal cancer for a worker continuously exposed (for 25 years) to this dose would be about $7x10^{-5}$ (7 in 100,000). If the site were to continue to be operated as an industrial facility, residual collective dose would be less than 0.2 person-rem per year or about 8 person-rem and 33 person-rem integrated over 50 and 200 years, respectively. This assumes that the facility employed 30 persons for the entire integration period and all persons receive the 5.5 mrem (5.5 E-2 mSv) per year estimated for the MEI or representative person of the critical group. Assuming a linear no threshold relationship between dose and health effects, the residual radioactive material on site after the cleanup would result in no radiation-induced cancers. The projected potential is 0.02 fatal cancers, or effectively zero, over 200 years of operation. However, it is expected that post-remedial action concentrations of uranium will be below the approved authorized limit and hence, potential doses and associated risks will be lower as well.

In the unlikely event that the site is used in a manner similar to the conditions set forth for the resident-farmer scenario, the maximum dose would be less than 21 mrem (0.21 mSv) in a year. This represents a $3x10^{-4}$ lifetime risk of cancer. Continuous exposure to such a dose (assuming the site could support six persons under the resident-farmer scenario) would produce a maximum collective dose of 0.1 person-rem/year or an integrated dose of about 25 person-rems over 200 years. Assuming the linear relationship between collective dose and health effects, 0.01 cancers over 200 years may be calculated.

A more likely potential use for the site is a condominium complex, which is not unusual for this type of property in this region. Given a 3-acre lot, assuming a maximum of about 15 dwellings per acre and four residents per unit, the area could house a maximum of about 180 individuals. A reasonably conservative dose assessment indicates that the maximum dose to individuals living on the first floor of a condominium would be about 9 mrem (0.09 mSv) per year (individual lifetime cancer risk about 1.5 in 10,000) and for higher floors about 1.5 mrem (0.015 mSv) per year (individual risk of about 1.5 in 100,000) assuming the 3 acres were uniformly contaminated to 100 pCi/g total uranium (a very conservative assumption as average concentrations following cleanup are normally many times less than the standard). The annual collective dose would be 0.07 person-rem. Integration over a 200 year period would indicate less than 11 person-rem (hypothetical 0.06 fatal cancers in 200 years).

Summary

Table 8-10 presents the summary of collective doses from the various scenarios. This analysis was prepared prior to completion of remedial action; however, preliminary engineering estimates at the proposed uranium criteria indicated the cost of the project would be on the order of $20,000,000. This cost includes building remedial action and renovation as well as soil cleanup. As noted above, it was anticipated that residual levels of uranium at the site would be below those used in the dose assessments reported above and hence, the actual potential doses and associated risks also would be lower.

TABLE 8-10. Ventron, Massachusetts, Exposure Scenario Collective Dose Analyses

Years	Residual Collective Dose person-rem	Residual Risk Total Potential Cancers
	Industrial Use Scenario	
25 200	4 33	0.002 0.02
	Residential Farmer Use Scenario	
25 200	3 25	0.002 0.01
	Condominium Complex	
25 200	18 144	0.009 0.07

For the two likely use scenarios (Condominium and Industrial) evaluated, remedial action to the authorized limit is expected to reduce doses well below the dose constraint. If the residential-farmer scenario were assumed (the worst plausible use) the selected authorized limit is well below the primary dose limit.

Table 8-11 reflects the impact of additional remedial measures implemented to reduce the potential maximum dose for the residential scenario.

TABLE 8-11. Impact of Additional Remedial Measures – Residential Scenario

Projected Dose Under Residential Scenario	Uranium Criteria for Remedial Action	Increase in Waste Volume	Additional cost*
21 mrem/yr	100 pCi/g (48 pCi/g U-238)		
15 mrem/yr	70 pCi/g (35 pCi/g U-238)	1,550 cubic yards (Figure 8-3)	$530,000

*assuming $220/cu.yd. for disposal and $120/cu.yd. for transportation

If the same reductions were taken for each of the likely use scenarios, Table 8-12 shows exposure reductions that would be anticipated (over the 200-year integration period).

TABLE 8-12. Anticipated Exposure Reductions

Post-remedial Use	Person-rem Reduction	Cost per Person-rem Avoided
Industrial	10	$53,000
Residential farmer	7	$76,000
Condominium	42	$12,000

This is equivalent to a cost per fatal cancer avoided of between $27,000,000 and $130,000,000, suggesting that the use of the semi-quantitative process employed to establish the authorized limit resulted in a decision that was reasonable.

Further reduction of the authorized limit could not be justified solely on the basis of health considerations. However, a clear drawback of this semi-quantitative “cost-effectiveness-type” of process using waste volume and concentration as surrogates for cost and dose, respectively, is that there is no easy way to assess overall benefit between no action and alternative cleanup levels.

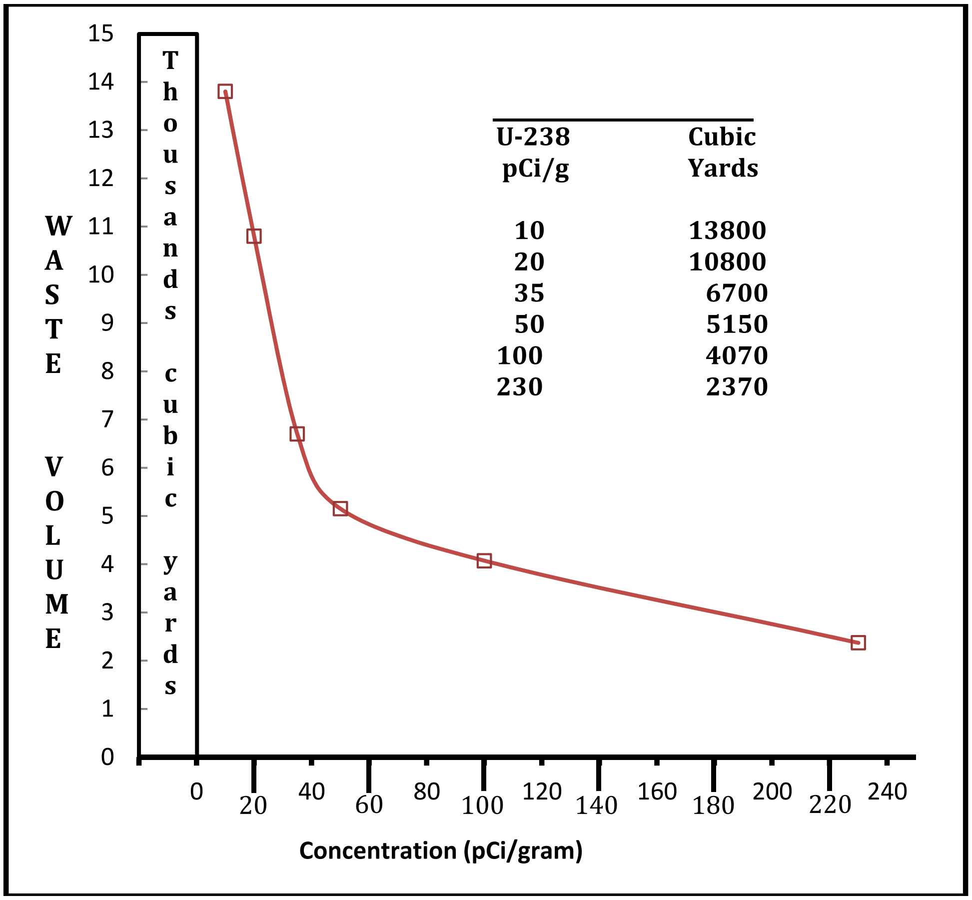

FIGURE 8-3. Alternative Concentration Limits vs. Estimated Waste Volume

8.5 Case Study #5: Weldon Spring Site, Missouri

The Weldon Spring remediation was based on an application of the ALARA process and the CERCLA process. It is a large site containing a large industrial complex for processing uranium. The uranium contamination distribution in soil, buildings, and quarry varies widely and the remediation decisions included radiological and non-radiological considerations.

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Ra-226, Ra-228, Th-230, Th-232, and daughters in soil (0-60 cm) 5 pCi/g. U-238 in soil 30 pCi/g (natural U).

Site

This 226-acre AEC site (now DOE) was originally part of 17,000 acres of land acquired by the U.S. Army to construct an ordnance works. Uranium and thorium ore concentrates were processed from 1957 to 1966. Many buildings were constructed to house the processing equipment. Waste streams, including raffinates from the refinery and washed slag from the uranium recovery process, were piped to the raffinate pits and the decanted liquids were drained through sewers to the Missouri River via a 2.4-km natural drainage channel. The site contamination was extremely non-homogeneous, with a few highly concentrated areas that extend to a depth of a few tens of centimeters and the bulk of the soil area relatively lightly contaminated on the surface only. The sludge, in four raffinate pits and two ponds, was highly contaminated but confined. Contaminated surface water runoff was contained in a quarry. Table 8-13 presents the estimated volume of contaminated media.

Basis for Standard

The site was cleaned in compliance with CERCLA and NEPA. The standard was derived in 1991, using a site-specific process similar to that required by DOE Order 5400.5. Contaminated debris from buildings and equipment constitute the bulk of the volume (and cost) disposed and the soil, regardless of the level selected, comprised a relatively small fraction of the total. When the contamination is highly concentrated in the hot-spots, there is relatively little difference in the volume of soil that has to be removed to reduce the residual contamination to a small fraction of the initial concentration. Hence, relatively more restrictive cleanup standards could be justified in this case through ALARA considerations. Nevertheless, the lifetime hypothetical risks could not be reduced to the EPA "target" range of 10^{-6} to 10^{-4}, due to exposures to radon. A dose limit of 25 mrem (0.25 mSv) per year, which EPA has used for several source-specific regulations including management of U and Th by-product material, also was considered but could not be achieved for the residential site-specific scenario in all site locations.

Cleanup targets for radium and thorium (Ra-226, Ra-228, Th-230, and Th-232) concentrations in surface soil of 6.2 pCi/g (background is 1.2 pCi/g) and 16.2 pCi/g in subsurface soil were considered. Table 8-14 shows the relationship of target U-238 concentrations in soil to cost and dose. An ALARA goal of 5 pCi/g was selected for Ra-226, Ra-228, Th-230, Th-232, and daughters in soil at all depths, including background, because it is the lowest concentration that can be reasonably achieved without excavating significant quantities of clean soils and without incurring costs that are disproportionately high for the corresponding risk reduction. (The cost for excavation and disposal of soil is $\$55/yd^3$.) The EPA acceptable indoor radon level of 4 pCi/L was considered.

The average U-238 concentration in soil was 190 pCi/g. The calculated annual dose to a farmer in the ash pond area is 42 mrem (0.42 mSv) per year, which represents a risk of 3×10^{-5}/y. Doses were calculated for concentrations in soil of 120, 60, 30, and 15 pCi/g for U-238. Removal of contaminated soil and backfill with clean soil would reduce and delay the dose after remediation due to shielding and erosion. For uranium, a soil cleanup target of 120 pCi/g without backfill (that would yield a calculated dose of 25 mrem (0.25 mSv) per year) was selected, with an ALARA goal of 30 pCi/g. Table 8-14 shows that there is little incremental risk reduction associated with the significant cost increases beyond the proposed action level.

Results

The primary cleanup effort to date has been directed toward remediating buildings and equipment – the most expensive part of remediation. A water treatment facility was planned for decontaminating the water from the quarry prior to disposal in the river. The site is adjacent to a large recreational area and that is the most likely use for the property after remediation. The potential doses to persons who may use the site for a variety of purposes, including rangers, visitors, recreational, residential, farming, and intruders, were estimated. It is anticipated that the

ALARA goals for concentrations in soil will be achieved. The incremental radiological risk to a resident would range from 0 to 6 x 10^{-3} with a median of 8 x 10^{-6} across the site. Background for radium in soil is 1.2 pCi/g and a small increment of 0.075 pCi/g corresponds to a risk of 1 x 10^{-4}. This reflects the difficulty in achieving either the target risk range or annual dose limit of 25 mrem (0.25 mSv) for residential scenarios for the areas of high contamination. However, the EPA acceptable indoor radon level of 4 pCi/L is likely to be met at all site locations. Dose projections for the site have focused on individual doses at various locations and times and not on collective doses to the population. State and EPA personnel have been involved with the proposed site cleanup plan.

TABLE 8-13. Volume of Contaminated Media at Weldon Spring, Missouri

Media	Volume (yd^3)
Sludge	220,000
Sediment	119,800
Soil	339,000
Structural Material	169,600
Process Chemicals	3,960
Vegetation	30,650
Total	883,000

TABLE 8-14. Relationship of Target U-238 Concentrations in Soil to Cost and Dose at Weldon Spring, Missouri

Concentration pCi U-238/g.	Volume yd^3	Backfill ft.	Cost $M	Annual dose Mrem
>120	—	0.5	—	20 @ 400 y
120	11,000	0	0.58	25 @ present
60	26,000	1.0	1.4	6.7 @ 800 y
30	—	2.0	—	1.5 @ 10,000y
30	37,000	0	2.0	6.7 @ present
15	50,000	2.0	3.0	8.38 @ 10,000y

Chapter 9. **QUANTITATIVE ALARA ANALYSIS**

As discussed in Chapter 4, a quantitative ALARA analysis generally requires the most effort and includes the following major steps:

- Identify and quantify the sources of radiation;
- Identify and define candidate radiation protection alternatives or systems (including waste stream treatment) that would reduce the exposure or doses;
- Quantify economic factors (cost of systems, operations, maintenance, etc.);
- Quantify exposures and doses to individuals and to populations in the vicinity of the DOE activity;
- Estimate the health risk and identify non-health detriments (or benefits); and
- Select one of the candidate radiation protection systems as ALARA.

Quantitative cost-benefit optimization methods are discussed in ICRP Publication 37, *Cost-Benefit Analysis in Optimization of Radiation Protection* (ICRP, 1982), and ICRP Publication 55, *Optimization and Decision-making in Radiological Protection* (ICRP, 1990). The most common quantitative ALARA analysis used is the cost benefit analysis and is discussed at length in this document. However, quantitative ALARA analyses can also be performed using a cost effect analysis, multi-attribute utility analysis, multi-criteria outranking analysis, Kepner-Tregoe (K-T) decision analysis, or analytical hierarchy process analysis. Each of these analyses are discussed further in this Chapter and applicable examples of optimization as applied to DOE occupational radiation protection issues are provided later in this Handbook and in Munson et al., 1988.

9.1 Cost Benefit Analysis

Very complex or contentious issues may need a quantitative cost-benefit analysis[16] to help decision-makers select among alternatives. Cost-benefit analysis is often a good approach to use when the primary basis for making a decision is the monetary cost vs. monetary benefits of the alternatives. This type of analysis describes benefits and detriments in terms of the economic or monetary cost, and requires all attributes to be described in these terms. This is the most quantitative method described in this Handbook, and requires the greatest amount of quantitative information.

Selection of an appropriate cost-benefit factor for reducing dose involves a judgment of the relative values of dose, normally in terms of dollars per rem avoided. Additionally, guidance on optimization methodology will provide the basis for selection of collective dose values above which an ALARA review is appropriate. Numerical criteria for ALARA decision making should include types of radioactive effluent contamination levels, and exposure scenarios.

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[16] U.S. Office of Management and Budget, OMB Circular No. A-94, *Guidelines and Discount Rates for Cost-Benefit Analysis of Federal Programs* (October 29, 1992) presents general guidance on conducting cost-benefit analyses. OMB updates the discount rates for the methodology annually.

9.1.1 Total Detriment Equations

Total detriment includes all deleterious effects, both health effects and non-health effects. These include real and imagined effects, perceived effects, anxiety, risk aversion, and any others associated with the radiation source. The *Total cost*, or the monetary equivalent of the total detriment (Y), can be written:

$$Y = \alpha S + \beta \Sigma_j N_j f_j(H_j) \qquad \textit{Equation 9-1}$$

Where:

α is the health detriment cost coefficient (dollars per person-rem),

S is the collective dose (person-rem),

ß is the non-health detriment cost coefficient (dollars per person-rem),

N is the number of individuals exposed,

f is a function of the individual doses, which would depend on risk aversion attitudes and regulations or company policies, and

H is the mean total effective dose (rem) where j represents a particular group of individuals for N, *f*, and H.

In Equation 9-1, all components of the non-health detriment are taken together and assumed to depend on individual doses. This section will not address the non-health detriment portion of the cost-benefit analysis further, but rather will focus on the health detriment and specifically on the radiation-related health detriment.[17] Thus, Equation 9-1 becomes:

$$Y = \alpha S \qquad \textit{Equation 9-2}$$

Two components of detriment are: 1) the assumed radiation-induced health effects that may be expressed in monetary terms through the use of the coefficient α ($/person-rem), and 2) a non-health coefficient ß ($/person-rem) that is related to societal considerations. Many ß "terms" are not predictable and can be strongly dependent on such factors as the local attitude and may be more suited for evaluation using multi-attribute type processes. Different values for the worth of the detriment might be warranted for workers and members of the public.

9.1.2 Cost-Benefit Optimization

The net benefit of an activity may be expressed mathematically in the following manner:

$$B = V - (P + X + Y) \qquad \textit{Equation 9-3}$$

[17] *Natural Resource Valuation: A Primer on Concepts and Techniques*, July 1997, provides examples of related techniques for valuation of non-health detriments to support cost-benefit assessments.

Where:

B is the net benefit of the activity,

V is the gross benefit of the activity,

P is the basic production costs,

X is the cost of achieving a selected level of protection, and

Y is the cost of radiation detriment of the activity at a selected radiation protection level.

The optimum level of radiation protection is obtained by maximizing the net benefit B of implementing an alternative. Assuming the collective dose (S) is the relevant independent variable; Equation 10-3 is differentiated with respect to S and set equal to zero:

$$\frac{dV}{dS} - \left(\frac{dP}{dS} + \frac{dX}{dS} + \frac{dY}{dS}\right) = 0 \qquad \textit{Equation 9-4}$$

The values of V and P are generally independent of S for a given activity, that is, the gross benefit worth and production cost of an activity generally are not affected by variations in S. Thus, components dV/dS and dP/dS are 0 and the optimum condition may be written as:

$$\frac{dX}{dS} = -\frac{dY}{dS} = -\frac{\alpha \mathrm{S}}{\mathrm{dS}} = -\alpha \qquad \textit{Equation 9-5}$$

The optimum degree of radiation protection is obtained at a value of S such that the incremental increase in the cost of the radiation protection per unit of collective dose is equal to the incremental reduction in detriment per unit of collective dose. This is a differential cost-benefit equation[18] and is used to optimize radiation protection efforts. This form is best-suited for applications where the exposures (and cost of health-detriment) can be associated with a release of radioactive material that can be described in an equation by a continuous variable.

In most cases, exposures are not continuous variables; rather, the alternative radiation protection options result in finite incremental changes in exposures (and cost of the health-detriment). The equation may be written:

$$\frac{(X_2 - X_1)}{(S_2 - S_1)} = \frac{(Y_2 - Y_1)}{(S_2 - S_1)} = -\alpha \qquad \textit{Equation 9-6}$$

[18] To select the optimum radiation protection system, it is necessary to define, cost, and evaluate the performance of several candidate systems which range from the most rudimentary to the more technologically sophisticated systems. When several candidate systems are considered, the ALARA process will identify the **optimum** system. If only two systems are evaluated, the only finding made is whether the change from the first system to the second system is **cost-effective**. There is a vast difference between the two applications, with economic savings favoring the optimization. A good example is a typical waste stream which will be discharged to the environment. The most rudimentary treatment can be expected to remove a significant fraction of the contaminant and cost relatively little. Further removal efforts will be less effective because there is less contaminant remaining in the waste stream and the more sophisticated removal components will be more and more costly. The ALARA process will indicate the choice of several candidate systems which will result in the minimum total cost, e.g., optimization.

The subscripts indicate the candidate radiation protection systems considered. System 2 is more costly than System 1, and results in less collective dose than System 1. This expression indicates that the optimum is achieved when the incremental cost of the radiological protection system equals the decremental cost of the detriment.

> If the dose to the maximally exposed individual (MEI) from all exposure pathways complies with the dose limit, the optimum choice using cost-benefit analysis is the alternative with the least total cost – where the total cost includes the reduction in the radiation detriment (negative) and the added cost of the control system.

9.1.3 Detriment and Monetary Equivalent

Quantifying detriment in terms of the economic or monetary equivalent for a specific factor is a feature of a quantitative cost-benefit analysis. Some of the concepts may also be applicable to other ALARA process evaluations.

9.1.4 Dose, Risk, and Health Detriment

The principal radiation protection benefit of the process system is the reduction of the dose to the individuals with the highest exposures and the collective dose to the exposed population. For radiation protection purposes, dose is presumed to be a surrogate for risk. The risk of serious health effects is assumed, for radiation protection purposes, to be linearly proportional to the effective dose (or effective dose equivalent under DOE Order 5400.5) for all values of dose greater than background.[19] The health detriment (risk of contracting radiation-induced cancer or serious hereditary disease) to the exposed population from an activity that causes exposures to radiation is assumed to be proportional to the collective dose to the population from: 1) direct exposures to the radiation external to the body; and 2) internal exposures (material taken into the body by ingestion, inhalation, and absorption). Even though the number of potential radiation-induced health effects within a population is assumed to be proportional to the collective dose, there is no promulgated limit for collective dose. However, a value of 100 person-rem in a year has been selected by DOE for reporting purposes, rather than a collective dose limit.

The magnitude of a dose, whether to individuals or collective dose to a population, will depend on:

- Radiation source geometry;
- Type and energy of radiation emissions;
- Exposure modes and potential exposure pathways;
- Population distribution;
- Location of the receptor with respect to the source location;
- Duration of exposure;

[19] There is scientific uncertainty about cancer risk in the low-dose region below the range of epidemiologic observation, and the possibility of no risk cannot be excluded (CIRRPC Scientific Panel Report No. 9).

- Quantity of radioactive material released;
- Dispersion by natural forces;
- Lifestyle of those exposed; and
- Other parameters.

If the health-detriment can be quantified, a cost of the detriment may be postulated for cost-benefit purposes.

9.1.5 Quantifying Risk of Radiation-Induced Serious Health Effects

Data used to derive quantitative risk values for radiation-induced serious health effects generally are based on human exposures to high levels of radiation delivered at high dose rates, such as the survivors of the nuclear weapons in Japan, radium dial painters, and the use of radiation to diagnose and treat a variety of illnesses. There are no data that demonstrate harmful effects for doses in the regime ranging from "background" exposure levels to doses at the limits selected for members of the public or for workers. Most authoritative organizations that have quantified radiation-induced risks caution that the values are applicable to doses of 10 rads or greater. DOE believes that it is prudent to be consistent with Federal guidance and to use the linear no-threshold assumption. DOE applies the concept for radiation protection purposes and for comparing and evaluating radiation protection alternatives for protection of the public and the environment for ALARA or other purposes.

9.1.6 Monetary Considerations for Reduction in Collective Dose

ALARA analyses require the comparison of many unlike factors such as collective dose, and control costs. For the purposes of quantifying and comparing such factors it is necessary to express them in like terms, using a common denominator. Although any unit of comparison can be used effectively in multi-attribute analyses, the unit used for cost-benefit analysis is cost. In such situations, the factor or attribute of interest (that is, collective dose, S), should be expressed in terms of a monetary equivalent.

Consistent with the assumptions of a linear relationship of health-effects with dose, it is generally assumed that alpha (α), the monetary value of a unit of collective dose, is independent of the magnitude of the individual doses comprising the collective dose – provided that the doses to individuals are within the appropriate dose limit.[20] In 1973, the AEC assumed a constant value α = \$1,000 for a rulemaking (Appendix I of 10 CFR Part 50). At that time, the AEC did not attempt to derive a value for the monetary worth of collective dose using first principles. Attempts to rationalize the value of such indicators as willingness to pay insurance premiums, commitment of resources for highway safety, cost of medical treatment for cancer, hospitalization cost, loss of years of life expectancy, loss of earnings, Gross National Product statistics, and the cost of worker replacement have been considered over the several decades since the need was identified. An AEC literature search in the early 1970s found values for α ranging from about \$10 to \$1,000 per person-rem.

[20] However, there are situations where varied monetary equivalent values have been applied that are dose-dependent.

The NRC reevaluated the monetary equivalent value that was used in Appendix I of 10 CFR Part 50[21] and issued regulatory analysis guidelines in 1995 that recommended $2,000 per person-rem as the current monetary equivalent value for converting collective dose to dollars. DOE also completed evaluations to determine the appropriate monetary conversion factors for collective dose[22] and, on the basis of these analyses, the Department recommends that the monetary equivalent for a collective dose used in DOE ALARA evaluations should be between $1,000 and $6,000 per person-rem. For most applications, the $2,000 per person-rem recommended by NRC is acceptable for DOE application. However, because of the uncertainty in the values, it is recommended that detailed ALARA evaluations use the range for comparing alternatives. Some have suggested significantly lower values on the basis of single analysis, while others have suggested a greater range of values.[23] After a broad review of the current literature, DOE believed that its recommended range is still appropriate. DOE ALARA analyses should apply monetary equivalents for a person-rem in the range from $1,000 to $6,000.

> The monetary value of a unit of collective dose is assigned a symbol α. NOTE: The results of the quantitative cost-benefit ALARA evaluation is not very sensitive to the value selected for α and must not combine health and non-health effects in the same coefficient. By assigning a monetary value to the willingness to avoid a serious health effect, one can express the health detriment (Y) in monetary terms. From equation 9-2, $Y=\alpha S$, where S is the collective dose of the exposed population and α is the health detriment cost coefficient, it is recommended that α be assigned a value in the range of $1,000 to $6,000 per person-rem.

For comparison, assuming one person-rem represents a potential risk for workers on the order of 5 in 10,000 ($5x10^{-4}$ fatal cancers per person-rem) and for the pubic about 6 in 10,000 ($6x10^{-4}$ fatal cancers per person-rem). The recommended range ($1,000 to $6,000 per person-rem) would thus equate to a range of about $2,000,000 to $12,000,000 per hypothetical radiation-induced cancer death averted.

9.1.7 Non-Health Detriment

There are non-health detriments, some of which may be introduced into a cost-benefit analysis, that are not readily expressed in monetary terms and are not linearly related to collective dose. For example, public policy considerations, comfort considerations for workers, or design or operating decisions made to avoid possible losses of environmental amenities. Non-health components generally are not proportional to collective dose and may not be related to actual dose at all, for example, increased risks in industrial safety.

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[21] NUREG-1530, *Reassessment of NRC's Dollar Per Person-Rem Conversion Factor Policy*, U.S. Nuclear Regulatory Commission, December 1995, and NUREG/BR-0058, *Regulatory Analysis Guidelines of the U.S. Nuclear Regulatory Commission*, U.S. Nuclear Regulatory Commission, November 1995.

[22] *Estimating Costs for Man-rem Exposures*, U.S. Department of Energy, Office of Waste Management: M.H. Chew & Associates, Inc., April 1996.

[23] The rationale discussed here, that is, the willingness to commit resources to avoid a radiation-induced serious health effect is only one of several rationales used to select a value for α.

The non-health component may be computed by determining the total cost of the completed radiation protection system and subtracting the cost of the radiation protection system with only those features that can be justified considering only the health-effect detriment rather than the total detriment. This difference should be included in the records of ALARA applications as well as the rationale for the non-health costs.

The monetary equivalent of non-health detriment is generally depicted by the symbol beta, β, and can be assigned a monetary value ($) or assigned a weighting factor through multi-attribute analyses or similar techniques, or simply recognized as a factor to be considered intuitively in the final selection of the radiological protection system. In some applications, the β coefficient is a complex function of potential individual doses and may be indicated symbolically as $\beta \, \Sigma_j \, N_j f(H_j)$. If β is the monetary coefficient of other (non-health) factors of detriment, N the number of individuals receiving a dose of H rem in a year.

> The value for β is much more difficult, *a priori*, to estimate than α because it can include considerations such as the cost of a Federal or State agency laying on requirements beyond those that can be rationalized by health risk evaluations to obtain a required permit or other approval. Additional confounding factors complicate the rationale, such as costs or impacts and benefits accrued to a population other than the one receiving the exposure. It could also include costs for purchasing property, expenses to avoid litigation, training or equipment costs, or demonstrations from interested or affected parties.

Other techniques, such as multi-attribute analyses, can permit some of the less quantifiable factors, such as comfort considerations or other environmental factors to enter into the decision-making process. Such non-health costs can be estimated by calculating the difference in cost between the optimum system based on radiation protection and the system selected. The cost difference should be determined and included in the records of ALARA decisions. When ALARA evaluations are based on the combined doses to workers and to members of the public, the values of α selected for the two groups generally should not differ substantially; however, the β factors might be quite different.

Although non-health components of the detriments are real, and should be recognized and quantified to the extent that one can do so, the methods used in quantification or other methods for introducing them in the decision-making process are variable and will not be discussed in this Handbook. However, several methods may be found in the literature and should be considered. For example, the report *Natural Resource Valuation: A Primer on Concepts and Techniques* (Ulibarri and Wellman, 1997) discusses a number of techniques that have been employed to estimate values for natural resources.

> In some cases, adequate information is available to permit a cost-benefit analysis to quantify elements important in the decision-making process. In other cases, the information might not be available or a quantitative cost-benefit analysis might not be practical to aid in a decision-making process involving ALARA exposures – in that case the decision will be based on less-quantitative factors. Documentation of the basis for the decision needs to be provided in all cases.

9.1.8 Cost-Benefit Example

As indicated previously, one characteristic of cost-benefit analyses is that the factors generally are expressed in monetary terms. The simplest case of optimization for radiation protection purposes may be demonstrated for the uranium mine example illustrated in ICRP Publication 55. In this case, a monetary value "alpha" (α), is selected for a unit of annual collective dose, S. Then, the monetary value of the collective dose (detriment), Y, is αS. The total annual cost is the sum of the annual cost for radiation protection, X, and the annual cost of the detriment, Y. The option that has the least total annual cost is the optimum selection.

To illustrate this technique consistent with ICRP Publication 55, a monetary value for collective dose of \$20,000 (person-Sv)$^{-1}$ will be assumed.[24] This is equivalent to \$200 per person-rem, which is outside of the range recommended in 9.1.6 of this Handbook. Table 9-1 presents the data for a simple cost-benefit analysis of the uranium mine example, provided above.

TABLE 9-1. The Simple Cost-Benefit Analysis for the Uranium Mine Options

Protection option	Annual protection cost X, \$	Annual detriment cost Y, \$	Total annual cost X + Y, \$
1	10400	11200	<u>21620</u>
2	17200	7100	24340
3	18500	6700	25200
4	32200	3900	36120
5	35500	3600	39060

Note: Assumes α = \$20,000 (person-Sv)$^{-1}$.
The optimum solution (minimum total cost) is underlined.

In Table 9-1, the annual protection cost, X_n, for each option, n, is estimated by conventional cost analyses and annualized. The annual cost of the detriment, Y_n is the product of α (\$20,000 per person-Sv) and the projected annual collective dose, S_n, for each option (see Table 9-2). The total annual cost for each option is the sum $X_n + Y_n$. Based on the Simple Cost-Benefit Analysis only, the first option is the optimum. However, note in Table 9-2, that the doses to Group I workers would be close to the 50 mSv worker dose limit for Option 1. To provide for sufficient operating flexibility, the preferred choice would then be Option 2 in the Simple Cost-Benefit Analysis.

[24] Historically, values for alpha ranging from "a few pounds Sterling" to \$1,000 per person-rem [\$100,000 per person-Sv] have appeared in the literature and have been assumed in many cost-benefit exercises. However, there is no specific value for the monetary value for a unit of collective dose that has been justified, rationalized, or endorsed by any national or international authority, nor is there any consensus value. The NRC has selected \$1,000 (person-rem)$^{-1}$ for some evaluations for rulemaking purposes, but only because it is the top of the range of values which was found in the literature at the time.

TABLE 9-2. Data for Options Considered in the Uranium Mine Example

Protection Option	1	2	3	4	5
Annual Protection Cost, $	10,400	17,200	18,500	32,200	35,500
Annual collective dose, person-Sv	0.561	0.357	0.335	0.196	0.178
Annual average individual dose to workers in group, mSv					
I	40.8	28.4	26.0	17.5	15.8
II	34.5	22.3	21.0	12.6	11.3
III	28.9	17.1	16.3	8.4	7.8
Discomfort from Ventilation	no problems	slight	slight	severe	difficult to work

1 sievert (Sv) = 100 rem,

1 person-sievert (person-Sv) = 100 person-rem

One of the radiological protection factors generally regarded as important, for decision-making purposes, is whether the individual doses are high or low relative to the appropriate dose limit. This type of consideration can be introduced into an extended cost-benefit analysis by introducing a "beta" (ß) term into the detriment:

$$Y_n = \alpha S + \Sigma \beta_j S_j \qquad \textit{Equation 9-7}$$

Where S_j is the collective dose comprised of the doses to the individuals in range j, and β_j is the additional monetary value assigned to unit collective dose in the range j.

Table 9-3 presents the distribution of average and collective doses of the workers among the three groups.

TABLE 9-3. Average Individual Doses to Workers in the Three Groups and Corresponding Collective Doses for the Options

Average annual individual dose (mSv)				Annual collective dose (person-Sv)		
Protection option	I	II	III	I	II	III
1	40.8	34.5	28.9	0.163	0.138	0.260
2	28.4	22.3	17.1	0.114	0.089	0.154
3	26.0	21.0	16.3	0.104	0.084	0.147
4	17.5	12.6	8.4	0.070	0.050	0.076
5	15.8	11.3	7.8	0.063	0.045	0.070

For illustration purposes, in the uranium mine example, the following additional criterion is assumed:

β_1 (<5 mSv) = 0

β_2 (5 to 15 mSv) = \$40,000 (person-Sv)$^{-1}$

β_3 (15 to 50 mSv) = \$80,000 (person-Sv)$^{-1}$

In the previous example, a constant value was assumed for alpha – the monetary value of the unit of collective dose regardless of the range of doses comprising the collective dose. That is, the importance of the doses received was assumed to be equal, regardless of the magnitude of the individual doses so long as the doses were within the applicable dose limit. The introduction of the beta terms permits one to place greater importance on the individual doses according to how close they are to the appropriate dose limit. Note that for doses that are a small fraction of the limit, there is no supplementary value at all, i.e., the beta term is $0.

The values assigned to the beta terms for each range of dose and the number of groups are arbitrary. Again, no national or international authorities have endorsed any values for beta or the ranges of importance for doses. However, some countries have applied the technique in providing guidance for their ALARA applications. The evaluations can be repeated with other values selected for alpha and beta to determine the sensitivity of the optimum determination to these parameters (sensitivity analysis).

As shown in Table 9-3, the average individual dose for workers in all three groups exceeds 15 mSv for Option 1, the entire collective dose of 0.561 person-Sv (see Table 9-4) is in the range 15 to 50 mSv, where the value of ß is $80,000 per person-Sv. The product, $80,000 x 0.561 = $44,880, is the partial detriment cost Y(ß) for considering the magnitude of the average dose relative to the dose limit. For Options 2 and 3, the average doses also are within range 15 to 50 mSv and are evaluated similarly. For Option 4, 0.070 person-Sv is in the range 15 to 50 mSv, and 0.126 person-Sv is in the range 5 to 15 mSv. Therefore, the cost Y(ß) for Option 4 is $80,000 x 0.070 + $40,000 x 0.126 = $5,600 + $5,040 = $10,640 and for Option 5, Y(ß) = $9,640. The partial detriment annual costs, Y(ß), are presented in Table 9-4.

TABLE 9-4. Annual Collective Doses in Each Individual Dose Range and Partial Y(ß) Detriment Cost for the Options Considered

Protection option	Annual collective dose - total (S) person-Sv	Annual collective dose - Range 1 (S1) person-Sv	Annual collective dose - Range 2 (S2) person-Sv	Annual collective dose - Range 3 (S3) person-Sv	Partial detriment annual cost, Y(ß), $
1	0.561	0	0	0.561	44,880
2	0.357	0	0	0.357	28,560
3	0.335	0	0	0.335	26,800
4	0.196	0	0.126	0.070	10,640
5	0.178	0	0.115	0.063	9,640

Note: [a] $ß_1$ (<5 mSv) = 0

$ß_2$ (5 to 15 mSv) = $40,000 (person-Sv)$^{-1}$

$ß_3$ (15 to 50 mSv) = $80,000 (person-Sv)$^{-1}$

Applying the selected beta values, as well as the alpha factor in the previous example (e.g., $20,000/person-Sv), the data in Table 9-5 were generated. The total annual cost for the several options, with consideration given to the annual collective dose and the average individual doses, is an extended cost-benefit analysis and is presented in Table 9-5.

TABLE 9-5. Extended Cost-Benefit Analysis for the Options Considered for the Uranium Mine Options

Protection option	Annual protection cost (X) $	Annual detriment cost Y(α), $	Annual detriment cost[a] Y(ß), $	Total annual cost = X + Y(α)+Y(ß), $
1	10,400	11,200	44,880	66,480
2	17,200	7,100	28,560	52,860
3	18,500	6,700	26,800	52,000
4	32,200	3,900	10,640	<u>46,740</u>
5	35,500	3,600	9,640	48,740

Note:[a] Assumes α = \$20,000 (person-Sv)$^{-1}$; $ß_1$ (<5 mSv) = 0; $ß_2$ (5 to 15 mSv) = \$40,000 (person-Sv)$^{-1}$; $ß_3$ (15 to 50 mSv) = \$80,000 (person-Sv)$^{-1}$

The optimum solution is underlined.

In the example of Extended Cost-Benefit Analysis above, the Options of choice would be either 4 or 5 however; the "comfort" factor was not included in the optimization determination. Note in Table 9-2 that the discomfort ratings for these two Options are severe and difficult to work, respectively. Taking all the factors into consideration, the likely decision would then be to select Option 3, since it provides sufficient dose reduction with only slight discomfort at a relatively median cost.

COST-BENEFIT ANALYSIS IN A NUTSHELL

A cost-benefit analysis can be a useful way to organize and compare the favorable and unfavorable impacts that a proposed action might have. It can help decision makers understand the implications of various options. In a cost-benefit analysis, the costs and benefits of an action are determined, quantified, and assigned monetary values to the extent possible. The difference in monetary value between costs and benefits is then calculated. In a very simple sense, a project can be said to benefit society if the monetary value of its benefits is greater than that of its costs. *Source: Poch, Gillette and Veil, 1998*

The standard criterion for deciding whether a program can be justified on economic principles is *net present value* – the discounted monetized value of expected net benefits (i.e., benefits minus costs). Net present value is computed by assigning monetary values to benefits and costs, discounting future benefits and costs using an appropriate discount rate, and subtracting the sum total of discounted costs from the sum total of discounted benefits. Discounting benefits and costs transforms gains and losses occurring in different time periods to a common unit of measurement. Programs with positive net present value increase social resources and generally are preferred. Programs with negative net present value generally should be avoided. When "benefits" and "costs" can be quantified in dollar terms (e.g., as avoided cost) over several years, these benefits can be subtracted from the costs (or dollar outlays) and the present value of the benefit calculated. Both intangible and tangible benefits and costs should be recognized. Costs should reflect opportunity cost of any resources used, measured by the return to those resources in their most productive application elsewhere. The alternative returning the largest discounted benefit is preferred. *Source: Guidebook to Decision-Making Methods (WSRC-IM-2002-00002) and OMB Circular No. A-94.*

9.2 Cost-Effectiveness Analysis

When performing an evaluation of a particular ALARA option, each has a level of protection cost and a corresponding collective dose. Only two variables are normally considered using cost-effectiveness analysis and the simplest way to express relationships between options is to plot the variables against each other.

In the simple example below, the variables are the annualized protection cost and the annual collective dose or “detriment.” In Figure 9-1, the various protection options are represented graphically. The options are discrete with no intermediate choices. By a simple examination of the figure, a pre-selection of options based on these two factors can be performed. The options illustrated by square points have neighboring options giving a lower collective dose at a lower cost. Provided the options are similar in other respects, these may be eliminated from further consideration, thus restricting the set of available options to those that are cost-effective. NOTE: Straight lines joining the cost-effective options illustrated by diamond points are added to improve clarity.

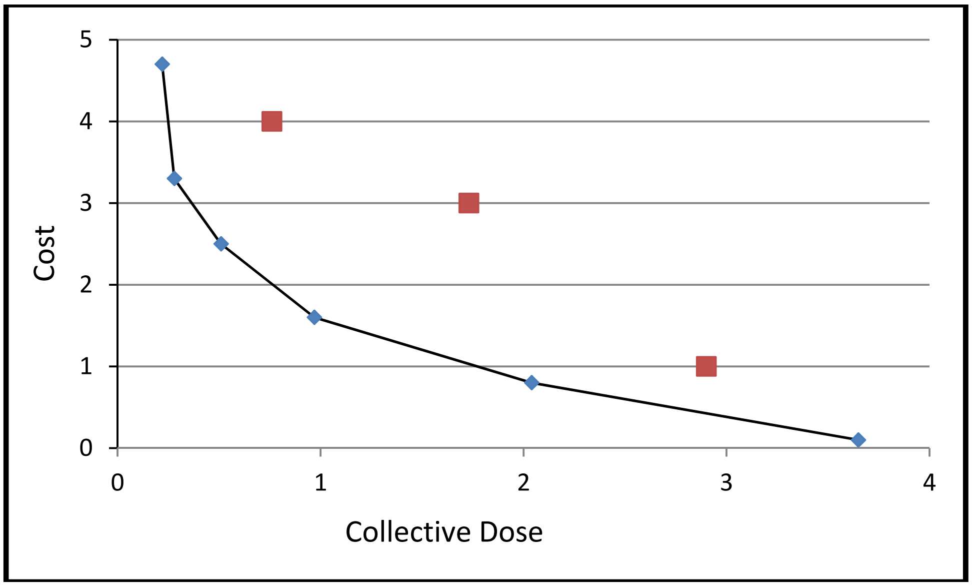

FIGURE 9-1. Typical Cost-Effectiveness Curve

The cost-effectiveness analysis is a relatively simple quantitative ALARA analysis technique that will give an analytical solution that directly indicates the optimum. However, this is predicated on the fact that only two factors are relevant, for example cost and collective dose.

ICRP 55, *Optimization and Decision-Making in Radiological Protection*, (1989), also includes a helpful example of a cost-effective analysis. Although it only considers occupational exposure, it provides some insight into the use of cost effectiveness in conjunction with multi-attribute utility analysis.

9.3 Multi-Attribute Utility Analysis

Multi-attribute utility analyses are discussed in most modern management texts, and there are a number of references available on its application and implementation. This method requires that the n relevant factors important to radiological protection be identified. These factors are known as attributes. Each of these attributes needs to be rated on a scale of 0 to 1 from the least desirable to the most desirable outcome for each option. The rating is the utility value, u_j. A scaling constant, k, is used to express the relative importance (or weight) assigned to each attribute. The scaling factors are generally normalized so that $\Sigma k_j = 1$. The multi-attribute utility function for option i, U_i, provides the figure of merit or "total" utility of each option, i, and is given by:

$$U_i = \sum_{j=1}^{n} k_j u_j \qquad \textit{Equation 9-8}$$

The higher the figure of merit, the better the overall ranking of the option so the optimum would be the option with the highest utility function.

A simple cost-benefit analysis, as discussed previously, can be thought of as a particular form of additive multi-attribute utility analysis and the results of the simple cost-benefit analyses can be duplicated using multi-attribute utility analysis. This is demonstrated in the following example. Consider the simple cost-benefit analysis summarized in Table 9-1.

Among the options, the range of protection cost is R(X) and the range of collective dose is R(S). Each factor will have a scaling constant, k(X) and k(S), and the value of alpha (α) will be used to relate the collective dose for each option to cost in a linear manner.

The value of the scaling factors can be obtained by solving the simultaneous equations:

$$\frac{k(X)}{R(X)} = \frac{k(S)}{aR(S)} \qquad \text{Equation 9-9}$$

$$k(X) + k(S) = 1 \qquad \text{Equation 9-10}$$

From Table 9-2, R(X) = \$35,500 - \$10,400 = \$25,100
R(S) = 0.561 - 0.178 = 0.383 (person Sv)
α = \$20,000 (person Sv)$^{-1}$

Solution of equation 9-9:

$$\frac{k(X)}{k(S)} = \frac{R(X)}{aR(S)}$$

$$\frac{k(X)}{k(S)} = \frac{25{,}100}{20{,}000 * 0.383}$$

$$k(X) = 3.276 * k(S)$$

Substituting k(X) into equation 9-10:

$$[3.276 * k(S)] + k(S) = 1$$

$$k(S) * (3.276 + 1) = 1$$

$$k(S) = \frac{1}{(3.276 + 1)}$$

$$\boldsymbol{k(S) = 0.23}$$

$$k(X) = 1 - k(S)$$

$$\boldsymbol{k(X) = 0.77}$$

Calculating the partial utility value [u(X)] for each option is similar to the R(X) calculation above:

$u_2(X) =$ [35,500 - 17,200] / 25,100 = 0.729

$u_3(X) =$ [35,500 – 18,500] / 25,100 = 0.677

$u_4(X) =$ [35,500 – 32,200] / 25,100 = 0.131

The lower annual protection cost is desirable so option 1 has a partial utility of 1; and the highest annual cost, option 5, is assigned the partial utility value of 0.

Calculating the partial utility value [u(S)] for each option is performed using the annual collective dose data from Table 9-2 and the following equation:

$$u_i(S) = \frac{S_{max} - S_i}{R(S)} \qquad \text{Equation 9-11}$$

$u_2(S)$ = [0.561 – 0.357] / 0.383 = 0.533

$u_3(S)$ = [0.561 – 0.335] / 0.383 = 0.590

$u_4(S)$ = [0.561 – 0.196] / 0.383 = 0.953

On the other hand, the lower annual collective dose is desirable so option 5 has a partial utility of 1; and the highest collective dose, option 1, is assigned the partial utility value of 0. Table 9-6 presents the complete data for the multi-attribute analysis corresponding to the simple Cost-Benefit Analysis example.

TABLE 9-6. Partial Utilities and Utility Analysis Corresponding to the Simple Cost-Benefit Analysis for the Options Considered

Protection Option	Annual protection cost, X $	Annual collective dose, S, person-Sv	Partial utility u(X)	Partial utility u(S)	Scaled partial utility k(X)u(X)	Scaled partial utility k(S)u(S)	Utility U
1	10,400	0.561	1	0	0.77	0	0.77
2	17,200	0.357	0.729	0.533	0.56	0.12	0.68
3	18,500	0.335	0.677	0.590	0.52	0.14	0.66
4	32,200	0.196	0.131	0.953	0.10	0.22	0.32
5	35,500	0.178	0	1	0	0.23	0.23

Note: The optimum option is underlined

Notice that the optimum found using either the simple cost-benefit analysis example or the simple multi-attribute analysis is the same option.

Similarly, multi-attribute utility analysis can be used to consider the beta functions – which weight the results according to the distribution of individual doses. Consider the results of the extended cost-benefit analysis summarized in Table 9-5. In this case, each portion of the collective dose will be considered separately with a linear partial utility. To obtain the three additional scaling constants, the three annual collective dose ranges [$R_n(S)$] are determined from Table 9-4 as:

$$R_1(S) = 0.0 - 0.0 = 0.0 \text{ person-Sv}$$

$$R_2(S) = 0.126 - 0.0 = 0.126 \text{ person-Sv}$$

$$R_3(S) = 0.561 - 0.063 = 0.498 \text{ person-Sv}$$

The scaling constant for the n portion of the collective dose is defined by:

$$\frac{k(X)}{R(X)} = \frac{k(S_n)}{\beta_n R(S_n)} \qquad \textit{Equation 9-12}$$

These equations are combined with the earlier equation for k(S) with the alpha term and using the normalizing condition:

$$k(X) + k(S) + \sum_1^3 k(S_n) = 1 \qquad \textit{Equation 9-13}$$

to obtain the set of values for the scaling constants:

$k(X)=0.323$

$k(S)=0.099$

$k(S_1)= 0.0$

$k(S_2)=0.063$

$k(S_3)=0.513$

Calculating the partial utility value of each range [u(Sn)] for each option is performed using the following equation:

$$u_i(S_n) = \frac{S_{n(max)} - S_n}{R_n(S)} \qquad \text{Equation 9-14}$$

$u_1(S_1) = [0.0 – 0.0] / 0.0 = 0.0$
$u_2(S_1) = [0.0 – 0.0] / 0.0 = 0.0$
$u_3(S_1) = [0.0 – 0.0] / 0.0 = 0.0$
$u_4(S_1) = [0.0 – 0.0] / 0.0 = 0.0$
$u_5(S_1) = [0.0 – 0.0] / 0.0 = 0.0$

$u_1(S_2) = [0.126 – 0.0] / 0.126 = 1.0$
$u_2(S_2) = [0.126 – 0.0] / 0.126 = 1.0$
$u_3(S_2) = [0.126 – 0.0] / 0.126 = 1.0$
$u_4(S_2) = [0.126 – 0.126] / 0.126 = 0.0$
$u_5(S_2) = [0.126 – 0.115] / 0.126 = 0.087$

$u_1(S_3) = [0.561 – 0.561] / 0.498 = 0.0$
$u_2(S_3) = [0.561 – 0.357] / 0.498 = 0.410$
$u_3(S_3) = [0.561 – 0.335] / 0.498 = 0.454$
$u_4(S_3) = [0.561 – 0.070] / 0.498 = 0.986$
$u_5(S_3) = [0.561 – 0.063] / 0.498 = 1.0$

The utility is calculated as the sum of each partial utility by its corresponding k value as summarized in Table 9-7. Thus, the protection option with the highest utility value is option 4.

TABLE 9-7. Partial Utilities and Utility Analysis Corresponding to the Extended Cost Benefit Analysis for the Options Considered

Protection option	Partial utility u(X)	Partial utility u(S)	Partial utility $u(S_1)$	Partial utility $u(S_2)$	Partial utility $u(S_3)$	Utility $U = \sum k_j u_j$
1	1	0	0	1	0	0.388
2	0.729	0.533	0	1	0.410	0.563
3	0.677	0.590	0	1	0.454	0.575
4	0.131	0.953	0	0	0.986	<u>0.642</u>
5	0	1	0	0.087	1	0.618

Note: k(X)=0.323, k(S)=0.099, $k(S_1)$= 0.0, $k(S_2)$=0.063, and $k(S_3)$=0.513

Although not included in the calculations in Table 9-7, the remaining factor, Comfort, can also be expressed as a utility function. This adds one further set of partial utilities to those in Table 9-7 and the scaling constants are then re-normalized to include the relative importance of this factor. If the decision maker is “fairly concerned” about the ventilation it might be assigned half the importance of the cost so that:

$$K(V) = ½\, k(X)$$

From Equation 9-13, new scaling factors are then:

$k(X)=0.278$

$k(S)=0.085$

$k(S_1)= 0.0$

$k(S_2)=0.055$

$k(S_3)=0.422$

$k(V)=0.140$

To determine the partial utility for this factor, a "No problem" would receive a value of 1 and "difficult to work" would be assigned a value of 0. A linear function can be assumed with "slight discomfort" assigned a value of 0.75 and "severe discomfort" assigned a value of 0.25.

The new utility calculation is then expressed in Table 9-8. By applying a cost to this factor, and since there are no further factors to include in the analysis, protection option 3 is definitively deemed the optimum. From the extended Cost-Benefit Analysis previously, this protection option was also deemed the optimum but only after a qualitative analysis of the Comfort factor.

TABLE 9-8. Partial Utilities and Utility Analysis Corresponding to the Extended Cost Benefit Analysis for the Options Considered

Protection option	Partial utility u(X)	Partial utility u(S)	Partial utility $u(S_1)$	Partial utility $u(S_2)$	Partial utility $u(S_3)$	Partial utility u(V)	Utility $U = \sum k_j u_j$
1	1	0	0	1	0	1	0.470
2	0.729	0.533	0	1	0.410	0.75	0.590
3	0.677	0.590	0	1	0.454	0.75	<u>0.600</u>
4	0.131	0.953	0	0	0.986	<u>0.25</u>	<u>0.590</u>
5	0	1	0	0.087	1	0	0.530

Note: k(X)=0.278, k(S)=0.085, k(S1)= 0.0, k(S2)=0.055, k(S3)=0.422, and k(V)=0.140

9.3.1 Additional Multi-Attribute Utility Analysis Example

To illustrate the multi-attribute process further, the following simplistic example is provided. Given that a control system is being evaluated for a specific project, the following major factors have been identified as relevant to the selection of the optimum system:

- Public protection;
- Worker protection;
- Environmental protection;
- Cost;
- Schedule;
- Public acceptance; and
- Protection of cultural resources.

Each of these factors is evaluated to define performance measures as: desired, acceptable, not desirable, and unacceptable. An unacceptable rating for any essential factor results in rejection of the alternative.

Although treated in the evaluation as independent attributes, these factors are not independent. For example, schedule clearly will be impacted by costs, and public acceptance is a function of the performance of the various other parameters. Similarly, public acceptance may be a function of the alternatives' projected success with regard to the public protection, the environmental protection, and the cultural resource protection factors as well as the schedule factor. Therefore, given that public information and participation programs are in place at the site where the facility is to be constructed, it may be possible to remove public acceptance as a separate factor and address it when considering the ratings in the other factors.

Given appropriate input from interested groups, the ALARA review team could eliminate, consolidate, supplement, and weight the factors considered. In this illustration, it is presumed that the team consolidated cultural resource protection and environmental protection, eliminated public acceptance as a separate factor, and addressed it in the other related factors.

> Combining factors does not suggest that one is less important than another; rather, such actions should be based on the best means of considering the factor in the analysis. In this example, public acceptance influenced by acceptability of alternatives under various factors and was felt best addressed in combination with the other factors.

To obtain factor weightings, each is compared to the other and the more important factor is labeled with a 1 and that of lesser importance with a zero. If both are of equal importance, they are given a 0.5. Table 9-9 presents the results of this rating. It is presumed that ALARA team consensus was used to establish the individual comparative scores in Table 9-9. The relative weighting is determined by the score for the factor divided by the sum of the scores.

TABLE 9-9. Example Weight of Factors (Attributes)

Factor below rated against factor to the right (numbers keyed as below):	**Factor 1** Public Protection	**Factor 2** Worker Protection	**Factor 3** Env/Cultural Resources	**Factor 4** Costs	**Factor 5** Schedule
Factor 1 Public Protection	N/A	0.0	0.0	0.0	0.0
Factor 2 Worker Protection	1.0	N/A	0.5	0.0	0.0
Factor 3 Env/Cultural Resources	1.0	0.5	N/A	0.5	0.5
Factor 4 Costs	1.0	1.0	0.5	N/A	0.5
Factor 5 Schedule	1.0	1.0	0.5	0.5	N/A
Score	4.0	2.5	1.5	1.0	1.0
Relative Weighting	0.4	0.25	0.15	0.1	0.1

Although the weighting indicates the relative importance of the factors in the analysis, these are each major factors and, therefore, it is reasonable to assume that an unacceptable rating in any single factor could make an otherwise desirable alternative unacceptable. The analysis would continue by establishing lower level factors on which to rate alternatives for each factor.

The new installation must at least ensure that public dose limits are achieved. In the absence of non-DOE radiation sources, this requires that doses to the MEI, or representative person of the critical group, from all DOE sources combined be less that 25 mrem (0.25 mSv) in a year. Given that the maximum dose from all other DOE activities on the site is less than 1 mrem (0.01 mSv) in a year, conceivably, this activity could contribute up to 24 mrem (0.24 mSv) without exceeding DOE dose constraints. However, it is not desirable to have one activity use so great a fraction of the allowable individual dose. Therefore, with regard to individual dose, the following conditions and scores were established:

> DOE dose constraint - unacceptable = alternative rejected

< Dose constraint but more than 15 mrem in a year = 0 pt

< 15 mrem in a year to the MEI = 0.5 pt

< 1 mrem in a year = 1 pt

DOE air pathway limit is 10 mrem (0.1 mSv) in a year. Therefore, for the air pathway alone, the following conditions were established:

> 10 mrem/year - unacceptable = alternative rejected

< 10 mrem/year = 0.5 pt

< 1 mrem/year = 1 pt

For this example, no separate water-related pathways were considered, and it was presumed that no emissions other than radiological are of concern. Collective dose was assumed in this case to be a negative cost using $2,000 per person-rem as the monetary equivalent for the dose. The public protection score for each alternative in this illustration will be the average of the score resulting from the total and air pathway elements.

Five alternatives were identified and were rated as shown in Table 9-10, by summing the products of the factor's score and the weighting for that factor for each alternative. In this simplified example, Alternatives B, C, and E are acceptable unless other special considerations indicated that Alternatives A or D should be considered. Alternative E, although not rejected, is sufficiently lower that "other factors or special considerations" would not permit its consideration unless these other factors were of major importance. In such a case, the other factors should be evaluated, incorporated into the matrix, and reevaluated.

TABLE 9-10. Scoring Alternatives in Illustration

Factor (weight)	**Alternative A**	**Alternative B**	**Alternative C**	**Alternative D**	**Alternative E**
Factor 1. (0.4)	Rejected	0.5	1.0	1.0	0.0
Factor 2. (0.25)	1.0	1.0	0.75	1.0	1.0
Factor 3. (0.15)	0.5	0.5	1.0	1.0	0.5
Factor 4. (0.1)	1.0	1.0	0.5	Rejected	1.0
Factor 5. (0.1)	1.0	1.0	0.5	Rejected	1.0
Score	Rejected	0.725	0.837	Rejected	0.5

9.4 Multi-Criteria Outranking Analysis

The analysis techniques described in the previous sections combine all the attributes representing the relevant factors influencing a decision into a single figure of merit, whether this is a total cost as in the cost-benefit analysis or a utility function as in the multi-attribute utility analysis. To do this, all factors considered need to be commensurable and tradeoffs (poor performance on one factor can be fully compensated by better performances) are acceptable over the full range of consequences. These two conditions may pose some difficulties where the factors being considered are heterogeneous or where they can only be evaluated in a qualitative manner. In such circumstances, the use of a multi-criteria outranking technique could prove more helpful.

The multi-criteria outranking technique initially compares each option (*i*) to every other option (*m*), in order to evaluate whether option *i* outranks option *m*. This comparison by pairs is generally based on two indicators:

A. An "advantage index" that expresses the amount by which option *i* is preferred to option *m* by the assessor conducting the study. The index, $Ad_{i,m}$, is equal to 1 when *i* is preferred or equivalent to *m* for all factors (*j*), it is equal to 0 when *i* is never preferred or equivalent to *m* and it varies in range from 0 to 1 when *i* is preferred or equivalent to *m* for some factors.

B. An "exclusion criteria" that expresses the degree to which the disadvantages of option *i* as compared to option *m* are significant for the factors where *i* is not preferred or equal to *m*. The criteria, $Ec_{i,m}$, is equal to 1 when the drawbacks associated with the choice of *i* rather than *m* are very substantial and equal to 0 otherwise.

> If $Ad_{i,m}$ is high enough and $Ec_{i,m}$ low enough, option *i* outranks option *m*.

The major difference of the multi-criteria outranking technique lies in the exclusion criterion. This is a means of formally rejecting options that do not comply with the fundamental trade-off requirements necessary for all the aggregative techniques. To apply it requires some qualitative or quantitative definition of the point at which the drawbacks become "very substantial". This definition is known as the "exclusion threshold" and is a further expression of judgment by the decision maker. If a factor is not judged sufficiently important to eliminate options then the exclusion threshold for that factor is set so that no comparisons between pairs give an exclusion criterion of 1.

ICRP 55 utilizes the multi-criteria outranking technique for the same uranium mine example presented in the Cost-Benefit Analysis example above. From this example, the outranking relationships result in a $Ad_{i,m} > 0.5$ and a $Ec_{i,m} = 0$. An additional elimination criteria of 0.5 for selection of the $Ad_{i,m}$ is introduced by inspection merely to reduce the number of outranking relationships from which the analytical solution is to be found. (ICRP, 1989) This leads to the result that:

Option 2 outranks Option 1

Option 3 outranks Option 1

Option 3 outranks Option 2

Option 5 outranks Option 4

Depicted graphically in Figure 9-2, these relationships illustrate that Options 3 and 5 each outrank the others but are not themselves outranked. This analysis did not yield a single solution, but application of a more discriminatory elimination criterion would do so.

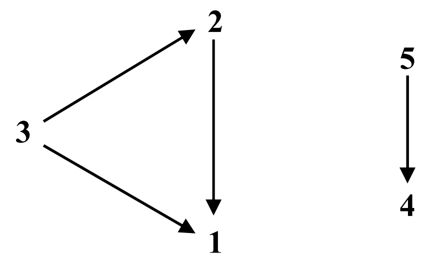

FIGURE 9-2. Multi-Criteria Outranking Relationships

As demonstrated in the uranium mine example in ICRP Publication 55, the same option was selected by both the multi-criteria outranking analysis and the multi-criteria utility analysis. NOTE: This is not always the case, however, as the multi-criteria outranking technique introduces preference criteria of a different form to the aggregate techniques and could therefore yield a different result.

9.5 Kepner-Tregoe (K-T) Decision Analysis

K-T Decision Analysis is a quantitative comparison method in which a team of experts numerically score criteria and alternatives based on individual judgments or assessments. The size of the team needed tends to be inversely proportional to the quality of the data available – the more intangible and qualitative the data, the greater number of people should be involved.

With this analysis, each evaluation criterion is first scored based on its relative importance to the other criteria (1 = least; 10 = most). These scores become the criteria weights. Once the goals are identified, each one is weighted according to its relative importance. The most important objective is identified and given a weight of 10. All others are weighted in comparison to the first. Alternatives are evaluated relative to each other against all objectives, one at a time.

Table 9-11 provides a generic example of what a K-T Decision Analysis may look like. Each of 5 criteria is evaluated for each of the 4 alternatives to arrive at a total score. Comparison of the weighted score totals indicates the fourth alternative as the one which most effectively meets all the requirements.

The K-T Decision Analysis is suitable for moderately complex decisions involving relatively few criteria. Its main disadvantage is that it may not be clear how much better a score of "10" is relative to a score of "8", for example. Moreover, the total alternative scores may be close together, making a clear choice difficult. (Baker, 2001)

TABLE 9-11. Example of K-T Decision Analysis

Criteria	Criteria Weight	Alternative 1	Alternative Score	Total Score
Installation	5	4-month delay	6	30
Safety	10	2.5-star rating	5	50
Efficiency	7	4.5-star rating	9	63
Reliability	9	80%	9	81
Cost	10	$260K	5	50
			Total:	**274**
Criteria	Criteria Weight	Alternative 2	Alternative Score	Total Score
Installation	5	1-month delay	9	45
Safety	10	4-star rating	8	80
Efficiency	7	4-star rating	8	56
Reliability	9	70%	7	63
Cost	10	$210K	8	80
			Total:	**324**
Criteria	Criteria Weight	Alternative 3	Alternative Score	Total Score
Installation	5	6-month delay	4	20
Safety	10	3-star rating	6	60
Efficiency	7	5-star rating	10	70
Reliability	9	65%	5	45
Cost	10	$170K	10	100
			Total:	**295**
Criteria	Criteria Weight	Alternative 4	Alternative Score	Total Score
Installation	5	Immediate	10	50
Safety	10	5-star rating	10	100
Efficiency	7	4-star rating	9	63
Reliability	9	85%	10	90
Cost	10	$240K	6	60
			Total:	**363**

9.6 Analytical Hierarchy Process Analysis

The Analytical Hierarchy Process (AHP) Analysis is a quantitative comparison method used to select a preferred alternative by using pair-wise comparisons of the alternatives on their relative performance against the criteria. This analysis method organizes the basic rationality by breaking down a problem into its smaller and smaller constituent parts and then guides decision makers through a series of pair-wise comparison judgments to express the relative strength or integrity of impact of the elements in the hierarchy. These judgments are then translated to numbers. The AHP includes procedures and principles used to synthesize the many judgments to derive priorities among criteria and subsequently for alternative solutions. (Baker, 2002)

The pair-wise comparisons are made using a nine-point scale:

1 = Equal importance or preference

3 = Moderate importance or preference of one another

5 = Strong or essential importance or preference

7 = Very strong or demonstrated importance or preference

9 = Extreme importance or preference

Using the same example illustrated in Section 9.5 above, matrices are developed so that each criterion/alternative is compared against the others (Table 9-12). If Criterion A is moderately more important to Criterion B (e.g., a value of 3), then Criterion B has a value of 1/3 compared to Criterion A. The “priority vector” (i.e., Normalized Weight) is calculated for each criterion using the geometric mean of each row in the matrix divided by the sum of the geometric means of all the criteria (see Table 9-13).

TABLE 9-12. Example of Pair-Wise Comparison of Criteria

Safety-Efficiency	7
Safety-Reliability	4
Safety-Installation	3
Safety-Cost	2

Efficiency - Installation	4

Cost-Efficiency	6
Cost-Reliability	2
Cost-Installation	1

Reliability-Efficiency	6
Reliability-Installation	2

TABLE 9-13. Example of Calculating Priority Vector

	Installation	Safety	Efficiency	Reliability	Cost	Geometric Mean	Normalized Weight
Installation	1	1/3	1/4	1/2	1	0.53	0.084
Safety	3	1	7	4	2	2.79	0.445
Efficiency	4	1/7	1	1/6	1/6	0.44	0.070
Reliability	2	1/4	6	1	1/2	1.08	0.173
Cost	1	1/2	6	2	1	1.43	0.228
					SUM=	6.27	

Next, pair-wise comparisons of the alternatives are performed with regard to each criterion. For example, a team of experts concludes that for the criteria of efficiency, Alternative 4 is given a 4 (moderately-strong importance or preference) as compared to Alternative 1, and 1 (equal importance or preference) as compared to Alternative 2, etc.

TABLE 9-14. Example of Pair-Wise Comparison of Alternatives with Respect to EFFICIENCY

Alternative 4 - 1	4
Alternative 4 - 2	1
Alternative 4 - 3	5

Alternative 2 - 1	2
Alternative 2 - 3	3
Alternative 1 - 3	3

TABLE 9-15. Example of Calculating Priority Vector with Respect to EFFICIENCY

Alternative	1	2	3	4	Geometric Mean	Normalized Weight
1	1	1/2	3	1/4	0.78	0.161
2	2	1	3	1	1.57	0.323
3	1/3	1/3	1	1/5	0.39	0.080
4	4	1	5	1	2.11	0.436

This process is repeated for all criteria. To identify the preferred alternative, multiply each normalized alternative score (Table 9-14) by the corresponding normalized criterion weight (Table 9-15) and sum the results for all alternatives. The preferred alternative, Alternative 4 in this example, will have the highest total score (see Table 9-16).

TABLE 9-16. Example of AHP Decision Analysis

Criteria	Normalized Criteria Weight	Alternative 1	Normalized Alternative Score	Total Score
Installation	0.084	4-month delay	0.161	0.014
Safety	0.445	2.5-star rating	0.114	0.051
Efficiency	0.070	4.5-star rating	0.227	0.016
Reliability	0.173	80%	0.300	0.052
Cost	0.228	$260K	0.076	0.017
Total:				**0.149**
Criteria	Criteria Weight	Alternative 2	Alternative Score	Total Score
Installation	0.084	1-month delay	0.323	0.027
Safety	0.445	4-star rating	0.266	0.118
Efficiency	0.070	4-star rating	0.138	0.010
Reliability	0.173	70%	0.122	0.021
Cost	0.228	$210K	0.270	0.062
Total:				**0.238**
Criteria	Criteria Weight	Alternative 3	Alternative Score	Total Score
Installation	0.084	6-month delay	0.080	0.007
Safety	0.445	3-star rating	0.109	0.048
Efficiency	0.070	5-star rating	0.307	0.021
Reliability	0.173	65%	0.073	0.013
Cost	0.228	$170K	0.532	0.121
Total:				**0.211**
Criteria	Criteria Weight	Alternative 4	Alternative Score	Total Score
Installation	0.084	Immediate	0.436	0.037
Safety	0.445	5-star rating	0.510	0.227
Efficiency	0.070	4-star rating	0.277	0.019
Reliability	0.173	85%	0.505	0.087
Cost	0.228	$240K	0.122	0.028
Total:				**0.398**

Chapter 10. ILLUSTRATIVE EXAMPLE OF ALARA APPLICATION

To assist in the practical application of the ALARA process, a number of example ALARA assessments are presented in the Appendices that follow. This chapter presents a simple hypothetical situation to illustrate the classical evaluations that accompany an ALARA analysis. The following example demonstrates the basic elements of optimization for radiation protection.

10.1 Input Data

Assume that a process is to be selected to accomplish a particular production goal and the process will result in the exposure of a number of persons to radiation. Further assume that there are other alternative processes that also could accomplish the same production goal, but each will have a different cost and will result in different exposure conditions. The objective is to select the particular system from the several candidates that will maximize the benefits and minimize the costs. Consider the data presented in Table 10-1.

TABLE 10-1. Hypothetical Cost and Collective Dose Data for Illustration of ALARA Principles

Options System Number	System Cost, $	Collective Dose, S (person-rem)	Health-Detriment Cost, αS $	Total Cost* $
1	80,000	250	500,000	580,000
2	120,000	60	120,000	240,000
3	160,000	10	20,000	180,000
4	200,000	4	8,000	208,000
5	240,000	1	2,000	242,000

In this example, the cost and health detriment values are taken as the total for the lifetime of the activity. If they were annual values, the same analysis would yield similar results, but they would be annual values.

10.2 Identity of the Optimum

As indicated in the total cost column of Table 10-1, the least cost is achieved by using System No. 3. In this example, where the value of α is assumed to be $2,000/person-rem, the same system (No. 3) would still be the optimum choice if the assumed value of α were $1,000 or $6,000/person-rem. This demonstrates that the assumed value for α generally is not a very sensitive parameter to the total cost yet the selection of System No. 3 is quite clear.

10.3 Graphical Illustration

This example of optimization is illustrated in the graphic presentation of the information on system performance in Figure 10-1. For each of five candidate systems, the cost, in dollars, is plotted as a function of performance, in person-rem. The data for each of the systems should be graphed linearly. Typically, the greater the performance of a system (as reflected in a lower collective dose), the higher the cost. Systems that result in greater collective doses generally have the lower costs. However, it is not uncommon to identify systems (options) that have higher cost and lesser performance. This is illustrated by the scatter of data points shown in Figure 10-2.

Performance of a system is not necessarily determined by the cost of radiological protection systems, but by how effectively the resources are expended.

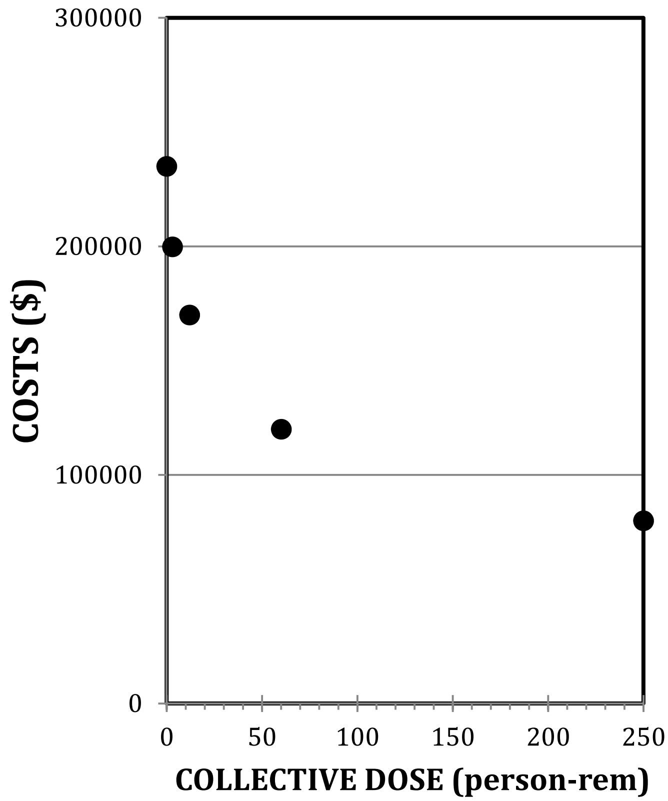

FIGURE 10-1. Graphical Illustration of the Data Demonstrating the ALARA Process

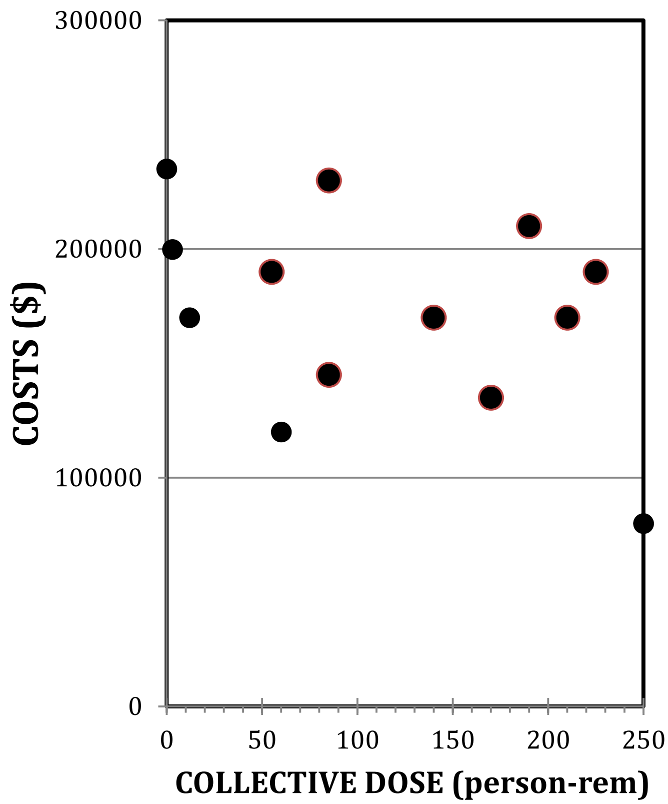

FIGURE 10-2. Graphical Illustration of Cost and Collective Dose for a Variety of Candidate Systems

The value of α, the monetary worth of a unit of collective dose, may also be placed on the graph. (The rationale for the selection of a value for α is discussed in Section 8.3.3). The straight line with a slope of α represents the assumed linear-relationship of health-detriment and cost over the range that the effects are stochastic, that is, random-like cancer induction. In the example above, the slope, α, is taken to be $2,000/person-rem. In Figure 10-3, the ovals are the data points for each of the system options, their locations determined by the cost and collective dose of each system, the rectangles are the presumed cost of health detriment (to prevent a health effect) for each of the systems, and the triangles are the total cost (system plus health-detriment) for each optional system. As can be seen, System No. 3, represented by the triangle on the left side of the graph, has the minimum total cost for the systems that were evaluated.

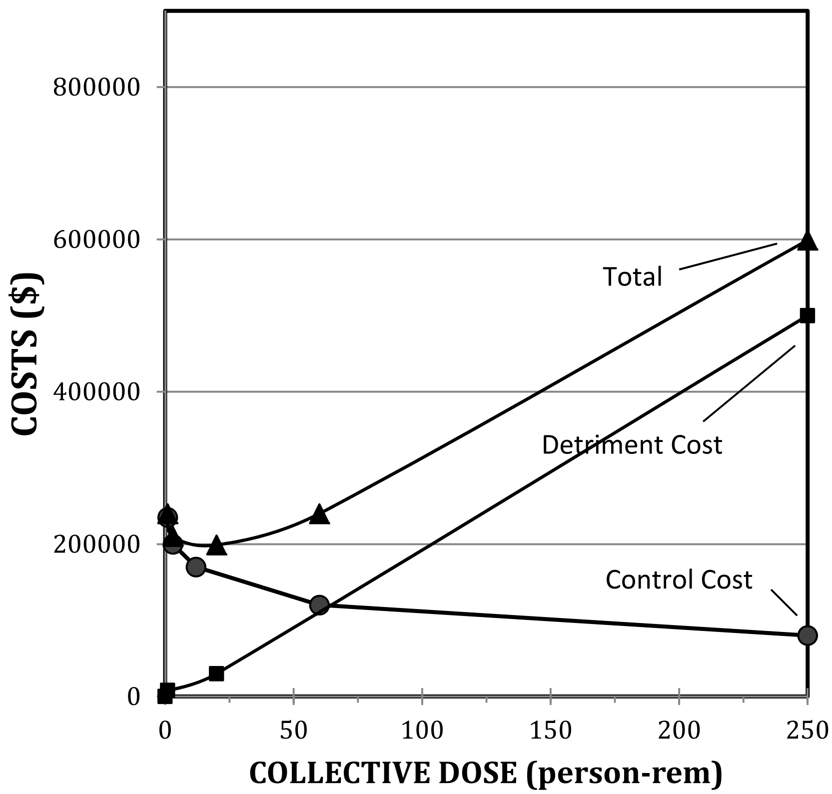

FIGURE 10-3. System and Total Cost for Candidate Systems with α = $2,000

The same data for the system costs and collective dose are presented in Figure 10-4. A straight-line with a slope -α has been drawn near the origin. While retaining the slope α, if the line (with slope -α) is moved to the right until it intersects the first point for an optional system, that system is the optimum. As may be seen, the selection is also System No. 3, represented by the "Optimum System" label on the graph.

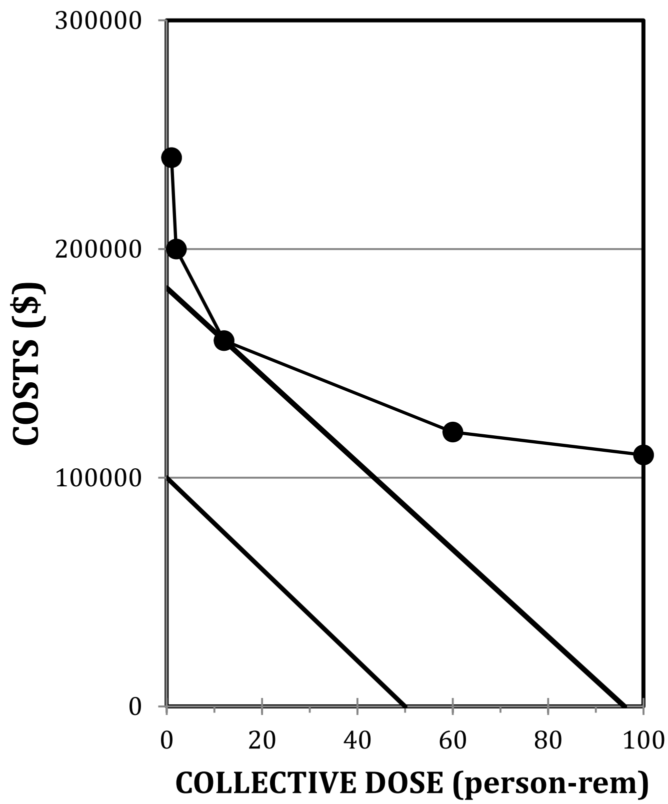

FIGURE 10-4. Graphical Method for Selection of Optimum System

In Figure 10-5, two other lines are shown intersecting the same point, one with a slope of α_1 = \$1,000/person-rem and the other with a slope α_3 = \$3,000/person-rem. This illustrates the fact that the selection of the optimum generally is not very sensitive to the assumed value of α, in this case it is an indication of the robustness in the selection process.

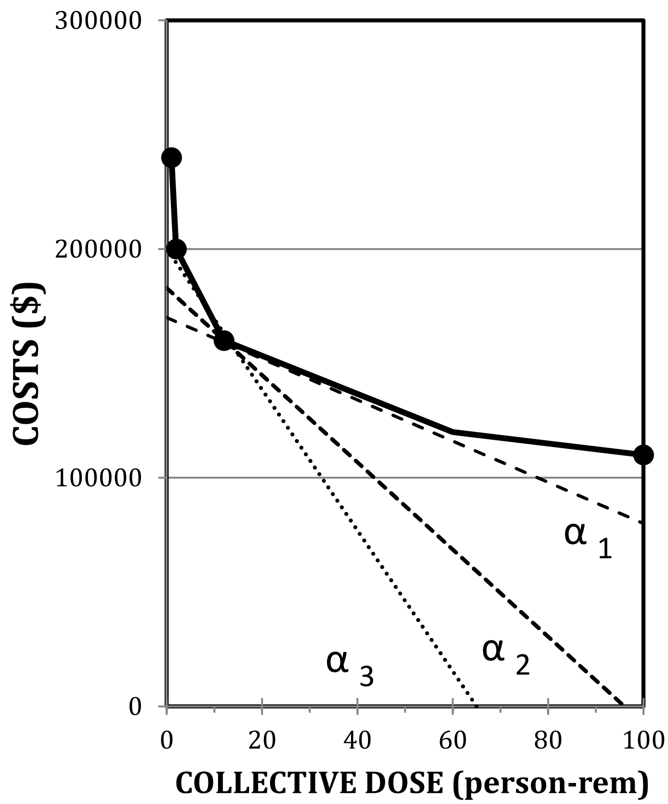

FIGURE 10-5. Illustration of the Effects of Three Values of α on Optimization

Notice that the dose (S) in the figures is *collective* dose. The primary dose limit for an individual is 100 mrem (1 mSv) in a year, but this is applicable for the total dose from essentially *all* radiation sources except natural background radiation. A dose in the range of 10 to 25 mrem (0.1 to 0.25 mSv) in a year is more likely to be "acceptable" or "appropriate" for a particular DOE activity. The least costly treatment system that achieves the "acceptable" dose to the MEI, or representative person of the critical group becomes the "base case" for the data base for identifying the optimum system. Other candidate systems will be compared to it.

In most cases, when the dose to the MEI, or representative person of the critical group, is well below the primary limit, no further treatment can be justified on the basis of health-risk considerations.

Most, if not all, of the factors used in cost-benefit analyses are variable or site-specific values subject to considerable uncertainty. Estimates generally are based on analytical models derived from limited measurements under specific parametric conditions. A series of points may be found with considerable scatter rather than the orderly progressions assumed in the examples used to demonstrate the cost-benefit analysis. (A more common distribution of data for optional systems is illustrated in Figure 10-2.) The same principles apply to these data however. Quantifying the costs and benefits is instructive and useful in the decision-making process, even though the values may be subject to considerable uncertainty and many intangible factors also need to be considered.

10.4 Other Considerations

The many factors and considerations entering the non-health detriment or ß-factors in the equation may defy quantitative evaluation. Techniques other than quantitative cost-benefit analyses generally are used in combination with or in place of cost-benefit analyses in making the ALARA decision when these factors are considered important in the process. Optimization means determining the alternative that has the minimum total cost (where cost is a measure of all negative factors or attributes considered). This also implies maximizing the benefit (benefit is typically expressed as a negative cost). The total cost, in such studies, includes a monetary equivalent for collective dose and any other considerations to the extent they can be quantified in terms of a cost equivalent.

The case studies presented in the following Appendices provide examples of ALARA process applications related to personal property; rulemaking; and remediation decisions. Appendix A and B provide topical examples for disposition of personal property and the use of optimization during the design of facilities, respectively. Appendix C-E provides examples from specific sites representing utilization of the ALARA process for large areas or facilities. These examples should not necessarily be considered templates for ALARA analyses and documentation, but are provided to illustrate ALARA considerations and types of ALARA assessments and to assist DOE personnel in reviewing ALARA determinations. The examples represent different situations and provide a general outline for issues that need to be considered. However, for some site-specific actions, these analyses may be too detailed.

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APPENDIX A.

FINAL DISPOSITION OF PERSONAL PROPERTY

The ALARA process balances the cost to perform certain activities and the dose reduction that could be seen by performing those activities. The result of the process is that the optimal of several alternatives is identified. Four examples of the application of ALARA principles that need to be considered before final disposition of personal property are discussed in this Appendix. These examples are for: (1) the recycle of copper, (2) the recycle of high explosives, (3) the remediation of a CERCLA site, and (4) the analysis of radiological risks and costs for the use of a bag monitor at one of the National Laboratories.

A.1 Recycle of Copper

This example illustrates a situation where both the collective dose and the individual dose are insignificant for all options. In the collective and individual dose estimates in this example, potential collective dose or health effects for all alternatives are so low that they are not an important factor in selecting among options considered.

This action was supported by an environmental assessment (EA). The data in the ALARA summary were based on analyses contained in the EA. This section summarizes the results of the EA and the ALARA documentation.

The copper is from the windings of a cyclotron. The most highly contaminated portions were removed and disposed of as radioactive waste prior to the action to recycle the copper. As a result, the action was to determine if the remaining copper was acceptable for recycle rather than to establish authorized limits for recycle of the copper. Had the more highly contaminated copper not already been disposed of, the action would have required an ALARA analysis to determine appropriate authorized limits to define the portion of copper that could be recycled. However, given the concentration and quantity of residual radionuclides in the remaining copper, that was not necessary.

In this example, the relative insignificance of both the dose to individuals and the collective dose for all options eliminates the health effects as a significant factor in choosing a course of action and illustrates the principle that the ALARA effort should be commensurate with the potential detriment associated with the activity.

A1.1 Background

A laboratory has 140 metric tons of copper that had become slightly activated from use as windings of a cyclotron. The copper has been stored in 32 wooden crates outdoors at a leased warehouse for several years and the laboratory would like to dispose of it. The amount of radioactive material is sufficiently low that the State’s Department of Health has approved burial of the copper as ordinary (i.e., non-radioactive) waste, without regard for the activity, and found that the recycle of the material is acceptable under the practice of risk-based regulations. However, the copper is a valuable resource and, when at the time this analysis was conducted, could be sold for scrap for about $0.80/lb (approximately $247,000 for the 140 metric-ton lot) and recycled. The laboratory would like to make a final disposition of the copper and comply with the ALARA policy and requirements.

A1.2 Contaminants

The high-purity (99.99%) copper has an average activity, principally cobalt (Co)-60 (half-life 5.26 years, beta and gamma emitter), of 3 pCi/g from activation and a maximum activity of 20 pCi/g. All of the copper with activity greater than 20 pCi/g has been disposed of at Hanford. The total amount of Co-60 in the remaining copper is about 0.42 mCi. If the total amount of Co-60 in the 140 metric tons of copper (0.42 mCi), could be concentrated into a single small unshielded source, the dose rate one foot from the source would be about 5.5 mrem (0.055 mSv) per hr.

A1.3 Proposed Action and Alternatives

The laboratory proposed to recycle the copper by selling it to a local scrap metal dealer. Several local dealers were interested. Five alternative actions also were considered and evaluated:

1. No action – continue to store the copper at the warehouse (this would require implementation of DOE storage requirements for low-level waste – the Co-60 activity would be undetectable through decay in about 50 years);
2. Recycle at a State-licensed facility, located in Oak Ridge, TN, for re-use at a DOE facility (the likely use would be as customized shielding blocks that eventually would be disposed as low-level waste);
3. Recycle by selling or giving the copper to a foreign government (e.g., a government interested in using the copper in synchrotron accelerators – transportation would be by common carriers);
4. Disposal at a local sanitary landfill (a local sanitary landfill was available but some additional testing would be required); and
5. Disposal at the Hanford Low-Level Waste Burial Facility (common carriers would be used to transport the copper to Hanford, Washington).

A1.4 Radiological Impact to Members of the Public and to Radiation Workers

A1.4.1 Members of the public

The likely uses by the public of the copper through recycling include home wiring, electronic components, and jewelry. A maximum collective dose of 0.072 person-rem was estimated from the reuse of the copper as jewelry. An additional 3.0 E-6 person-rem would result from transportation to the recycle facility. The potential biological risk of a fatal cancer occurring, assuming 500 radiation-induced fatal cancers per million person-rem, would be about 4.0 E-5 given the exposed population. This is essentially zero cancers (no chance of an additional fatal cancer) considering that the normal incidence of cancer among individuals in the United Sates is about 1 cancer per 3 persons, about half of which are fatal.

A1.4.2. Radiation workers

Transporting and recycling the copper were estimated to cause collective doses of 4.0 E-4 and 0.04 person-mrem, respectively, to workers. Potential fatal cancers would be 2.0 E-10 and 2.0 E-8, respectively. Workers in the warehouse, for the storage option, would receive 0.0001 person-rem, with an associated fatal cancer incidence of 6.0 E-8.

A1.5 Dose and Cost/Benefit Summary

A summary of the cost and doses for the alternative copper disposal actions is presented in Table A-1. The collective dose is so small that the choice of alternatives would not change if the EA value of $10,000 per person-rem were to be assumed. This value is slightly higher than the DOE-suggested range for α ($1,000 to $6,000 per person-rem). From a health-effect consideration, an assumption of $10,000 per person-rem appears to be an excessive value for monetary equivalent unit dose unless other considerations are included. In any case, as noted above, the potential doses are so small that the factor is not significant in the selection process.

A1.6 Other Considerations

Benefits of the proposed recycling action would include:

1. Provide money for the DOE laboratory which would offset Federal funds from taxpayers;
2. Reduce environmental consequences, such as air emissions, water quality, energy use, and traffic, associated with the mining and processing of copper ore to produce an equivalent quantity of copper would be averted;
3. Valuable, and expensive, low-level radioactive waste burial space for material that is actually classified as radioactive waste would be preserved;
4. Valuable sanitary landfill space would be preserved;
5. Currently used storage space would be released;
6. Compliance with the DOE waste minimization and pollution prevention policy would be achieved; and
7. Copper, a valuable resource, would be preserved.

In this example, the analysis so definitively indicates the optimum that there is no need to attempt to evaluate the cost values associated with each of the additional benefits. If it were not so obvious, the value of each could have been quantified.

In the review of this action, potential impacts on special industries such as the electronics or photographic industry were considered and determined to be minimal or nonexistent. The levels of residual radioactive material in the subject copper are very low. Also, the relatively short half-life of Co-60 (5.2 years) ensures that there is no buildup of this material in the metals pool.

A1.7 Discussion and Conclusions

Clearly, the proposed recycle option is preferred from ALARA considerations, not only on the basis of cost, but also in consideration of the benefits. In this case, both the individual and collective doses to the public and to workers are too small to be a significant factor in selecting between any of the options.

TABLE A-1. Summary of the Costs and Doses for the Alternative Copper Disposal Actions

Alternative Action	Maximum public individual dose, (mrem)	Collective dose public + worker (person-mrem)	Cost [saving] of alternative ($1,000s)	Net cost [saving][c] ($1,000s)
Unrestricted use	0.15	72	[247]	[247][e]
Storage [50 yr]	0.015	0.115	50/[247][bd]	[197][e]
Process/Recycle	a	0.14	323	323
Sale/gift-foreign	a	0.047	30	30
Dispose as radioactive waste at Hanford	3.0 E-6	0.0034	235	235
Sanitary fill	a	0.0034	4.2	4.2

a. Dose is essentially averted by alternative.

b. Assumes 50 years storage at $1,000 per year. However, at that time the copper could be recycled and $247,000 recovered for a net savings of about $197,000.

c. A monetary equivalent of $1,000 per person-rem collective dose ($1 per person-mrem) was assumed in this summary. However, the collective dose is so small that there would be no significant change if $10,000 per person-rem had been selected. (A range of α values between $1,000 and $6,000/person-rem is recommended in this guidance.)

d. The interest considerations for cash received from the sale of the copper and payments for storage over the 50-year period were not included in this evaluation.

e. No attempt was made to assign a monetary value for the avoidance of environmental impacts from processing copper for which the reused copper is substituted, or other considerations.

A.2 Recycle of High Explosives

This example discusses the use of ALARA analysis to support the establishment of authorized limits to recycle high explosives containing residual tritium. An ALARA assessment normally should investigate the impacts and benefits of various authorized limits (e.g., 10,000 dpm/100 cm^2, 1000 dpm/100 cm^2 and 100 dpm/100 cm^2 or 0.2, 0.002 and 0.0002 microcuries per gram). However, in this case, the individual and collective doses associated with the proposed authorized limit were so low that there was no value in assessing the lower limits and it was qualitatively determined that a higher limit would provide no significant cost savings. Hence, a single authorized limit based on 0.002 microcuries of tritium per gram of high explosives (HE) for recycling was compared to the existing practice of open burning. The example is illustrative of the principle that the ALARA effort should be commensurate with the potential benefit that might be gained or detriment that might be averted by the action.

A2.1 Background

The current mission of the Pantex Plant is to dismantle nuclear weapons that are no longer needed for the defense of the United States. These dismantlement operations produce high explosive (HE) material that may be slightly contaminated with tritium. Although much of the tritium contamination is on or near the surface of the HE, some of the contamination may have penetrated through the depth of the HE. Tritium diffusion into HE is similar to its diffusion into other materials such as metals and plastics.

Pantex Plant proposed to make this HE available for commercial use, rather than processing the HE onsite by regulated open burning/open detonation. The recycled HE would be sold to industrial users in the mining industry. Consideration was given to recycling about 50,000 pounds of high explosives into the (public) market per year for several years. The recycled HE was estimated worth about $15 per pound in the open market.

A2.2 Alternatives Considered

Two alternatives (options) were considered for the disposition of high explosive (HE) main-charges. The currently used method involved removing the HE part and treating the HE through open burning/open detonation (OB/OD) at the Pantex Plant's Burning Ground. The second option was to recycle the HE by making it available to commercial users.

The analysis considered the following factors for each option:

1. Radiation doses and risk (individual and collective);
2. Economic factors;
3. Operational constraints; and
4. Societal impacts and perceptions.

A2.2.1 Open Burning/Open Detonation Alternative

Under this alternative, the HE main-charges would continue to be disposed of by treating them via open burning and open detonation at the Burning Ground. The site's "Burning Ground" is operated under a Resource Conservation and Recovery Act (RCRA) interim strategy permit and written grant of authority issued by the Texas Natural Resource Conservation Commission (TNRCC) of the State of Texas. This activity releases small quantities of carbon monoxide (CO), carbon dioxide (CO_2), oxides of nitrogen (Nox), fluorides (F-1), chlorides (Cl-1), and airborne tritium in the form of HTO. All releases of CO, CO_2, Nox, F-1, and Cl-1 are in full compliance with applicable regulations. In addition, the release of the airborne tritium activity is in full compliance with 40 CFR Part 61, Subpart H, "Environmental Protection Agency Regulations on National Emissions Standards for Hazardous Air Pollutants – National Emissions Standards for Emissions of Radionuclides Other Than Radon from Department of Energy Facilities." Over 50,000 pounds of HE, containing an estimated 0.144 curies (Ci) of tritium in the form of tritiated water (HTO), were treated by OB/OD during 1993.

It was estimated that this practice resulted in a maximum individual dose of 6.0 E-5 mrem (6.0 E-7 mSv) in a year. Collective doses were projected to be less than 1.0 E-4 person-rem in a year.

A2.2.2 Recycling Alternative

The second alternative was to dispose of all HE below a specified bulk tritium contamination of 2.0 E-3 microcuries of tritium oxide per gram of high explosives (μCi HTO/g HE) by recycling it to a commercial HE manufacturer for use in commercial explosives. It was estimated that this alternative could produce a savings of about $1,000,000 per year over the open burning alternative.

The recycle option might produce maximum doses to the workers using the explosives of 4.0 E-5 mrem (4.0 E-7 mSv) in a year and to members of the public on the order of 5.0 E-5 mrem (5.0 E-7 mSv) in a year. Collective doses were estimated to be about 1.5 E-6 person-rem in a year.

A2.3 Analysis

The final dose analysis supporting this ALARA analysis examined two scenarios: (1) worst case and (2) realistic case. Both cases represent conservative assessments of the potential exposures but the assumptions used in the "realistic case" were less conservative. It is necessary that dose assessments supporting ALARA evaluations be as realistic as possible (without substantially underestimating doses) so that all options can be compared equitably. Although worst-case analyses may be useful in ensuring compliance with dose limits they are not generally acceptable for ALARA analyses except for screening purposes. If the collective dose were to be based on the realistic case, the collective dose would be less than a person-mrem per year. For example, given a range of monetary equivalents from $1,000 to $7,000 per person-rem and 0.001 person-rem (1 person-mrem) per year (well above the collective dose of the proposed alternative), committing more than about $1 to $7 per year for dose reduction (i.e., reducing dose to zero), based on health risk considerations cannot be justified.

Since all projected doses are extremely low (and despite the fact that the proposed action indicated slightly lower collective doses), the details of the dose estimates in this specific application are moot; the decision was made primarily based on economic benefits. The highest dose to an individual is about 5.0 E-3 person-rem per year and the collective dose to workers and the public was estimated to be 1.5 E-6 person-rem per year for the recycle case. The present disposal method is estimated to result in a collective dose of 1.0 E-4 person-rem per year. The potential doses are so low in this application that no alternatives to recycle for health detriment considerations need be considered. Although the recycle alternative had additional environmental benefits compared to alternative disposal methods, given the low doses associated with the action, these need not be addressed in the quantitative assessment. Ordinarily, it would be useful to consider other alternative concentrations in the selection of the authorized limits; however, in this case, it was qualitatively determined that higher allowable concentrations would not save costs or significantly improve measurability and lower concentrations limits would not affect doses significantly. Therefore, on the condition that the release of the subject material was coordinated with the appropriate state regulators, DOE approved the authorized limits for recycle of Pantex high explosives.

A.3 Weldon Spring Site Remedial Action Project

This example discusses the ALARA analysis used to support remediation of the Weldon Spring site conducted under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) and as part of the DOE's Environmental Restoration and Waste Management Program. The major goals of the Weldon Spring Site Remedial Action Project (WSSRAP) were to eliminate potential hazards to the public and the environment, and to the extent practicable, make surplus real property available for other uses.

A3.1 Background

At the time this ALARA analysis was reported in 1999 the WSSRAP was in progress at a site approximately 48 km (30 miles) west of St. Louis, in St. Charles County, Missouri. The project involved environmental restoration of a 166-acre inactive uranium feed materials plant (usually referred to as the chemical plant), a 51-acre raffinate pit area, a 9-acre limestone quarry (located approximately four miles from the chemical plant), and associated vicinity properties. The scope of remediation included cleanup of both radiological and chemical contaminants resulting from previous operations that included trinitrotoluene and dinitrotoluene, and uranium metals production.

The quarry bulk waste removal and chemical plant remediation required the construction of treatment plants to treat contaminated waters impounded on the sites, storm water contaminated from contact with wastes on the site, and water used for decontamination. Two water treatment plants were constructed between 1990 and 1995 – the quarry water treatment plant (QWTP) and the chemical plant site water treatment plant (SWTP) which had two trains. Bulk waste removal from the quarry was completed in 1995. Planning for quarry restoration included dismantling and/or demolishing of the quarry water treatment plant and the process equipment.

The chemical stabilization and solidification (CSS) full scale process plant was commissioned in 1998 to chemically solidify and stabilize raffinate sludges so they are suitable for containment in an on-site disposal cell. Raffinate sludges are dredged from the raffinate pits, mixed with Portland cement and fly ash, and then pumped into the disposal cell as a CSS grout mixture. In November 1998, the CSS plant completed dredging and processing the remaining sludge from Raffinate Pit 3. Sludge from the other three pits had been consolidated into pit 3. Approximately 122,000 cubic yards of sludge had been treated since the plant began operations in July 1998. The CSS plant was dismantled in 1999.

The structures enclosing the site and quarry water treatment equipment contain very little, if any residual radioactive material. During the period of use they did not come into direct contact with radioactive waste streams.

A3.2 Property Description

The property considered for release consists of the building shells surrounding the water treatment plants and the structural and process modules of the CSS processing plants. These plants include the quarry WTP, Site WTP (Trains 1 and 2), CSS Production Facility, and the CSS Pilot Scale Plant. The largest contribution of recyclable metals will come from the CSS Production Facility.

Recyclable metals from the water treatment plants consist of structural elements of hot rolled and cold formed steel shapes, built-up plate sections, grating, tubing, piping, and wall and roof panels. It is expected that demolition/dismantlement methods will be done using torch cutting and mechanical shearing rather than by unbolting and taking the structures down as a reversal of the erection process. Thus the steel will have little, if any, reuse value. Its main value will be for recycling. Contamination, if any, would initially consist of surface contamination potentially having been transferred to a metal surface from an accidental spillage, slow leak, or from airborne dust particles. During the recycling process, any surface contamination will become inherent bulk contamination due to the smelting process.

Metal building components will be subjected to radiological surveys, as appropriate, and sorted into piles. Wall and roof panels will be stacked and secured in piles separate from the structural steel. Structural members will be torch cut or mechanically sheared into linear members suitable for placement into roll-off scrap containers or transport vehicles.

The total surface area and weight for the various salvage materials are estimated to be 210,900 ft^2 and 400 tons respectively. Dividing 210,900 ft^2 by the total weight of 800,000 lbs (400 tons) gives an average surface-to-mass ratio of 0.264ft^2/lb. This site-specific factor was used for dose calculations.

A3.3 Contaminants

All material released under the proposed release limits have the potential to be contaminated as a result of deposition of airborne radioactivity, spills, or buildup from inadvertent spreading of low levels of contamination. Therefore, contamination is initially expected to be only surficial and either loosely adhered or fixed via oxidation or applied paint.

Based on the history of operations at the various facilities, the contaminants are expected to vary dependent upon facility. The various facilities can be categorized into three general areas: Quarry Water Treatment Plant, Site Water Treatment Plant, and Raffinate Chemical Stabilization and Solidification (CSS) Facilities. Tables A-2, A-3 and A-4 provide radiological profiles for the three general areas. These profiles were used to compute fractional surface activities by dividing the activity for a specific alpha emitting radionuclide by the total activity for all emitters.

A3.4 Description of Alternatives

Through initial screening, the following alternatives were identified to be viable and were analyzed in the optimization study required by the ALARA process for the development of authorized limits.

Alternative 1: Unrestricted release of all material at or below dose-based contamination levels. Recyclable steel would be sold as scrap metal without restrictions, provided that contamination levels do not exceed levels corresponding to applicable dose limits.

TABLE A-2. Contamination Pro

Radionuclide	**Quarry Water Treatment Plant**[1] Max. Concentration in filter cake (pCi/g)	**Site Water Treatment Plant**[2] Max. Influent concentration (pCi/l)	**Raffinate CSS Facilities**[3] Ave. Concentration in pit 3 raffinate (pCi/g)
Ra-226	3.7	1,580	320
Ra-228	5.3	251	64
Th-228	0.8	7.63	91
Th-230	58.6	1,900	17,000
Th-232	11.4	8.36	320
U-234	16,800	3,220	295
U-235	750	144	13.2
U-238	16,600	3,180	292

1 Reference: DOE/OR/21548-550, "Safety Analysis for the Quarry Water Treatment Plant" Rev. 2, March, 1996

2 Reference: DOE/OR/21548-527, "Safety Analysis for the Site Water Treatment Plant" Rev. 2, November, 1997

3 Reference: DOE/OR/21548-074, "Remedial Investigation for the Chemical Plant Area of the Weldon Spring Site", Rev. 0, November, 1992

Note 1: Th-232 value is from Raffinate Pit 4 analyses. Th-232 values were not reported for Pit 3 due to interference with high Th-230 concentrations.

Alternative 2: Unrestricted release of all material at or below DOE Order 5400.5, Figure IV-1 values. Recyclable steel would be decontaminated, as needed, and comprehensively surveyed in order to meet DOE Order 5400.5 values. The steel would then be sold as scrap metal without restrictions.

Alternative 3: Unrestricted release of only material at or below DOE Order 5400.5, Figure IV-1 values (no decontamination). Remaining material buried in on-site disposal cell. Recyclable steel would be comprehensively surveyed. Material at or below DOE Order 5400.5 values would be sold as scrap metal without restriction. Material above DOE Order 5400.5 values would not be decontaminated and subsequently placed in the on-site disposal cell.

Alternative 4: Burial of all material in on-site disposal cell. All recyclable steel would be disposed as low-level radioactive waste with WSSRAP's disposal cell. No further surveys or decontamination efforts would be performed.

A3.5 Radiological Assessment Assumptions

An overarching assumption was that all activities, regardless of alternative, would be conducted in compliance with applicable DOE and, when applicable, NRC (or authorized state) regulations.

The following are general assumptions used to conduct public dose analyses for each alternative:

- A total of 400 tons of surface-contaminated steel would be processed, with no restriction on the amount processed in a year; i.e., up to 400 tons per year;
- All released steel would be recycled. Steel recycling scenarios in document PNL-8724 would be considered representative of WSSRAP-recycled steel;

- Any surface contamination becomes bulk/volumetric contamination during the steel recycling process; and
- Calculated risk of fatal cancer is based upon current ICRP fatal cancer risk factors of 4.0 E-7 per mrem (4.0 E-9 per mSv) for workers and 5.0 E-7 per mrem (5.0 E-9 per mSv) for members of the general public.

A3.6 Analysis of Alternatives

A3.6.1 Radiological Assessment of Alternative 1

The surface-contaminated recyclable steel generated during demolition of the various WSSRAP facilities was calculated to have an average surface-to-mass ratio of 0.541 cm^2/g. Using this conversion factor and radiological control levels (RCLs) based on an annual individual dose of 1 mrem (0.01 mSv) from the recycle of 400 tons of steel in one year (PNL-8724), the average surface contamination release limits (SCRL) could be calculated for each radionuclide present at WSSRAP. The results of such calculations are presented in Table A-3. [Note: All RCLs given in Table A-3 (and used throughout this Weldon Spring example) were obtained from Table E.1 of PNL-8724. Because RCLs for radionuclides in equilibrium with their immediate progeny are not listed on Table E.1 of PNL-8724, appropriate RCLs were derived by applying ratios derived from total dose values, in mrem, provided on Table E.2 of that document.]

In comparison to DOE Order 5400.5, Figure IV-1 values for average allowable total residual surface contamination (see Table A-4) the above derived values were higher for Ra-226 and Th-230. However, the above values were lower than DOE Order 5400.5 values for Th-232 and natural uranium. For waste streams which consisted of a combination of the above radionuclides, the "sum of fractions" rule applied. To demonstrate compliance with the above limits when surveying contamination comprised of a mixture of radionuclides, a "limit-weighted" effective surface contamination release limit ($SCRL_{eff}$) could be calculated using the fractional surface activities ($f_{\alpha i}$) and the average SCRL ($SCRL_i$) as depicted in Equation A-1.

TABLE A-3. Dose-Based Surface Contamination Release Limits (SCRLs)

Radionuclide	RCL for 400 tons/yr (pCi/g)	Average SCRL ($dpm/100cm^2$)
Ra-226 + D	1.59	648
Th-230	3.25	1,330
Th-232 + D	0.568	232
U-234	6.5	2,660
U-235	7	2,860
U-238 + D	1.32	538

Ra-226 + D represents Ra-226 in equilibrium with Rn-222 (with short-lived Po-218, At-218, Pb-214, Bi-214, Po-214 and Tl-210), Pb-210, Bi-210 and Po-210.

Th-232 + D represents Th-232 in equilibrium with Ra-228, Ac-228, Th-228, Ra-224 (which includes short-lived Rn-220 and Po-216), Pb-212, Bi-212, Po-212, Tl-208 and Pb-208.

U-238 + D represents U-238 in equilibrium with Th-234, Pa-234m and Pa-234.

Limit ($SCRL_{eff}$) may be calculated using Equation A-1.

$$SCRL_{eff} = \left[\sum_i \frac{f_{\alpha_i}}{SCRL_i} \right]^{-1}$$

Equation A-1

Due to the relatively large variance in each facility's contamination profile, an independent $SCRL_{eff}$ should be calculated for each. Using Equation A-1, the following effective limit values were obtained for each:

Quarry Water Treatment Plant: 912 dpm-α/100 cm^2

Site Water Treatment Plant: 844 dpm-α/100 cm^2

CSS Facilities: 1150 dpm-α/100 cm^2

Material survey methodology would have to employ instrumentation capable of detecting the above contamination levels. Portable alpha-sensitive survey instruments could provide this capability for all three facilities. Because only the "Ra-226 + D, U-238 + D and Th-232 + D" are generally detectable through the use of beta/gamma-sensitive field instrumentation (e.g., a Geiger Mueller (GM) "pancake" probe), use of such instrumentation would require the implementation of a correction factor to account for the relative abundance of "GM-probe detectable" radionuclides in each facility's waste stream. Due to its greater durability, decreased source self-attenuation concerns and less restrictive operational considerations (e.g., source geometry, survey speed, etc.) the GM "pancake" probe would be a more practical survey instrument for release of recyclable steel from the QWTP and SWTP.

For the CSS Facilities, use of beta/gamma-sensitive survey instrumentation was not possible because 92.4% of the activity was comprised of Th-230 – a radionuclide that is not "GM-probe detectable."

The radiological impact of Alternative 1 would be an annual dose of 1 mrem (0.01 mSv) to the MEI or representative person of the critical group. This corresponds to a potential excess risk to fatal cancer of 5.0 E-7. Actual annual individual dose and subsequent risk would be less than 1 mrem (0.01 mSv) and 5.0 E-7 respectively. This is because all material released would be surveyed, as appropriate, to verify that contamination levels are less than the respective $SCRL_{eff}$. Since the $SCRL_{eff}$ value would be treated as a maximum allowable release limit, the average contamination levels would be less, therefore resulting in lower dose/risk to the public.

A3.6.2 Radiological Assessment of Alternative 2

The potential individual dose from an annual release of 400 tons of recyclable steel at or below DOE Order 5400.5, Figure IV-1 values is given in Table A-4.

TABLE A-4. Release of Material at or below DOE Order 5400.5 Values

Radionuclide	DOE Order 5400.5, Figure IV-1 Ave. Surface contamination limit ($dpm/100cm^2$)	RCL for 400 tons/yr(pCi/g)	Annual individual Dose (mrem)
Ra-226	100 Note 1	1.59	0.154
Th-230	100 Note 1	3.25	0.0752
Natural Thorium	1,000	0.568	4.31
U-234	2460 Note 2	6.5	0.925
U-235	110 Note 2	7	0.038
U-238	2430 Note 2	1.32	4.52

Note 1: Value adopted by WSSRAP as the applicable surface contamination guideline as documented by letter from J.R. Powers to the DOE (McCracken), dated 10/24/90. File: MN-01-02.

Note 2: Calculated from the DOE Order 5400.5 natural uranium limit of 5000 dpm /100 cm^2 and the activity fractions of U-234, U-235 and U-238 which comprise WSSRAP natural uranium.

The doses listed in Table A-4 are not representative of the actual individual dose that would result from the recycle of 400 tons of steel in a year from the WSSRAP facilities. Due to the contamination profiles of the specific areas/facilities and the need to demonstrate compliance with DOE Order 5400.5 limits using "field" instrumentation (which do not assess radionuclides separately), actual resultant doses would vary, dependent on facility. Therefore, each facility would be assessed separately and then summed to assess public exposure and subsequent risk.

A3.6.3 Alternative 2 for the Quarry Water Treatment Plant (QWTP)

Material release from the QWTP would be performed utilizing beta-sensitive survey instrumentation/techniques (i.e., GM "pancake" probe at 1/2 inch). This surveying methodology is capable of detecting U-238 (due to its daughter product Pa-234m). Detection of the remaining isotopes was not expected due a low relative fractional abundance and/or lack of beta particle emission (> 30 keV average beta energy).

The calibration of GM "pancake" probes at WSSRAP provided GM operational efficiencies which represent detection of U-238 (and possibly Ra-226 + D). Table A-5 represents the expected radionuclide profile for compliance with the natural uranium DOE Order 5400.5 limit value of 5000 dpm/100 cm^2 and the subsequent potential dose to a member of the public for the release of 20 tons of QWTP recyclable steel (0.05 x 400 tons). The calculations utilized the site-specific surface-to-mass ratio of 0.264 ft^2/lb. As Table A-5 shows, the maximum annual dose to a member of the public from the recycle of 20 tons of QWTP steel at DOE Order 5400.5 limits is 0.274 mrem (2.74 E-3 mSv). This corresponds to a potential excess risk to fatal cancer of 1.37 E-7.

TABLE A-5. Dose from 20 Tons of QWTP Steel at DOE Order 5400.5 Values

Radionuclide	Expected Contamination Level (dpm/100 cm^2)	RCL for 20 tons/yr (pCi/g)	Annual Individual Dose (mrem)
Ra-226	0.54	31.8	4.15 E-5
Th-230	8.6	65	3.26 E-4
Natural Thorium	1.82	11.4	3.90 E-4
U-234	2460	130	4.63 E-2
U-235	110	140	1.92 E-3
U-238	2430	26.4	2.25 E-1
		TOTAL:	2.74 E-1

A3.6.4 Alternative 2 for the Site Water Treatment Plant (SWTP)

To meet DOE Order 5400.5, Figure IV-1 contamination limits, material release from the SWTP would be performed utilizing alpha-sensitive survey instrumentation/techniques. This is because Th-230 comprised 18.5% of the total activity and had a limiting average contamination release limit value of 100 dpm/100 cm^2. Table A-6 represents the expected radionuclide profile for 100 dpm of detected α activity and the subsequent potential dose to a member of the public for the release of 40 tons of SWTP recyclable steel (0.10 x 400 tons). The calculations utilized the site-specific surface-to-mass ratio of 0.264 ft^2/lb.

As Table A-6 shows, the maximum annual dose to a member of the public from the recycle of 40 tons of SWTP steel at DOE Order 5400.5 limits is 0.0108 mrem (1.08 E-4 mSv). This results in a potential excess risk to fatal cancer of 5.4 E-9.

TABLE A-6. Dose from 40 tons of SWTP Steel at DOE Order 5400.5 Values

Radionuclide	Expected Contamination Level (dpm/100 cm^2)	RCL for 40 tons/yr (pCi/g)	Annual Individual Dose (mrem)
Ra-226	15.3	15.9	2.35 E-3
Th-230	18.5	32.5	1.39 E-3
Natural Thorium	0.16	5.68	6.89 E-5
U-234	31.3	65	1.18 E-3
U-235	1.4	70	4.89 E-5
U-238	30.9	13.2	5.72 E-3
		TOTAL:	1.08 E-2

A3.6.5 Alternative 2 for the CSS Facilities

To meet DOE Order 5400.5, Figure IV-1 contamination limits, material release from the CSS Facilities would be performed utilizing alpha-sensitive survey instrumentation/techniques. This is due to the fact that Th-230 comprises 92.4% of the total activity and has a limiting average contamination release limit value of 100 dpm/100 cm^2 (surface contamination survey technique is such to provide detection of average contamination guidelines of DOE Order 5400.5).

Table A-7 represents the expected radionuclide profile for 100 dpm of detected α activity and the subsequent potential dose to a member of the public for the release of 340 tons of recyclable steel (0.85 x 400 tons). The calculations used the site-specific surface-to-mass ratio of 0.264 ft^2/lb. As Table A-7 shows, the maximum annual dose to a member of the general public from the recycle of 340 tons of CSS Facilities steel at DOE Order 5400.5 limits is 0.0726 mrem (7.26 E-4 mSv). This corresponds to a potential excess risk to fatal cancer of 3.6 E-8.

TABLE A-7. Dose from 340 Tons of CSS Facilities Steel at DOE Order 5400.5 Values

Radionuclide	Expected Contamination Level (dpm/100 cm^2)	RCL for 340 tons/yr (pCi/g)	Annual Individual Dose (mrem)
Ra-226	1.74	1.87	2.28 E-3
Th-230	92.4	3.82	5.91 E-2
Natural Thorium	2.24	0.668	8.20 E-3
U-234	1.60	7.65	5.11 E-4
U-235	0.0717	8.24	2.13 E-5
U-238	1.58	1.55	2.49 E-3
		TOTAL:	7.26 E-2

A3.6.6 Summary for Alternative 2

The summing of all three locations results in an annual dose of 0.357 mrem (3.57 E-3 mSv) to the MEI or representative person of the critical group. This corresponds to a potential excess risk to fatal cancer of 1.8 E-7. Actual annual individual dose and subsequent risk would be less than 0.357 mrem (3.57 E-3 mSv) and 1.8 E-7 respectively. This is because all material released would be surveyed, as appropriate, to verify contamination levels are less than DOE 5400.5 limits. Since the limits would be treated as maximum allowable release limits, the average contamination levels would be less, therefore resulting in lower dose/risk to the public.

A3.6.7 Radiological Assessment of Alternative 3

It was estimated that approximately 90% of the bulk material from the water treatment plants and 50% of the bulk material from the CSS Facilities were contaminated at levels less than DOE Order 5400.5, Figure IV-1 values. Maximum annual individual dose from the recycle of the "releasable" fraction of steel is given in Table A-8.

TABLE A-8. Recycling Dose for Alternative 3

Facility	Estimated Fraction Releasable	Annual Individual Dose for 100% release (mrem)	Resultant Annual Individual Dose (mrem)
QWTP	0.90	0.274	2.47 E-1
SWTP	0.90	0.0108	9.72 E-3
CSS Facilities	0.50	0.0726	3.63 E-2
		TOTAL:	2.93 E-1

The annual individual dose from the disposal of contaminated material within the on-site disposal cell was calculated using the RESRAD computer code. The RESRAD calculations assumed the following:

- The non-releasable fraction of steel was contaminated (on average) to a level of 10 times the average surface contamination release guidelines of DOE Order 5400.5.
- It is assumed that 10% of the activity deposited on the buried steel is transferred to and uniformly dispersed within the soil of a disposal trench. The transfer mechanisms included wash-off and corrosion.

- The activity is mixed in a 1-meter thick layer of soil (1.6 g/cm^3) in a 1,000 m^2 area and covered with a 1-meter thick layer of clay (1.8 g/cm^3).
- Radon inhalation exposure pathway is applicable.
- All other parameters are RESRAD default.

Results of the RESRAD computations gave a maximum annual individual dose of 0.165 mrem (1.65 E-3 mSv). Because it is highly unlikely that a single individual could be the recipient of the both maximum recycling and burial doses, the respective values were not summed. Therefore, the radiological impact of Alternative 3 would be an annual dose of 0.293 mrem (2.93 E-3 mSv) to the MEI or representative person of the critical group. This corresponds to a potential excess risk to fatal cancer of 1.5 E-7.

A3.6.8 Radiological Assessment of Alternative 4

The radiological impact from disposal of all material, regardless of contaminated status, was determined using the RESRAD computer code. The burial exposure calculations utilize the same assumptions as in Alternative 3 with one exception: the average surface contamination levels were determined by including the releasable fraction of steel assumed to be contaminated at DOE Order 5400.5 guidelines. The resultant annual dose to the MEI, or representative person of the critical group, is 0.184 mrem (1.84 E-3 mSv), corresponding to a potential excess risk to fatal cancer of 9.2 E-8.

A3.7 Economic Assessment

The estimated costs for each of the four alternatives considered was weighed against the collective doses assessed previously. The following general assumptions were made for cost estimating purposes:

- Fifty percent of CSS steel, ten percent of Site Water Treatment Plant steel, and ten percent of Quarry Water Treatment Plant Steel were potentially contaminated and required a 100 percent field survey for unrestricted release.
- Of the potentially contaminated steel, fifty percent of the CSS steel and all of the water treatment building steel underwent decontamination for Alternatives 1 and 2.
- The average steel surface area to mass ratio is 0.264 ft^2/lb.
- Surveying would be done by a crew of two ES&H technicians with field instrumentation supported by a grapple with operator. Estimated labor cost is $35 per hour per technician.
- Radiation survey rate with a β/γ instrument is 75 square feet per hour. Survey rates with an α instrument are 60 square feet per hour for dose-based release limits and 30 square feet per hour for DOE Order 5400.5 release limits.
- Decontamination is accomplished with a 4 gallon per minute high pressure washer. Treatment cost for decontamination water is $0.10 per gallon. Decontamination is done with a crew of two laborers, one grapple operator, and an ES&H technician. Decontamination can be accomplished as a rate of 50 square feet per crew hour for dose

based release limits and 25 square feet per crew hour for DOE Order 5400.5 release limits.

- On site disposal in the disposal cell costs $156 per bulk cubic yard.
- Scrap salvage value is $75 per ton for CSS steel and $50 per ton for all other steel.
- Metals are size-reduced by demolition subcontractor and stockpiled for survey. Materials for recycle are placed in recycle vendor's roll-off containers for release and transport off-site.

Table A-9 summarizes the results of cost analyses for each alternative. The cost estimates were based upon realistic assumptions from vendor information, process knowledge, operating experience, and site specific work practices and subcontract wage rates. The costs for the various alternatives could vary considerably from the estimated values if the actual levels of contamination vary significantly from estimated values and if the actual effort to decontaminated steel to achieve release values is significantly at variance with estimated.

TABLE A-9. Cost Summary for Alternatives

Element	Alternative 1 Dose-based limits W/ decon & release	Alternative 2 DOE Order 5400.5 limits W/ decon & release	Alternative 3 DOE Order 5400.5 limits No decon.	Alternative 4 On-site disposal
Survey Costs	$160,200	$320,400	$320,400	0
Decon Costs				
Transport	$660	$660	0	0
Decon	$215,340	$423,780	0	0
Water Treatment	$23,060	$45,480	0	0
On-site DisposalCosts	0	0	$19,200	$84,240
Salvage	($28,500)	($28,500)	($21,800)	0
Total	$370,760	$761,820	$317,800	$84,240

Alternative 1 release limits were based on an individual dose of 1 mrem (0.01 mSv) per year for the most restrictive scenario presented in PNL-8724. The major costs were associated with survey and decontamination of CSS steel to the dose-based limits. The principal constituent of CSS plant contamination was Th-230. The assumed survey rate for calculating costs was 60 ft^2 per hour with alpha sensitive instrumentation. An assumption was made that, of the half (or 170 tons) of CSS plant steel surveyed for contamination; approximately half of the surfaces encountered would be above the calculated dose-based release limit and thus would require decontamination for release. A factor of 50 ft^2 per crew hour was used to determine decontamination costs. It was assumed that all steel would be successfully decontaminated to release limits at that rate.

The site water treatment plant and the quarry water treatment plant only accounted for 15 percent of the 400 tons of structural and building steel proposed for release. For Alternative 1, it was assumed that surveying would be done at the two treatment plants with a beta-gamma instrument at the rate of 75 ft^2 per instrument hour. The decontamination rate used for the treatment plants was the same as that used for the CSS plant. Decontamination accounts for about 64 percent of the tabulated overall costs to release under Alternative 1. This was also the cost element with the highest degree of uncertainty. The actual amount of contaminated steel could not be determined in the absence of surveys and the decontamination factor used did not have a strong basis in on-site experience. The small return for recyclable steel for the large expenditure in decontamination effort eliminates Alternative 1.

Alternative 2 release limits are based upon Figure IV-1 values from DOE Order 5400.5. The costs for survey and decontamination were estimated to be higher than for Alternative 1 because of the lower release limit for Th-230, which was present at limiting quantities at both the CSS plant and the site water treatment plant. The assumed survey rate for calculating costs was 30 ft^2 per instrument hour. The decontamination rate was assumed at 25 ft^2 per crew hour. Decontamination accounts for about 61 percent of the tabulated overall costs for Alternative 2. As with Alternative 1, there was a great deal of uncertainty with this estimated figure. Again there is a small return in salvage for a potentially large expenditure of resources to decontaminate. For these reasons Alternative 2 should be eliminated from further consideration.

Alternative 3 was the same as Alternative 2 except that no effort was spent in decontamination. The principal costs were those associated with the survey process with perhaps some minor administrative costs associated with the release process.

Alternative 4 consisted of taking all of the steel to the disposal cell. Cost elements considered were the costs to transport the steel to the disposal cell and the costs of the expected added volume to the cell.

Local salvage dealers were queried as to the expected salvage value of the scrap metal. Their response was that current (October 1998) market forces were depressing the price for scrap metal. Thus the estimated values used were $75 per ton for thick hot rolled structural and $50 per ton for panels, cold formed structural, and small hot rolled structural and tubing.

A3.8 Collective Dose Assessment

A very accurate assessment of collective dose could not be performed using PNL-8724 because dose values were listed only for the MEI for each analyzed scenario. However, conservative collective dose estimates could be derived by grouping the exposed individuals into two general categories (i.e., recycling workers/product users and population downwind of a smelter) and assuming each individual received the same dose as the respective category MEI. “Recycling workers” included all individuals involved with scrap delivery, smelting operations, initial and final fabrication and distribution of the steel.

Because each alternative’s individual dose calculation accounted for the quantity of steel recycled from each facility, the number of recycling workers was not adjusted further. That is, the additional individual exposure time had already been accounted for in the calculation of the individual doses and no additional individuals were required to process the steel.

The recycled steel was assumed to be used for the production of automobiles. Because 100 tons of recycled steel is estimated to result in the production of 600 automobiles, the number of exposed individuals for this category was corrected for the total quantity of steel recycled and assumed an average occupancy of two individuals per vehicle. The collective dose was indicated for a single year of automobile use for a total annual exposure of 300 hours per individual.

To conservatively estimate the collective dose this exposed population, it was assumed that 10,000 individuals receive a dose equivalent to the MEI. Dose values were calculated by using the maximum radionuclide concentrations (pCi/g) in the recycled steel from each WSSRAP facility. The concentrations were multiplied by the limiting dose values provided in Table H.1 of PNL-8724 and corrected for the total quantity of steel recycled for each alternative.

The Weldon Spring Site is immediately surrounded by government-owned property. Local demographics represent a mixture of rural and suburban populations beyond the government-controlled area. Because of this, collective dose determinations from on-site burial scenarios assumed that 1,000 individuals were exposed to the level of the RESRAD MEI dose results.

A3.9 Assessment of Other Factors

The calculation of dose-based surface contamination release limits resulted in values greater than DOE Order 5400.5, Table IV-1 values for some radionuclides. Because of this, the release of materials for recycle and unrestricted use at dose-based limits would not conform to approved standards in site-specific CERCLA record-of-decision documents. Taking into consideration that DOE Order 5400.5, Table IV-1 values are equivalent to Regulatory Guide 1.86, *Termination of Operating Licenses for Nuclear Reactors*, Table 1 values, licensing concerns from the NRC were also a possibility. Therefore, the option of unrestricted release of materials at dose-based limits (i.e., Alternative 1) may not be viable, regardless of dose and cost comparisons.

Economic analysis of each alternative showed that on-site disposal resulted in maximum cost savings. However, permanent disposal would waste a large volume of potentially recyclable material. This option was not consistent with DOE's commitment to promote conservation of energy and natural resources (as recycling does). The recycle of steel also eliminates other risks associated with the mining and milling of virgin ores. Below are the parameters of consideration for each of the alternatives.

TABLE A-10

Parameter	Alternative 1	Alternative 2	Alternative 3	Alternative 4 *100% On-Site Cell Disposal*
Number of recycling workers	132	132	132	
Number of automobile users	4800	4800	2688	
Total individuals	4932	4932	2820	
Annual Dose to MEI	1 mrem	0.357 mrem	0.293 mrem	
Collective Dose	4.932 person-rem (A)	1.760 person-rem (A)	0.830 person-rem (A)	
Population Downwind of Smelter	10,000	10,000	10,000	
Annual Dose to MEI	0.040 mrem	0.015 mrem	0.012 mrem	
Collective Dose	0.400 person-rem (B)	0.150 person-rem (B)	0.120 person-rem (B)	
Population Affected by Burial			1000	1000
Annual Dose to MEI			0.165 mrem	0.184 mrem
Collective Dose			0.165 person-rem (C)	
Total Annual Collective Dose	5.332 person-rem	1.910 person-rem	1.115 person-rem	0.184 person-rem

Although the economic analyses showed decon and survey labor costs to be in excess of disposal costs, scheduling of a facility's demolition during "non-peak" construction periods may permit such decon/survey activities regardless of cost. Because the associated work crews must be kept on-site to maintain their availability during peak construction periods, the work would be performed as "fill-in" duties to sustain crew productivity during slow periods.

A3.10 Selection of the Proposed Alternative

Table A-11 summarizes doses and costs for all four alternatives. As Table A-11 shows, the doses associated with all alternatives are very low and subsequently fully protective. Therefore, selection of an alternative would be based on other factors, such as costs and potential regulatory conflicts.

TABLE A-11. Dose and Cost Summary for Recyclable/Reusable Steel

Alternative	Maximum Annual Individual Dose (mrem)	Annual Collective Dose (person-rem)	Cost ($)	Dose-Adjusted Cost ($) *
Alternative 1: Unrestricted release of all material at dose-based values	1.0	5.332	370,760	381,400
Alternative 2: Unrestricted release of all material at DOE Order 5400.5 values	0.357	1.910	761,820	765,600
Alternative 3: Unrestricted release at DOE Order 5400.5 values/on-site burial combination	0.637	1.115	317,800	320,000
Alternative 4: 100 % on-site burial	0.184	0.184	84,240	84,600

* Cost is adjusted by adding $2,000 for each person-rem of annual collective dose

A3.10.1 Alternative 1, Unrestricted release of all material at dose-based values

Because the ALARA analysis demonstrated Alternative 3 to be more cost-effective and due to potential conflicts with release limit values in Regulatory Guide 1.86 and CERCLA record-of-decision documents, this alternative was not selected.

A3.10.2 Alternative 2, Unrestricted release of all material at DOE Order 5400.5 values

An aggressive decontamination program in order to release all recyclable steel was demonstrated to be cost-prohibitive, primarily due to a lack of scrap metal worth. Subsequently, Alternative 2 was not selected. However, for items with potential worth, a simple economic analysis could be performed to justify a decontamination effort. A complete ALARA analysis would not be necessary because the DOE Order 5400.5, Table IV-1 values had been demonstrated as being protective to the public for an annual release of all 400 tons of the recyclable/reusable steel.

A3.10.3 Alternative 3, Unrestricted release at DOE Order 5400.5 values/on-site burial combination

If recycling of the steel were to be performed, then Alternative 3 would be exercised. Due to the relative inexpensive burial costs and depressed resale value of scrap steel, minimal time should be committed to reduction of contamination levels to DOE Order 5400.5, Table IV-1 values. An economic comparison showed that disposal costs were at least 50% cheaper than costs associated with decontamination and recovery of the steel. The collective dose to the public was also less for disposal than for recycle.

A3.10.4 Alternative 4, 100% on-site burial

Because recovery of a significant portion of the steel is likely to be possible through utilization of a workforce maintained on-site for other purposes, complete disposal would not be performed. Creative scheduling of work for idle crews should allow Alternative 3 to be exercised for recyclable-only steel and Alternative 2 for items determined to have resale potential. In the event that support was not available from on-site crews, then disposal would be exercised prior to acquisition of additional labor.

A3.11 Statement of Proposed Authorized Limits

Because the surface contamination release guidelines listed in DOE Order 5400.5 and Regulatory Guide 1.86 were demonstrated as being protective to the public for the unrestricted release of 400 tons of WSSRAP steel, it was recommended that these values be used when economically feasible. Table A-12 summarizes the proposed surface contamination release guidelines for each radionuclide or class of radionuclides.

TABLE A-12. Surface Contamination Guidelines
Allowable Total Residual Surface Activity (dpm/100 cm^2)[1]

Radionuclides[2]	Average[3/4]	Maximum[4/5]	Removable[6]
Group 1 - Transuranics, I-125, I-129, Ac-227, Ra-226, Ra-228, Th-228, Th-230, Pa-231	100	300	20
Group 2 - Th-natural, Sr-90, I-126, I-131, I-133, Ra-223, Ra-224, U-232, Th-232	1,000	3,000	200
Group 3 - U-natural, U-235, U-238, and associated decay products, alpha emitters	5,000	15,000	1,000
Group 4 - Beta-gamma emitters (radionuclides with decay modes other than alpha emission or spontaneous fission) except Sr-90 and others noted above[7]	5,000	15,000	1,000

NOTES:

1. As used in this table, dpm (disintegrations per minute) means the rate of emission by radioactive material as determined by counts per minute measured by an appropriate detector for background, efficiency and geometric factors associated with the instrumentation.
2. Where surface contamination by both alpha and beta-gamma emitting radionuclides exists, the limits established for alpha and beta-gamma emitting radionuclides should apply independently.
3. Measurements of average contamination should not be averaged over an area of more than 1 m^2. For objects of smaller surface area, the average should be derived for each object.
4. The average and maximum dose rates associated with surface contamination resulting from beta-gamma emitters should not exceed 0.2 mrad/hr and 1.0 mrad/hr, respectively, at 1 cm.
5. The maximum contamination level applies to an area of not more that 100 cm^2.
6. The amount of removable material per 100 cm^2 of surface area should be determined by wiping an area of that size with dry filter or soft absorbent paper, applying moderate pressure, and measuring the amount of radioactive material on the wiping with an appropriate instrument of known efficiency. When removable contamination on objects of surface less that 100 cm^2 is determined, the activity per unit area should be based on the actual area and the entire surface should be wiped. It is not necessary to us wiping techniques to measure removable contamination levels if direct scan surveys indicate that the total residual surface contamination levels are within the limits for removable contamination.
7. This category of radionuclides includes fission products, including the Sr-90 present in them. It does not apply to Sr-90 that has been separated from other fission products or mixtures where the Sr-90 has been enriched.

A4 Bag Monitor Comparative Analysis of Radiological Risks and Costs at Brookhaven National Laboratory

Introduction

Personal protective clothing worn at environmental restoration sites must be treated as potentially contaminated when there is a potential for contamination with radioactive material. The traditional approach for measuring radioactive contamination on protective clothing is to “frisk” each worker with a hand-held radiation detector or for the worker/protective clothing to be counted in a portal monitor.

An innovative approach is to use a bag monitor. This method of measuring contamination on over 20 articles of protective clothing at a time is more sensitive, more effective, and less costly than the traditional approach. The traditional disposal options are: 1) disposing of the contaminated clothing after hand "frisking" or portal monitoring and sorting out of the clean from the contaminated or 2) disposing of all potentially contaminated protective clothing as low-level waste.

Potential radiological risk and costs for four different disposal options were compared. These options were to dispose of those bags that have radiation levels greater than the assumed radiation test criteria:

- In a hazardous waste disposal site;
- At a municipal landfill;
- At an on-site incinerator; and
- A base case consisting of disposal of all bags as low-level radioactive waste.

Approach

Potential exposures to future residents on the site with residual radioactive material from the four disposal options were estimated using the dose assessment software RESRAD version 5.61 (Yu et al., 1993). The RESRAD analysis included potential groundwater contamination as well as direct radiation, inhalation, and food-chain pathways. Exposure estimates for workers and public exposure from airborne releases from an incinerator were derived from Aaberg et al. (1995) and compared with results from TSD-DOSE.

Exposure to workers transporting waste to a disposal site and receiving and handling waste at the disposal site were estimated with TSD-DOSE v. 1.1β (Pfingston et al., 1997) and MicroShield version 5.01 (Grove, 1996). The bags and their contents were assumed to be plastic. TSD-DOSE and Aaberg et al. (1995) assume soil. Since for landfill exposures the bags are in soil and incinerator emissions are reduced to particles, the assumption of soil is not unreasonable. The density of material in the bags was specified in TSD-DOSE as the density of plastic. The MicroShield estimates were based on PVC plastic. It was assumed that Cs-137 was the radionuclide of concern in all cases.

The maximum allowable activity per 100 cm^2 area on a single article of protective clothing is 1,000 dpm. It was assumed that no fixed activity existed on the protective clothing and therefore the 5,000 dpm/100 cm^2 did not apply. The 1,000 dpm/100cm^2 was used as the radiation test criteria per bag for unrestricted release. Thus, if a single article of the 20 articles in the bag exceeds this criterion, the bag is disposed as low-level radioactive waste. Only those bags that successfully pass this radiation test criteria are considered in this analysis.

In the case of public exposure, population density was addressed parametrically. Three densities were used following Aaberg et al. (1995): (1) metropolitan high-medium density (80 people/km^2), (2) metropolitan low density (20 people/km^2) and (3) rural (10 people/km^2).

Analysis was done on a unit basis. One hundred drums of slightly contaminated plastic protective clothing were assumed to require disposal each year.

Data Sources

Costs were obtained from Brookhaven National Laboratory (BNL) and the Town of Brookhaven Landfill.

A truck is assumed to carry 80 drums per load. Landfilling requires more space per drum than the actual drum. Estimated landfill volume is 9.2 ft^3 (0.26 m^3) per drum. It is expected that about 100 drums per year will be produced at BNL, primarily from environmental restoration work.

The base data for incineration were taken from Aaberg et al. (1995). An incinerator processing 30,000 tons/year (2.7 E+7 kg/yr) was assumed. Cesium was assumed to partition as 0.20 to flyash, 0.80 to slag, and 0.002 released from the stack.

Analysis

Calculation of Common Parameters:

DOE's 1,000 dpm/100 cm^2 limit is 16.7 dps/100 cm^2.

$$\frac{16.7\ dps}{3.7\ x\ 10^{10} dps\ Ci^{-1}} = 4.5\ x\ 10^{-10}\ Ci$$

This value, 0.45 nCi or 450 pCi, is the maximum allowable for 100 cm^2 on a single article of protective clothing. This is essentially the detection limit per individual article of protective clothing for hand frisking, but the detection limit of the bag monitor is below this for 20 articles of protective clothing.

A bag of 20 articles of protective clothing weighs about 3.5 pounds (1590 g). Bags are compacted in drums for shipment or disposal. About 6 bags are compacted in a 55 gallon (0.208 m3) drum. The density in the drum is:

$$\frac{6 \text{ x } 1590\ g}{2.08 \text{ x } 10^5\ cc} = 0.05\ g/cc$$

The bag monitor detection limit for a density of 0.1 g/cc is 300 pCi.

Maximum allowable activity per 100 cm^2 area on a single article of protective clothing was determined as the maximum allowable level per bag. If the upper limit for a bag is set at 450 pCi/bag, no article exceeding the maximum is released. For six bags per drum, the maximum in a drum will be:

$$450\ pCi/bag \text{ x } 6\ \ bags/drum = 2{,}700\ pCi/drum$$

Public Exposure in Land Disposal

Public exposure in land disposal of bags consists of the possibility of people living on the landfill site at some point in the future. The maximum allowable exposure to the public is 25 mrem (0.25 mSv) per yr (10 CFR Part 20), although DOE sets a goal of a few mrem/yr. RESRAD analysis determined a maximum allowable concentration of Cs-137 in soil for residential use as

11.1 pCi/g for an allowable exposure to the public of 25 mrem (0.25 mSv) per yr. This soil concentration was more than sufficient to avoid exposure from well water over 4 mrem (0.04 mSv) per yr. This was a conservative analysis, assuming no cover material on the landfill, no liner, sandy loam soil, and 5 meters to ground water. The analysis assumed K_d values for Cs-137 between 44 cm^3/g and 320 cm^3/g, which is similar to the range of K_d values found in BNL soil.

The concentration of the Cs-137 in the bag waste is:

$$\frac{450\, pCi/bag}{1590\, g/bag} = 0.28 pCi/g$$

assuming each bag contains the maximum allowable amount. Disposal in a landfill requires more space per drum than the actual drum. Estimated landfill volume based on an 80% increase in the bags volume, i.e., air space, is 0.26 m^3 per drum. This is due to the decrease in the density of the waste when buried in a 55 gallon drum. Thus, the concentration in the landfill will be 0.22 pCi/g.

RESRAD analysis finds exposure to residents living on the waste site would be 2.2 mrem (0.022 mSv) per yr per pCi/g if they lived there immediately after initial emplacement. This assumes the contaminated material is mixed with the soil and thus can be ingested and inhaled. No credit is taken for shielding from the drum itself. These assumptions are extremely conservative for residents living on the landfill immediately following emplacement. Over time these assumptions may hold, but the exposure to pCi/g at emplacement will be lower at such time. It is more likely that the land would not revert to residential use for years after emplacement. Exposure levels decrease over time. In 10 years residential exposure under these assumptions would be 1.7 mrem (0.017 mSv) per yr; after 50 years, 0.7 mrem (0.0017 mSv) per yr; and after 100 years, 0.2 mrem (0.002 mSv) per yr. These values are for a MEI, but here it is assumed it applies also to the average individual.

Before estimating population exposure, however, it is useful to consider the area potentially involved. One hundred drums per year require:

$$(100 \text{ drums/yr} \times 0.26 \text{ m}^3\text{/drum}) = 26 \text{ m}^3\text{/yr}.$$

If drums are emplaced in a single layer the height of the drum (34 inches or 0.36 m), this requires 72 m^2/yr. Ten years of operation would require 720 m^2 (0.18 acres). This is too small an area for residence, but the results can be scaled to estimate for larger operations. The RESRAD analysis was based on a much larger area for conservatism.

Population exposure is calculated as the land area times the population density times the dose to source ratio times the concentration of Cs-137 in the landfill. For example, for the high-medium density case:

$$80 \text{ people/km}^2 \times 72 \text{ m}^2 \times 0.001 \text{ km}^2\text{/m}^2 \times 2.2 \text{ mrem/yr per pCi/g}$$

$$\times\, 0.001 \text{ rem/mrem} \times 0.22 \text{ pCi/g} = 0.003 \text{ person-rem/yr}$$

for each year's emplacement of 100 drums.

Values for all three population densities are given in Table A-13. This does not take into account radioactive decay during the 10 year operation period or during any intervening time between ceasing operation and residential use. The population exposure is small, but can be scaled to larger operations.

TABLE A-13. Annual Population Exposure in Landfill Operation at 100 Drums/Year

Density Category	Persons/km^2	Person-rem/yr for each year's emplacement
High-medium metropolitan	80	3.0 E-3
Low metropolitan	20	7.0 E-4
Rural	10	3.0 E-4

Worker Exposure in Land Disposal

Exposure to workers involved in landfilling waste was estimated by Aaberg et al. (1995) at 0.22 mrem (0.0022 mSv) per yr per pCi Cs-137 per gram of waste. Exposure assumptions were: 1500 hours/yr with limited ingestion of soil. Since the waste in drums contains 0.22 pCi/g, exposure to workers over the course of a year would be:

0.22 mrem per yr per pCi per g x 0.22 pCi/g = 0.05 mrem per yr

for a continuous operation, but 100 drums of waste at 9.2 ft^3 is 0.34 CY. At 1.6 hours/CY, this is only 55 hours for 100 drums. Taking the ratio of 55 hours to 1500 hours times the 0.05 mrem (5,0 E-4 mSv) per yr for an annual exposure yields:

$$\frac{55\ h/100\ drums/yr}{1500\ h/yr} = 0.05\, mrem/yr = 0.02\ mrem/yr$$

for 100 drums. Assuming two workers are exposed, the population exposure is 0.004 person-rem/year. This is highly conservative since the waste is in drums, avoiding exposure from inhalation or ingestion.

Worker Exposure at Incinerator

Worker exposure at the incinerator was based on scenarios developed and exposure estimates of Aaberg et al. (1995). Cesium partitions in the incinerator as 20% flyash, 80% slag, and 0.2% to the stack. Individual jobs at the incinerator include waste receiving, waste treatment, bag filter maintenance, scrubber maintenance, and incinerator maintenance. Due to the high fraction of Cs-137 collected in the slag, the workers that maintain the incinerator receive the greatest exposure from cleaning out the rotary kiln or afterburner chamber during shutdowns. Estimates for 2.7 E+7 kg/yr waste throughput and for 100 drums/yr are given in Table A-14.

TABLE A-14. Worker Exposure from Cs-137 at Incinerator for 2.7 E+7 kg/yr Waste Throughput with Waste Consisting of 100% Bags (after Aaberg et al., 1995) and at 100 drums/yr

Job Category	mrem/yr per pCi/g in waste for 2.7 H 10^7 kg/yr waste throughput	mrem/yr for 100 drums/yr
Receiving & sampling	0.13	4.5 E-6
Waste treatment	0.02	7.0 E-7
Bag filter maintenance	0.03	1.1 E-6

Scrubber maintenance	0.02	7.0 E-7
Incinerator maintenance	0.11	3.9 E-6

Assuming two workers in each job category yields a total worker population exposure of 2.2 E-5 person-rem/yr for 100 drums/yr.

As a comparison, analysis with TSD-DOSE for the 100 drums/yr case estimates 2.3 E-5 mrem (2.3 E-7 mSv) per year exposure in receiving and sampling, 1.3 E-6 mrem (1.3 E-8 per year exposure in incinerator maintenance, 7.3 E-6 mrem (7.3 E-8 mSv) per year exposure in incinerator operations, and 3.4 E-4 mrem (3.4 E-6 per year exposure in storage operations. Total person-rem to incinerator workers was estimated at 8.8 E-7 mrem (8.8 E-9 mSv) per year. The higher value above is used in the summary tables.

Aaberg et al. (1995) address incineration for contaminated soil, which would leave a much larger amount of total ash and slag. The concentration of Cs-137 would thus be lower, but the amount or radioactive material would be unchanged.

Public Exposure in Incineration of Bags

A reference incinerator is assumed based on the reference incinerator described by Aaberg et al. (1995). The incinerator was characterized as a rotary kiln with a single stack, 30 m high and 2 m in diameter with an exit velocity of 5.4 m/s with a bag filter system for collecting flyash. Waste throughput for the incinerator was 30,000 tons/yr (2.7 E+7 kg/yr). These values are within the range of commercial hazardous waste incinerators. Public exposure estimates were based on air dispersion modeling using CAP88-PC (Aaberg et al., 1995). Exposure routes included direct inhalation, deposition, and food-chain.

With a drum of mass 9.5 kg, a waste throughput of 2.7 E+7 kg/yr implies:

(2.7 7E+7 kg/yr) / (9.5 kg/drum) = 2.8 E+6 drums/yr

assuming such bags constitute 100% of the waste. The 100 drums/yr expected in BNL operations are thus a small fraction of the total incinerator throughput (3.5 E-5).

Table A-15 shows the concentration of Cs-137 in incinerator throughput at 2.7 E+7 kg/yr that produces an exposure to the MEI, or representative person of the critical group, of 1 mrem (0.01 mSv) per yr. These values are from Aaberg et al., (1995). The table also translates these into values of mrem per pCi/g in the waste throughput.

TABLE A-15. Concentration (pCi/g) of Cs-137 in Waste that Produces Given Exposure to Maximum Individual in Public with 30,000 tons/yr (2.7 E+7 kg/yr) Waste Throughput (Derived from Aaberg et al., 1995) and the Inverse of that Value, in Units of mrem/yr

Population Density	pCi/g producing 1 mrem/yr	mrem/yr per pCi/g
High-medium metropolitan	2.7 E+3	3.7 E-4
Low metropolitan	2.5 E+3	4.0 E-4
Rural	2.4 E+3	4.2 E-4

The higher exposure per unit concentration in the waste in rural areas is due to the assumed increased exposure via the food chain. The maximum concentration in the bag is 280 pCi/g. The exposure to the MEI is thus the mrem per pCi/g value from Table A-13 times 0.28 pCi/g. For example, for the high-medium metropolitan population density, if the bags constituted 100% of the 30,000 tons waste throughput exposure would be:

3.7 E-4 mrem/yr per pCi/g x 0.28 pCi/g = 1.0 E-4 mrem/yr

Since only 100 bags/year was considered, this value is multiplied by the mass fraction,

[(100 drums/yr x 3.5 lbs/bag x 6 bags/drum) / 2000 lbs/ton] / 30,000 tons/yr

= 3.5 E-5.

1.0 E-4 mrem/yr x 3.5 E-5 = 3.5 E-9 mrem/yr

Results for the three population density categories are given in Table A-16.

TABLE A-16. Exposure to Maximum Individual in Public at 30,000 Tons/yr (2.7 E+7 kg/yr) Waste Throughput with Waste Consisting of 100% Bags and with Only 100 Drums Filled with Bags Per Year

Population Density	mrem/yr to max individual for 30,000 tons/yr bags	mrem/yr to max individual for 100 drums/year
High-medium metropolitan	1.0 E-4	3.5 E-9
Low metropolitan	1.1 E-4	3.9 E-9
Rural	1.2 E-4	4.2 E-9

Estimates of population exposure depend on the number of people exposed and the level of exposure to the average individual, not the MEI. Calculations of exposure around a facility are generally made with a Gaussian plume model addressing exposure within a 50 mile or 80 km radius. This provides an area of π x 80 km^2 or 20,100 km^2. Since the peak exposure (MEI) is relatively near the source, and concentrations decrease beyond that, the average exposure within the 80 km radius is considerably lower than the peak. Examination of Gaussian plume results from Aaberg et al. (1995) and TSD-DOSE indicates the average exposure ranges from 0.01% to 1% of the peak exposure. The calculation of the population exposure for the high-medium population density for 100 drums/yr is calculated below using a ratio of 0.1% as an example. Table A-17 provides estimates of population exposure for each population density.

3.5 E-9 mrem/yr x 0.001 mean/peak x 2.0 E+4 km^2 x 80 people/km^2

x 0.001 rem/mrem = 5.6 E-9 person-mrem/yr.

TABLE A-17. Population Exposure in 80 km Radius per pCi/g Cs-137 at 2.7 E+7 kg/yr Waste Throughput with Waste Consisting of 100% Bags and at 100 Drums/yr

Density Category	Median persons/sq mi	Person-mrem, 100% bags (2.7 E+7 kg/yr)	Person-mrem, 100 drums/yr
High-medium metropolitan	80	1.6 E-4	5.6 E-9
Low metropolitan	20	4.4 E-5	1.6 E-9
Rural	10	2.4 E-5	8.4 E-10

Public Exposure of Landfill of Ash and Slag from Incinerator

Public exposure from the landfill of ash and slag from the incinerator is primarily due to the possibility of future residential use of the landfill site.

The original drummed waste was estimated to have a concentration of 0.28 pCi/g. Cesium, however, is concentrated in the flyash and slag from the incinerator. Of the original waste, all but 0.2% of the Cs-137 remains in the flyash and slag whereas, only 70% of miscellaneous solids are captured as flyash or slag (Aaberg et al., 1995). This results in a concentration of Cs-137 in the flyash and slag to be landfilled of:

$$(0.28 \text{ pCi/g}) \times 0.998 / 0.7 = 0.4 \text{ pCi/g},$$

well below the clean-up guideline of 11 pCi/g. The ash and slag is a much smaller volume than the original waste. Aaberg et al. (1995) estimate a landfill area of 10,000 m^2 for the full throughput of the incinerator of 2.7 E+7 kg/yr. For 100 drums/yr translates to 950 kg/yr, a ratio of 3.5 E-5. This yields a landfill area of 0.35 m^2/yr. As was the case for direct landfilling of drums, this is too small an area for residence, but the results can be scaled to estimate for larger operations. In addition, an area this size would qualify as a "hot spot" for which the soil cleanup guideline would be multiplied by 10 (Yu et al., 1993).

Population exposure estimates for small areas (e.g., less than 1 m^2) are of little direct practical value in an analysis. It is calculated in this example for potential scaling purposes. The calculation is the land area times the population density times the dose to source ratio times the concentration of radionuclide in the soil. For example, for the high-medium density case:

$$207 \text{ people/mi}^2 \times 3.86 \text{ E-7 mi}^2\text{/m}^2 \times 0.35 \text{ m}^2 \times 2.2 \text{ mrem/yr per pCi/g}$$

$$\times\ 0.4 \text{ pCi/g} \times 0.001 \text{ rem/mrem} = 2.5 \text{ E-8 person-rem}$$

This is only a hypothetical exposure since the area is so small. It provides a basis for scaling to larger areas. Exposure for the three population densities assuming the production of 100 drums/yr is given in Table A-18**.**

TABLE A-18. Annual Population Exposure in Public from Landfilling Incinerator Ash and Slag with 100 Drums/yr of Cs-137 Waste through the Incinerator

Population Density	Person-rem/yr
High-medium metropolitan	2.5 E-8
Low metropolitan	6.3 E-9
Rural	3.1 E-9

Worker Exposure of Landfill of Ash and Slag from Incinerator

Given the estimated concentration of Cs-137 in the ash and slag of 0.4 pCi/g and the estimate from Aaberg et al. (1995) that workers' landfilling ash and slag containing Cs-137 was 0.22 mrem (2.2 E-3 mSv) per yr per pCi/g, worker exposure rate is estimated at 0.09 mrem (9.0 E-4 mSv) per year if the worker was landfilling this material for the entire year. As shown above, however, the 100 drums of waste constitute only 55/1500ths or 3.7% of the annual landfill effort on an hourly basis, the worker's exposure is:

0.4 pCi/g x 22 mrem/yr per pCi/g = 0.09 mrem/yr

0.09 mrem/yr x 0.037 = 3.0 E-3 mrem/yr.

If it is assumed that only one worker is exposed in this small operation then the population exposure is 3.0 E-6 person-mrem/yr.

Exposures in Transportation

Transportation includes load and secure, drive, rest, and maintenance. The need for transportation and the length of trip varies by circumstances. For 100 drums/yr, only 1.25 trips per year are required at 80 drums per truckload.

Trucking waste from BNL to the Envirocare radiation disposal site is a trip of 2,200 miles. With two drivers driving straight through, averaging 55 miles per hour, this would take 40 hours. Assuming drivers work 2000 hours/yr, this is 2% of a year.

Based on Aaberg et al. (1995), the exposure to workers transporting drums by truck was estimated to be 0.016 mrem (1.6 E-4 mSv) per year per pCi/g Cs-137 in the waste. This assumed full-time drivers, 10 hr/d in the truck and 8 hr/d in the sleeping compartment, with the truck loaded one-half the time, i.e., returning empty. Assuming two drivers, population exposure is 0.02 person-mrem/yr. Since the time to transport 100 drums/yr is only 3% of the working year, exposure to drivers was estimated to be 6.0 E-4 person-mrem/yr.

The estimate exposure to drivers using TSD-DOSE was 1.7 E-3 mrem (1.7 E-5 mSv) per trip, or 2.1 E-3 mrem (2.1 E-5 mSv) per 100 drums. The estimate assuming PVC plastic in MicroShield was 1.04 E-4 mrem (1.04 E-6 mSv) per hour at a six foot distance. Given the estimated 63 hours in TSD dose, total exposure was 6.3 E-4 mrem (6.3 E-6 mSv) per 100 drums. The two estimates are essentially identical. For two drivers, population exposure would be 3.4 E-6 person-rem per 100 drums. Given the very small worker exposure level, exposure to the public, which would be much smaller, was not calculated.

Transportation to a local municipal landfill involves only a few miles and exposure to workers will be nil.

TABLE A-19. Summary of Exposure in Person-rem for 100 Drums with Disposal in High-Medium Population Density for Four Different Disposal Options

Activity	Baseline (low-level rad waste disposal)	Hazardous waste disposal site	Municipal landfill	Incineration on site
Public exposure to future residents on landfill site	3.0 E-3	3.0 E-3	3.0 E-3	3.0 E-8
Public exposure to air pollution	nil	nil	nil	6.0 E-9
Worker exposure	4.0 E-3	4 .0 E-3	4.0 E-3	2 .0 E-5
Transport exposure (worker)	1.0 E-6	1.0 E-6	nil	nil
Total public exposure	3.0 E-3	3.0 E-3	3 .0 E-3	4.0 E-8
Total worker exposure	4.0 E-3	4.0 E-3	4.0 E-3	2.0 E-5

Bag Monitor Radiation Test Criteria

Exposures from disposal of the bag-monitored waste are extremely low. This is desirable and consistent with the ALARA principle. Given the potential costs of land disposal, one may question the reasonability of maintaining such low concentrations in the waste.

As an exercise, it is possible to back-calculate the alarm setting on the bag monitor that will just meet the soil cleanup guidance for residential use. That guideline was determined by RESRAD to be 11 pCi/g for Cs-137. The current limit is 0.45 nCi/bag, which translates to 0.28 pCi/g. Increasing the concentration to 11 pCi/g would allow the maximum test criteria or alarm setpoint to increase by a factor of 39. The associated increase in worker exposure would be an increase from 0.08 person-mrem/yr to about 3 person-mrem/yr.

This calculation shows the degree of conservatism that is associated with the current maximum allowable limit of 1,000 dpm/100cm^2 for the bag monitor.

Costs

Direct monetary costs for the different cases are provided in Table A-20. Baseline costs and costs for administration, drum preparation, and transportation costs to low-level waste and hazardous waste sites are from Miltenberger (1995). Results are re-expressed in tabular form on the basis of 100 drums annually in Table A-19. The baseline case is transport of bags to Hanford for disposal as low-level waste.

Health physics support was assumed to require 10 minutes/bag at $45/hour.

For disposal in a municipal landfill, the drum is assumed to be disposed with the waste. Tipping fee at the Brookhaven Town Landfill is $0.045/lb. At 3.5 lbs/bag, 6 bags/drum, the weight of the waste in the drum is 21 lbs. The tare weight is 55 lbs., yielding a total weight of 76 lbs/drum. This yields a cost of $342/100 drums.

For incineration, drums are not assumed to be incinerated. Incineration costs are $4.63/lb (BNL Environmental Restoration Division). At 3.5 lbs/bag, 6 bags/drum, the weight of the waste is 21 lbs/drum. This yields a cost of $9,723/100 drums. This is the cost for at an off-site incinerator.

Since the incinerator is assumed to be on site, this cost is assumed to include capital and operating and maintenance costs of incinerator.

The cost of the bag monitor itself is about $60,000. Assuming a useful life of 20 years and an interest rate of 5% per yr, the capital recovery factor is 0.08024. This results in an annualized cost of $4,814. This costs are added to all the cost estimates except the base case, in which the bag monitor is not used (assume the hand monitors are already in place).

Results

Results are expressed on the basis of 100 drums annually in Table A-19. The baseline case is transport of bags to Hanford for disposal as low-level waste. Given the concentration of Cs-137 in the waste, the results for a municipal landfill and a hazardous waste landfill are identical except for cost and transport distance. Incineration is assumed to be on-site.

TABLE A-20. Costs

Activity	Baseline (low-level rad waste disposal)	Hazardous waste disposal site	Municipal landfill	Incineration on site.
Health physics support	25 person-h $1,125	100 person-h $4,500.	100 person-h $4,500.	100 person-h $4,500.
Drum prep	125 person-h $5,625	8.4 person-h $378	8.4 person-h $378	8.4 person-h $378
Administration	40 person-h $2,250	0.63 person-h $28	0.63 person-h $28	1.3 person-h $59.
Transport	$7,500	$10,000	Nil	Nil
Disposal	$40,500	$10,000	$342	$9,723
Bag monitor	None	$4,814	$4,814	$4814
TOTAL COSTS	$57,000	$29,720	10,062	$19,474

Conclusions

Exposure to Future Populations Residing On or Near the Landfill

The concentration of Cs -137 in the bagged waste that passes the screen of the bag monitor is an order of magnitude lower than the soil cleanup goal for residential land-use. A landfill entirely filled with any amount of these bags would never require remediation. Although cesium concentrates in the ash, the concentration remains well below the soil cleanup goal for residential land-use. A landfill entirely filled with the ash and slag resulting from incineration of any amount of these bags in a hazardous waste incinerator would never require remediation.

Because the concentration of Cs-137 in the waste is so low, the difference among different types of landfill (low-level radioactive waste, hazardous waste, or municipal waste) is nil. The key conclusion from this, however, is that, once passing the bag monitor screen, bags or drums of protective clothing can be disposed in municipal landfill rather than in low-level radioactive waste disposal sites.

Exposure to the Public from Air Pollution

Exposure to the public from airborne dust at landfills is nil since the waste is packaged in bags and drums. Exposure to airborne incinerator emissions from all routes to the MEI, or representative person of the critical group, for a throughput of 100 drums per year is very low. Population exposure within a 1.0 E+5 m radius is on the order of 1.0 E-8 person-rem/y.

Worker Exposure

Worker exposure was estimated to be a fraction of a mrem/yr. Total person-mrem for workers was less than 0.02 person-mrem/yr for all cases.

Costs

All three disposal options using a bag monitor were estimated to produce substantial cost reductions compared to the base case of sending all material to a low-level radioactive waste site. As would be expected, disposal in a nearby municipal landfill reduced the cost by one-third to one-half of the other options.

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APPENDIX B.

OPTIMIZATION OF THE DESIGN OF LWR-RADWASTE TREATMENT SYSTEMS BY COST-BENEFIT ANALYSIS

This case study evaluated the designs of liquid and gaseous radwaste systems and components for all existing light water reactor (LWR) sites at the time this study was performed. The source terms of radioactive materials generated in LWRs, i.e., boiling water reactors (BWRs) and pressurized water reactors (PWRs), their transfer to other plant systems and their ultimate release to the environment were determined for each alternative system. Each system was subject to a cost-benefit analysis and evaluated with the intent of determining that releases complied with the requirement in 10 CFR Part 50 that all releases of radioactive material in effluents from the LWR be “As Low As Practicable (ALAP).” Collective doses to the population and the dose to the MEI were also were evaluated.

This example of an ALARA application is quite comprehensive because it applied to a rulemaking where the design and operation of all licensed light water-cooled nuclear power stations would be affected. It is also the first known application of the ALARA process for radiological protection purposes. When the original analysis was developed very little information on the cost and operational data from the operation of LWR rad-waste systems was available. While the specific cost and equipment data presented in this example may not be current, the methods are still valid. They are presented here to provide a procedure and workable format for contemporary applications.

Since this case study is based on a 1972 analysis, doses are presented in terms of dose equivalent rather than total effective dose (TED) as it would currently under DOE O 458.1.

Background

In 1971, the AEC published for comment “Proposed Numerical Guides for Design Objectives and Limiting Conditions for Operation to Meet the Criterion ‘As Low As Practicable’[25] for Radioactive Material in Light Water-Cooled Nuclear Power Reactor (LWR) Effluents.” The proposed regulation, 10 CFR Part 50, Appendix I, set numerical values for radioactive material in effluents from operation of LWRs by which licensees could demonstrate compliance with the 10 CFR Part 50 requirement that releases of radioactive material in effluents from those facilities be "as low as practicable." This requirement was added as a revision to 10 CFR Part 50 in December 1970. The proposed guides were the subject of a rulemaking (Docket No. RM-50-2), which was one of the first documents subject to National Environmental Policy Act (NEPA) and for which an Environmental Impact Statement (EIS) was required. As part of the effort to address the impact of the proposed guides, a substantial technical effort was made to study radwaste treatment design options and to provide a cost-benefit analysis. The draft EIS was published in January 1973, the final EIS was published in July 1973 (WASH-1258), and the "Concluding Statement of Position of the Regulatory Staff" was published on February 20, 1974.

[25] The phrase "A Low As Practicable" (ALAP), as used in the early 70s, is identical in meaning to the phrase "As Low As [is] Reasonably Achievable" (ALARA), that is commonly used today.

Based upon the information developed for the EIS, the AEC regulatory staff concluded that the radwaste treatment systems for LWR stations could practicably be designed such that the MEI would be unlikely to receive more than 5 mrem (0.05 mSv) in a year during normal operation. The determination of practicability was based on estimated performance and a cost-benefit analysis of several candidate radwaste system designs.

The following example of a quantitative cost-benefit analysis is based on the information developed for that rulemaking. While some of the specific parametric values selected for the study might be changed if the study were repeated today, the principles of the application remain valid. The evaluation would now be termed an "optimization" analysis. As previously noted in this Handbook, the amount of technical effort needed for cost-benefit or ALARA studies should be commensurate with the potential impact of the activity or facility being evaluated. Since the study of radwaste treatment systems was in support of rulemaking that would have a substantial impact on the design and operation of all nuclear power plants in the country, the effort to develop a technical database was also substantial. Considerations of a major new facility or activity, or a major modification of an existing facility might justify such a comprehensive study. However, facilities or activities with little potential for dose or contamination impact might require only rudimentary technical efforts. The procedure and results of the AEC technical effort for the rulemaking are summarized and described briefly to serve as an example of how such analyses can be accomplished.

The procedure used in the AEC rulemaking application was very similar to that described in this Handbook for applying the ALARA process. All proposed and licensed LWRs, comprised of BWRs and PWRs, and their sites were used to obtain a database to develop realistic and typical characteristics and parameters for the generic study. The "reference" LWR stations evaluated in the study for each site were assumed to be comprised of two reactors.

The specific goals of the study were:

1. To estimate the sources (origin, identity, and quantity) of radioactive material within LWR power generating stations that are subject to release.
2. To identify candidate radwaste treatment components and systems, ranging from the most rudimentary to the most technologically advanced, and to estimate the performance of each with respect to removal of radionuclides from the waste streams.
3. To estimate the quantity of each radionuclide released from LWR stations with a variety of possible radwaste treatment systems, that is, identifying where and why the releases of radionuclides occur and the quantity and identity of each that is released.
4. To characterize: the sites (inland river, lake shore, and sea shore), dispersion of effluents in the environments, distribution of populations within 50 miles of the sites, and pathways by which persons in the environment might become exposed to the radioactive material, such as direct exposure from presence in the vicinity of the radioactive material, internal exposure from ingestion of radionuclides that enter the food chains, and inhalation of air containing radioactive material.
5. To determine potential doses to the most exposed individual and collective dose to the population around typical sites.

6. To estimate the cost of the radwaste treatment components and systems, including installation, maintenance, operation, and other costs.
7. To select and apply a monetary cost per unit of collective dose so that the collective dose can be factored directly into the total cost of the operation.
8. To determine the sensitivity of the specific monetary cost assumed per unit of collective dose.
9. To identify, from among the several candidate radwaste treatment system designs, the radwaste system that provides the desired degree of radiological protection[26] at the minimum total cost.
10. Based on economic and technical considerations, to determine the practicability of designing and operating LWR stations such that the dose to the most exposed individual is unlikely to exceed a small fraction of the annual dose from natural background (for example, about 5 mrem (0.05 mSv) in a year) from exposure to liquid or gaseous effluents.

While some elements of the results from the entire LWR radwaste study will be summarized, only portions of the analysis for PWRs on a typical river site will be presented in detail to simplify this example.

Source Terms

The starting point for the study of liquid and gaseous radwaste systems was the source term. At the time of the LWR radwaste study in 1972, little detailed information was available to characterize the release of radionuclides (fission and activation products and tritium) from the core of LWRs to the primary coolant, to other plant systems, the route to their release to the environment, and their ultimate fate. In essence, much of the information had to be generated from first principles.

The procedure to determine the identity, quantity, and concentration of radionuclides in effluents from LWR stations was to identify design options for radwaste treatment systems for both liquid and gaseous waste streams (compatible with the type of LWR considered), and then to determine a series of source terms for each LWR alternative radwaste component or treatment system. A source term was needed for each optional design feature or auxiliary system that could affect the amount or concentration of specific radionuclides in the liquid or gaseous effluent and in solid waste, since the supporting solid waste systems would also be affected. Figure B-1 is a diagram indicating the origin of the liquid and gaseous radwaste sources from a PWR with two reactors. A computer code was developed to calculate the source terms in effluents using appropriate parametric values.

[26] In this case, the primary interest of the study was to determine the extent to which the doses to maximally exposed individual(s) could be kept well below the dose limits (which at the time was 500 mrem in a year) considering the economic factors and attendant collective dose to the general public. The effective dose concept, whereby doses to various organs can be multiplied by organ weighting factors related to risks, had not been introduced in 1973. Therefore, doses were all expressed in units of rem (dose equivalent). If the calculations were done today, the dose estimates would be expressed in terms of effective dose and might be somewhat higher or lower for a variety of reasons. The costs would also likely be greater than those presented here.

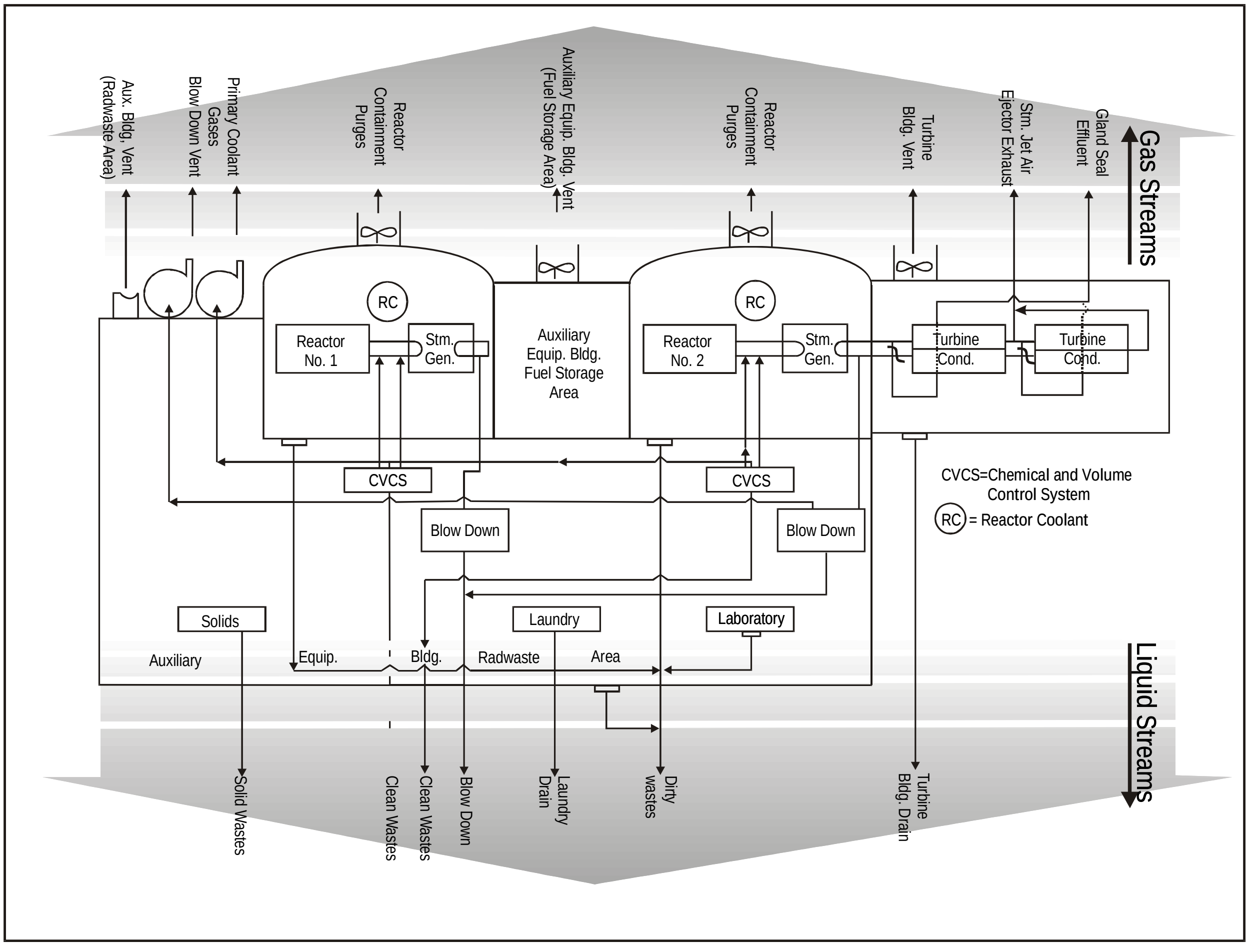


FIGURE B-1. Origin of Liquid and Gaseous Radwaste Sources

Parameters for Source Terms

The principal parameters that had to be evaluated and used in source term calculations (fission products, activation products, and tritium) for BWRs and PWRs are identified in Figure B-2. The bases for the quantification of the principal parameters are provided in the cited references. Some values were based on measurements, some based on theoretical considerations, and others were based on design data, best engineering judgment, or a combination of the several methods.

Radwaste Treatment System Design Options

The objective of a quantitative optimization analysis is to identify, from among several optional radwaste treatment systems, the option that provides the least total annual cost, including a cost component related to the potential biological risks that may be associated with the doses. Liquid and gaseous radwaste treatment systems and components of all existing LWR stations were identified, evaluated, and costed. Combinations of components including some based on advanced technology were studied to identify systems with potentially better performance than those in use at that time.

Thermal power level; Plant capacity factor; Fraction of fuel releasing fission products to the primary coolant; Equilibrium primary coolant radionuclide concentrations; Turbine building steam leakage rate (gaseous source term only) Turbine gland seal steam leakage rate; Partition/decontamination factors for radioiodine; Decontamination factors for demineralizers; Removal factors for plate-out; Decontamination factors for evaporators; Holdup times for charcoal delay systems; Air in-leakage to the main condenser; Decontamination factors for cryogenic distillation; Chemical regeneration of condensate demineralizers; Guidelines for calculating liquid waste holdup times; Liquid waste term normalization; and Guidelines for rounding numerical numbers.
Miscellaneous building and system parameters for PWRs Primary to secondary leakage rate; Containment building leakage rate; Auxiliary building leakage rate; Frequency of containment building purge; Primary system volume degassed per year; Waste storage tanks - holdup time; Steam generator blow-down rate; and Liquid waste flow rates.
Miscellaneous building and system parameters for BWRs Reactor building leakage rate; Radwaste building; Start-up of main condenser vacuum; and Liquid waste flow rates.

FIGURE B-2. Principal Parameters Evaluated for Source Term Estimates from BWRs and PWRs

For PWR stations, the liquid radwaste treatment options include filters, demineralizers, evaporators, recycle, and reverse osmosis. Six optional designs (Cases L-1 through L-6) were identified initially for PWR liquid radwaste treatment systems. L-1 is the base case for PWRs that contains essentially the minimum radwaste treatment that might be considered. Table B-1 presents a summary of liquid radwaste treatment systems for L-1 through L-4 to illustrate the type of variations evaluated. Figure B-3 is a schematic flow chart for L-1, indicating the various plant systems and the contributions to the total annual curie releases from each location. The liquid cases evaluated included all of the specific designs found in the license applications and some additional components not used routinely in the 1973 designs. Subsequent to the detailed evaluations of the performance and cost of individual components and the six systems, three additional alternative PWR liquid radwaste treatment systems (Cases L-A, L-B, and L-C) were defined that featured additional combinations of components, different from those identified in the original six options, offering potential economic advantages or more efficient use of components.

TABLE B-1. Summary of PWR Liquid Radwaste Treatment Systems (L1 through L4)

Type of Waste	Process Steps
PWR Liquid Case No. 1	
Clean Wastes (includes shim bleed and reactor coolant controlled leaks)	Collection
Dirty Wastes (includes chemical containment and auxiliary building drains)	Collection
Steam Generator Blowdown	None
Turbine building drains	None
Laundry	Collection-discharge
PWR Liquid Case No. 2	
Clean Wastes	Filter, demineralizer
Dirty Wastes	Filter, demineralizer
Turbine building drains	None
Laundry	Filter
PWR Liquid Case No. 3	
Clean Wastes	Filter, demineralizer, evaporator, demineralizer
Dirty Wastes	Filter, evaporator
Turbine building drains	None
Laundry	Filter
PWR Liquid Case No. 4	
Clean Wastes	Filter, demineralizer, evaporator, demineralizer
Dirty Wastes (includes turbine building drains)	Filter, demineralizer, evaporator
Laundry	Filter, evaporator

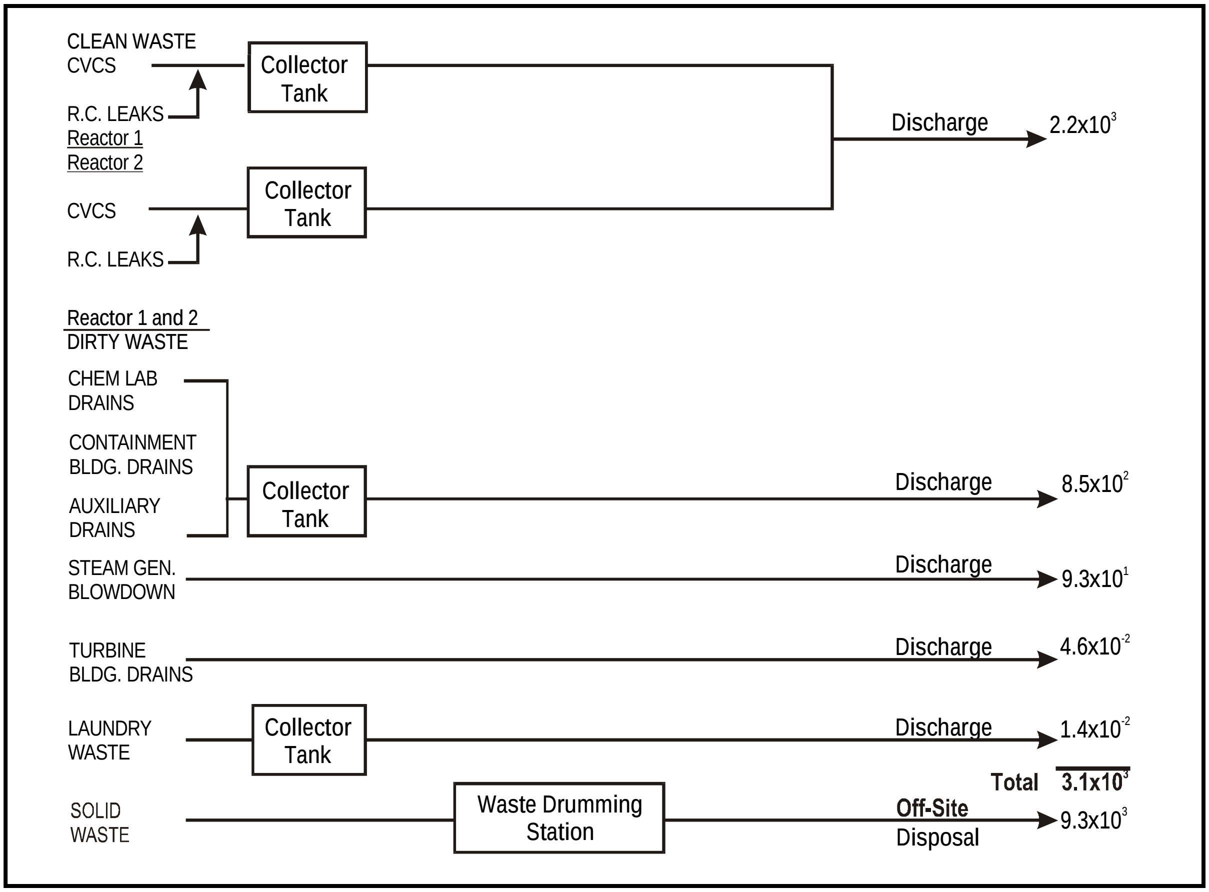


FIGURE B-3. Flow Chart for the Radwaste Treatment Systems for PWR - Liquid Case 1

Similarly, components and systems for gaseous radwaste treatment were identified, evaluated, and costed. These included pressurized holdup tanks, HEPA filters, charcoal absorbers, catalytic recombiners, cryogenic distillation, recycle, ion exchange, vents, and stacks. Nine optional designs (Cases G-1 through G-9) were identified initially for PWR gaseous radwaste treatment systems. An additional six alternative treatment systems (Cases G-A through G-F) that appeared to offer some possible advantages over the initial nine optional PWR gaseous radwaste treatment systems were identified (most of which featured discharges through stacks or slightly different combinations of components). The basic features of the candidate gaseous radwaste treatment systems G-1 through G-9 are described in Table B-2.

Each optional liquid and gaseous radwaste treatment system presents different requirements with respect to solid waste. Consequently, several modified solid radwaste systems necessary to support each candidate liquid and gaseous radwaste treatment systems evaluated and costed.

PWR Liquid Radwaste Treatment System Case 2 (L-2) and PWR Gaseous Radwaste Treatment System Case 6 (G-6) have been selected to illustrate some of the procedures involved in a cost-benefit analysis and optimization determination. The features of each system are indicated in the flow diagrams Figure B-4 and Figure B-5 for liquid and gaseous treatment systems, respectively. More details of the features of the systems are provided in the discussions of cost. Gross release rates for the source terms resulting from the calculations based on the parameters listed above are also indicated at the end of the flow lines for each system. Radionuclide-specific source terms were used in dose estimations.

Site Characteristics

Three types of sites were used in the study to characterize sites typically used for locating LWR stations: sites on river banks; sites on lake shores (fresh water); and sites on seashores (oceans). Each type of site presents a different spectrum of potential pathways for exposure of persons located in the site environment, different marine organisms, and different dispersion patterns for the sources in the environment. Data from each actual LWR site were used to characterize typical liquid and atmospheric dispersion parameters and population density and distribution in 22.5 degree sectors at incremental distances (radii) required for estimating potential individual and collective doses to the population. Atmospheric dispersion typical for each type of site was estimated using actual data on the joint frequency of occurrence of wind speed, wind direction, and stability for the several LWR sites.

Figure B-6 presents the atmospheric dispersion factor (sec/m^3) as a function of distance from the release point, calculated for the typical site on a river (in-land). This figure also indicates the differences in ground-level concentrations resulting from release via vents (essentially, ground-level due to building wake effects) and release via a 100-meter stack.

Population growth studies around LWR sites were performed and the population distribution projected for the year 2000 around a typical river site out to 5 miles is presented in Figure B-7 and between 5 and 50 miles is presented in Figure B-8.

TABLE B-2. Summary of Variables for PWR Gaseous Radwaste Treatment Systems

	PWR Gas Case No.								
	1	2	3	4	5	6	7	8	9
Degree of Isotope Removal									
Xe	Low	High	High	High	High	High	High	High	Low
I	Low	Medium	Medium	High	High	High	Medium	High	Medium
Kr	Low	Low	Low	Low	High	High	Low	Low	Low
Equipment Unit or Function and Flowsheet Reference[a]									
Primary system gases	None	60-day decay storage tanks, HEPA filter	60-day decay on charcoal bed, HEPA filter	60-day decay on charcoal bed, HEPA filter	Recombiner, 60-day decay storage tanks, selective adsorption	Cover gas recycle	60-day decay on charcoal bed, HEPA filter	60-day decay on charcoal bed, HEPA filter	None
Secondary system gases	None	None	Charcoal adsorber for iodine, HEPA filter, clean steam for gland seal, blowdown tank vented to condenser	Charcoal adsorber for iodine, HEPA filter, clean steam for gland seal, blowdown tank vented to condenser	Charcoal adsorber for iodine, HEPA filter, clean steam for gland seal, blowdown tank vented to condenser	Charcoal adsorber for iodine, HEPA filter, clean steam for gland seal, blowdown tank vented to condenser	Charcoal adsorber for iodine, HEPA filter, secondary steam for gland seal, blowdown tank vented to condenser	Charcoal adsorber for iodine, HEPA filter, secondary steam for gland seal, blowdown tank vented to condenser	Charcoal adsorber for iodine, HEPA filter, secondary steam for gland seal, blowdown tank vented to condenser
Reactor containment purge	None	Charcoal kidney adsorber for iodine	Charcoal kidney adsorber for iodine	Charcoal kidney adsorber for iodine, charcoal adsorber for iodine, HEPA filter	Charcoal kidney adsorber for iodine, charcoal adsorber for iodine, HEPA filter	Charcoal kidney adsorber for iodine, charcoal adsorber for iodine, HEPA filter	Charcoal kidney adsorber for iodine	Charcoal kidney adsorber for iodine, charcoal adsorber for iodine, HEPA filter	Charcoal kidney adsorber for iodine
Auxiliary building ventilation	None	None	None	Charcoal adsorber for iodine, HEPA filter	Charcoal adsorber for iodine, HEPA filter	Charcoal adsorber for iodine, HEPA filter	None	Charcoal adsorber for iodine, HEPA filter	None
Turbine building ventilation	None	None	None	Charcoal adsorber for iodine, HEPA filter	Charcoal adsorber for iodine, HEPA filter	Charcoal adsorber for iodine, HEPA filter	None	Charcoal adsorber for iodine, HEPA filter	None

[a] All gases are released through a 50-meter roof vent unless a stack is indicated.

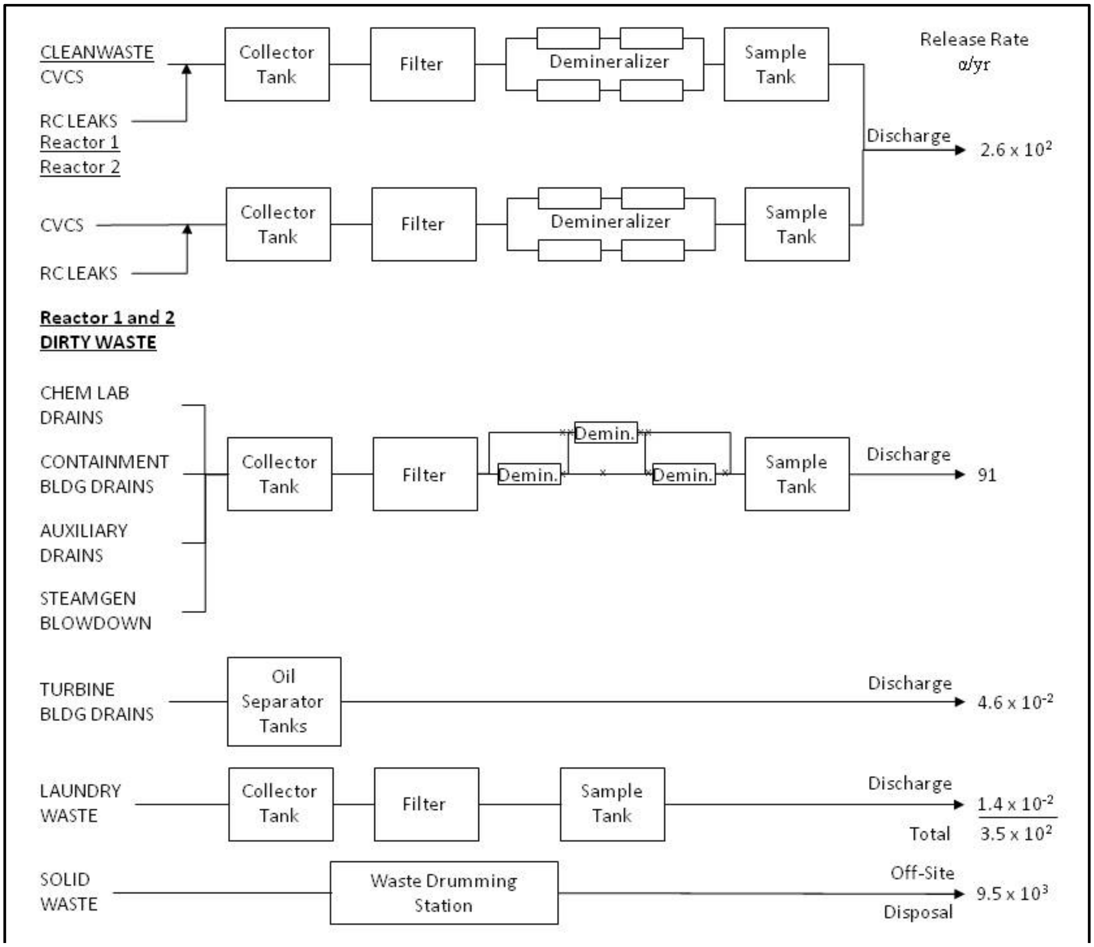


FIGURE B-4. Radwaste Treatment System for PWR – Liquid Case 2

Dose Calculations

Centerline ground-level concentrations of specific radionuclides in the plumes as a function of direction and distance from the release point were calculated for use in conjunction with the population distributions and exposure modes typical for such sites to estimate exposures and doses to the maximally exposed individuals, assumed to be located at the site boundary, and the collective doses to the population within 50 miles of the facility.

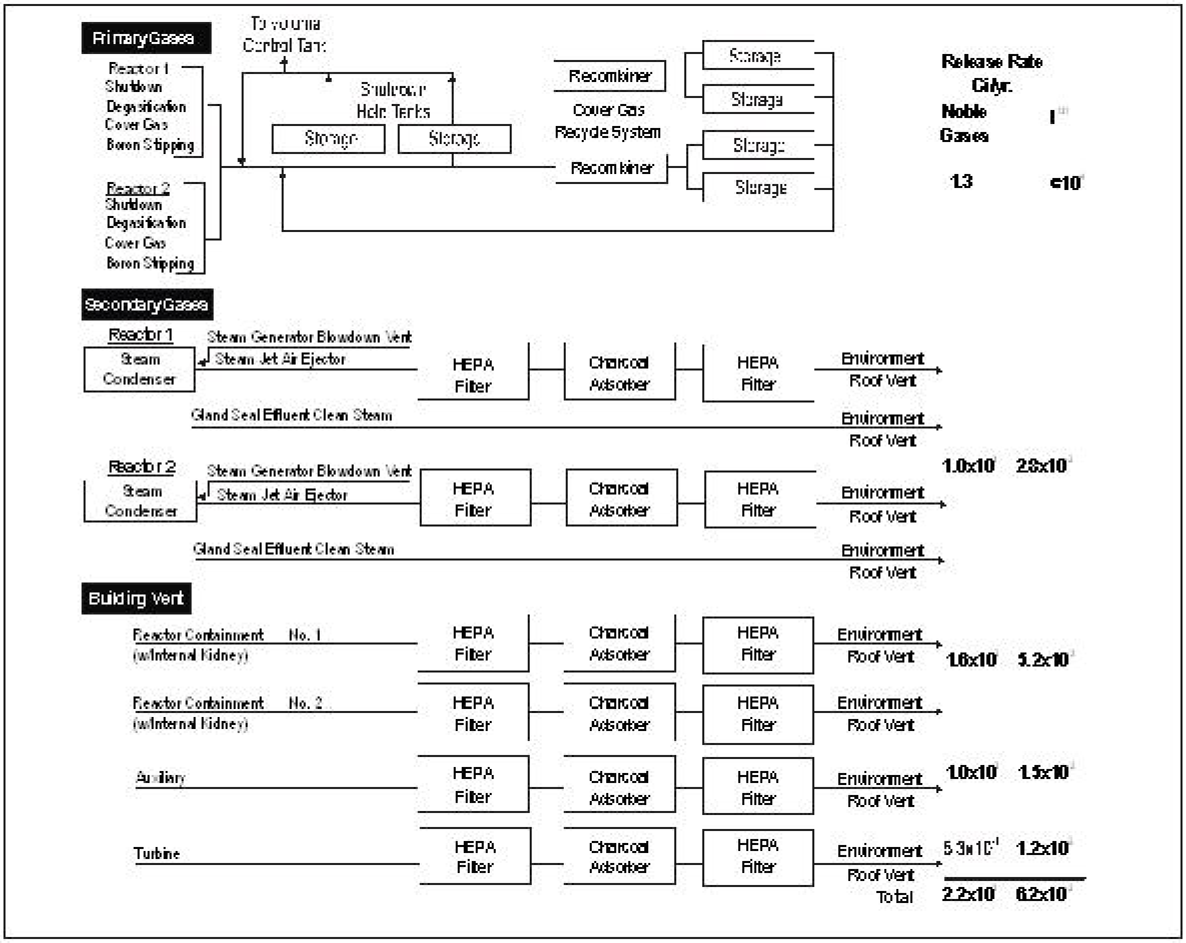


FIGURE B-5. Gaseous Radwaste Treatment Systems for PWR – Base Case No. 6

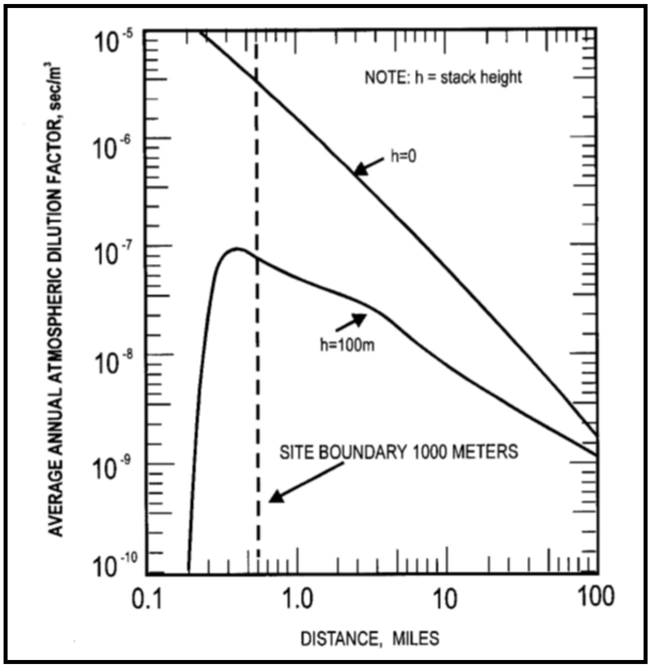
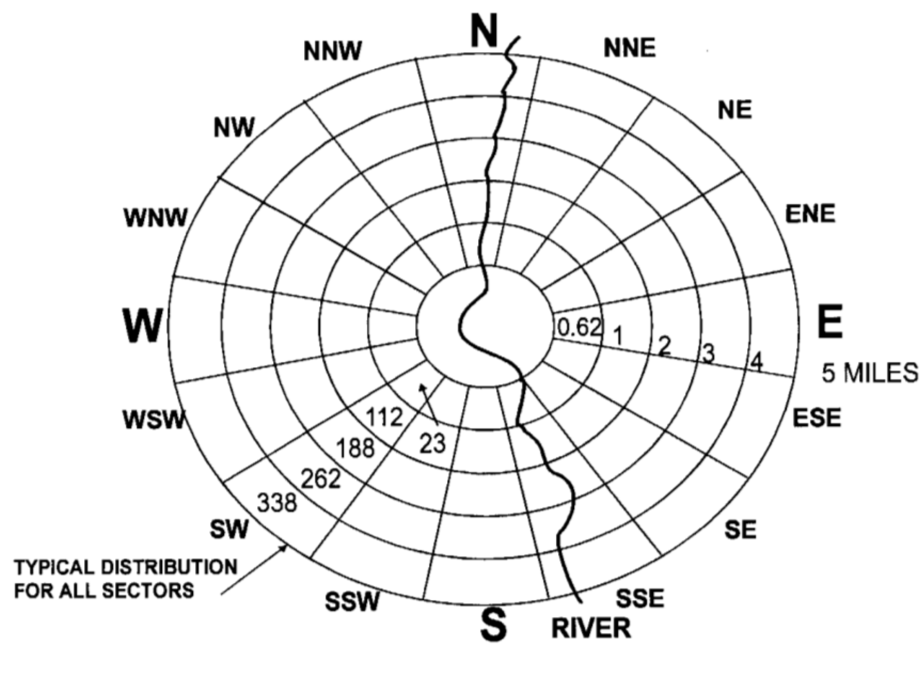


FIGURE B-6. Atmospheric Dilution – River Site

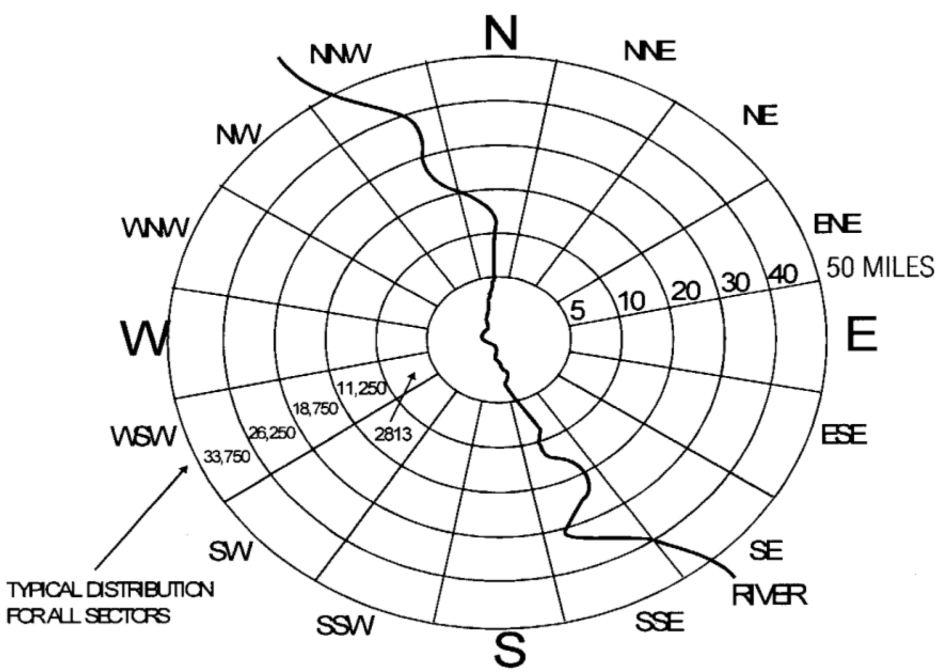


ANNULUS	0.62-1 MI	1-2 MI	2-3 MI	3-4 MI	4-5 MI
POPULATION	368	1800	3000	4200	5400
CUMULATIVE	368	2168	5168	9368	14,768

FIGURE B-7. Projected Population Distribution to the Year 2000 at a River Site

Dispersion in each of the waterways (river, lake, and ocean) was estimated, and the results used in conjunction with the exposure modes typical and appropriate for each of the three types of sites. These calculations were also used to estimate the doses to the maximally exposed individuals and the collective doses to the population within 50 miles of each site.

Several AEC "regulatory guides" were written to present details of the models and analytical methods used to estimate potential doses from the several exposure modes, typical and specific for each of the three types of sites. Table B-3 identifies the exposure pathways evaluated for persons and aquatic organisms in the environs around each of the typical sites for each of the optional liquid radwaste systems. Table B-4 presents the pathway parameters used to calculate the doses from liquid effluent at a typical river site. Table B-5 provides additional parameters used in pathway evaluations. The potential doses to the thyroid was of special interest in the study and Table B-6 presents the parameters used to calculate the thyroid doses from inhalation and ingestion.



ANNULUS	5-10 MI	10-20 MI	20-30 MI	30-40 MI	40-50 MI
POPULATION	45,000	180,000	300,000	420,000	540,000
CUMULATIVE	59,768	239,768	539,768	959,768	1,499,768

FIGURE B-8. Projected Population Distribution at River Site (5-50 Miles)

TABLE B-3. Exposure Pathways Evaluated at Each Reactor Site

Type of Waste	Reactor Site	Exposure Pathway to Man	Organisms Probably Receiving Highest Dose
Liquid	Seacoast	Fish, crustacea, molluscs Food from seaweed Swimming and boating Shoreline exposure	Crustacea, molluscs
Liquid	River and Lakeshore	Fish Drinking water Swimming and boating Shoreline exposure Irrigated agricultural products	Fish Muskrat or raccoon
Gaseous	Seacoast, River, and Lakeshore	Gas submersion Inhalation Deposition and transfer to agricultural products	Grazing animals
Solid	Seacoast, River, and Lakeshore	Transportation through populated areas	Not applicable

TABLE B-4. Parameters Used for Calculation of Radiation Doses from Liquid Effluents at a River Site

Pathway	Location	Annual Usage	Effluent Dilution	Decay Time
Individual (Adult)				
Fish	Near outfall	18 kg	0.5	24 hr
Swimming	Near outfall	100 hr	0.5	1 hr
Boating	Near outfall	100 hr	0.5	1 hr
Shoreline	Near outfall	500 hr	0.25	1 hr
Drinking Water	At site boundary	730 liters	0.1	3 hr
General Population (1.5 x 10^6 persons)				
Fish	25 miles downstream	7.3 kg[a]	0.0/0.05[b]	24 hr
Swimming	25 miles downstream	2 hr[c]	0.07/0.05	24 hr
Boating	25 miles downstream	4 hr[c]	0.07/0.05	24 hr
Shoreline	25 miles downstream	4 hr[c]	0.07/0.05	24 hr
Drinking water[d]	25 miles downstream	438 liters	0.07/0.05	24 hr

a. One-half of this is derived downstream of the reactor.

b. (PWR Reactor Flow, 2690 cfs) ÷ (River Flow, 5 x 10^4 cfs) = 0.05; (BWR Reactor Flow, 3450 cfs) ÷ (River Flow, 5 x 10^4 cfs) = 0.07

c. (cfs=cubic feet per second)

d. These are the hours spent downstream of the reactor; additional time spent upstream and at nearby lakes.

e. 5 x 10^5 persons consume water derived from the river below the reactor and within 50 miles of the site.

TABLE B-5. Recommended Adult Values for Up to be used in lieu of Site-Specific Data

Pathway	Individual Adult	References[a]	Average Adult	References[a]
Air Submersion	8766 hr/yr	(2)	8766 hr/yr	(2)
Inhalation	7300 m^3/yr	(6)	7300 m^3/yr	(6)
Drinking Water	2.0 liters/day	(2)	1.2 liters/day	(6)
Local Seafood • fish • crustacea • molluscs	 18 kg/yr 9 kg/yr 9 kg/yr	 (12) (12) (12)	 2.3 kg/yr 0.9 kg/yr 0.25 kg/yr	 (11) (11) (11)
Local Fresh Water Fish	18 kg/yr	(12)	2.2 kg/yr	(11)
Holdup Time for Aquatic Foods	24 hr/yr	(12)	24 hr/yr	(12)
Aquatic Recreation Ocean • shoreline activities • swimming • boating	 500 hr/yr 100 hr/yr 100 hr/yr	 (13) (14) (14)	 4 hr/yr[(a)] 1 hr/yr[(a)] 1 hr/yr[(a)]	 (2) (2) (2)
River • shoreline activities • swimming • boating	 500 hr/yr 100 hr/yr 100 hr/yr	 (13) (14) (14)	 2 hr/yr[(b)] 4 hr/yr[(b)] 4 hr/yr[(b)]	 (2) (2) (2)
Lake • shoreline activities • swimming • boating	 500 hr/yr 100 hr/yr 100 hr/yr	 (13) (14) (14)	 1 hr/yr[(a)] 2 hr/yr[(a)] 2 hr/yr[(a)]	 (2) (2) (2)

a. References can be found in AEC 1973, Appendix F.

b. These are hours spent in the vicinity of the site. Other hours are spent in areas unaffected by the liquid effluent from the facility.

c. These are hours spent downstream of the site. Other hours are spent upstream and at nearby lakes.

d. U_p = Usage: The exposure rate or intake rate associated with pathway p.

TABLE B-6. Parameters Used for Calculations of Thyroid Doses from Inhalation

Parameter	Air	Milk	Leafy Vegetables
Growing Season	–	6 months	4 months
Time between crop appearance and harvest	–	1 month[(a)] (pasture grass)	3 months
Relative Concentration of ^{131}I	1.0 pCi/m^3	650 pCi/liter[(b)]	4300 pCi/kg[(b)]
Relative Concentration of ^{133}I	1.0 pCi/m^3	110 pCi/liter	690 pCi/kg
Intake Rate • Adult • Child	 7300 m^3/yr 2045 m^3/yr	 365 liter/yr 365 liter/yr	 24 kg/4 months 6 kg/4 months
mrem/yr per pCi/m^3 Air ^{131}I • Adult • Child	 11 13	 220[(c)] 1840[(c)]	 200[(c)] 400[(c)]
mrem/yr per pCi/m^3 Air ^{133}I • Adult • Child	 2.6 5.4	 9.0[(c)] 130[(c)]	 7.7[(c)] 28[(c)]

a. The cow re-grazes the same spot every 30 days.

b. See ICRP-2.

c. Corrected for growing season.

"KRONIC," a computer program, was used to calculate annual average doses[27] from chronic atmospheric releases of radionuclides from each of the optional radwaste systems. The program is described in BNWL-B-264 by Strenge and Watson, 1973. The whole-body dose is a function of the:

- Radionuclides present;
- Release path phenomena from fuel to atmosphere;
- Climatology for the site;
- Time-dependence of fission product concentrations;
- Energy and number of photons and beta particles emitted from the nuclides; and
- Physical properties describing the interaction of photons and beta-particles with air and tissue.

Dose Estimates

The individual and collective doses resulting from the release of liquid and gaseous wastes from a PWR station on a river site is presented in Table B-7 and Table B-8, respectively. Estimated thyroid doses from gaseous effluent are presented in Table B-9. The estimated potential doses to the MEI are important because regulatory limits are generally expressed, or implemented in terms of dose to the individual. On the other hand, for regulatory purposes, it is generally assumed that the collective dose to the population is linearly related to the impact, that is, potential radiation induced health effects. In either case, the dose and cost evaluations should be as realistic as possible to avoid deliberately biasing the study.

TABLE B-7. Summary of Radiation Doses Resulting from Release of Liquid Wastes – River Site

Liquid Case	Skin	Total Body	GI-LLI	Thyroid	Bone
Collective Dose - man-rem/yr					
PWR 1	190	4,570	980	6,820	3,630
2	90	2,110	160	120	1,680
3	0.013	0.90	0.37	3.1	0.25
4	0.00024	0.60	0.31	0.82	0.0046
Individual Dose - mrem/yr					
PWR 1	79	210	92	130	180
2	37	96	34	32	82
3	0.0055	0.018	0.0085	0.031	0.012
4	0.00010	0.0046	0.0024	0.0065	0.00021

[27] Note that the effective dose equivalent concept had not been proposed in 1973, but estimates for doses to total body, skin, GI and LLI, bone, and thyroid were calculated separately. In 1973, potential radiation-induced risk coefficients for adults were estimated to be about 140 fatalities from neoplasms (including leukemia) and 100 thyroid cancers (rarely fatal) per million person-rem.

TABLE B-8. Estimated Annual Radiation Dose from Gaseous Effluents – Three Sites

Gas Case	Site	Individual Doses (mrem/yr) Total Body At Site Boundary	Total Body At 3.5 Miles	Thyroid At Site Boundary Child	Thyroid At Site Boundary Adult	Thyroid At 3.5 Miles Child	Thyroid At 3.5 Miles Adult	Collective Dose 0-50 miles Cumulative (man-rem/yr)	Collective Dose 0-50 miles Average Annual (mrem/yr)
PWR-1	Seacoast	1.5	0.19	560	110	68	11	48	0.013
	River	2.0	0.23	670	130	76	12	22	0.014
	Lake	1.1	0.13	420	80	51	8.1	7.5	0.010
PWR-2	Seacoast	0.026	0.003	375	71	39	7.4	0.86	0.00023
	River	0.035	0.004	470	88	43	8.1	0.38	0.00026
	Lake	0.019	0.002	280	53	29	5.5	0.13	0.00017
PWR-3	Seacoast	0.026	0.003	83	16	8.3	1.6	0.86	0.00023
	River	0.035	0.004	99	19	9.2	1.7	0.38	0.00025
	Lake	0.019	0.002	62	12	6.1	1.2	0.13	0.00017
PWR-4	Seacoast	0.026	0.003	14	2.6	1.4	0.26	0.86	0.00023
	River	0.035	0.004	17	3.1	1.5	0.29	0.37	0.00025
	Lake	0.019	0.002	10	1.9	1.0	0.19	0.12	0.00017
PWR-5	Seacoast	0.026	0.003	14	2.6	1.4	0.26	0.84	0.00022
	River	0.035	0.004	17	3.1	1.5	0.29	0.38	0.00025
	Lake	0.019	0.002	10	1.9	1.0	0.19	0.13	0.00017
PWR-6	Seacoast	0.019	0.002	12	2.1	1.1	0.21	0.55	0.00015
	River	0.026	0.003	13	2.6	1.2	0.24	0.24	0.00016
	Lake	0.014	0.002	8.3	1.6	0.83	0.16	0.084	0.00011

Cost Estimates

Specific cost information for components and subsystems were difficult to obtain at the time of this study. While general overall costs for LWR stations were available, vendors were reluctant to provide specific cost information and considered it company-confidential. Some cost data were eventually made available through cooperative efforts with licensees, other data were developed through engineering analyses and information obtained in a cooperative effort with the AEC national laboratories.

TABLE B-9. Estimated Annual Thyroid Doses from Gaseous Radioiodine at a River Site (mrem/year)

Gas Case [a]		At Site Boundary Inhalation	At Site Boundary Milk	At Site Boundary Vegetables	At Site Boundary Total	At 3.5 Miles Inhalation	At 3.5 Miles Milk	At 3.5 Miles Vegetables	At 3.5 Miles Total[b]
PWR-1	Child	4.3	550	120	670	0.40	64	11	75
	Adult	3.4	66	58	130	0.32	6.2	5.4	12
PWR-2	Child	3.1	380	84	470	0.29	35	7.7	43
	Adult	2.4	46	40	88	0.22	4.2	3.7	8.1
PWR-3	Child	0.69	81	18	99	0.064	7.5	1.6	9.2
	Adult	0.52	9.7	8.5	19	0.048	0.89	0.78	1.7
PWR-4	Child	0.11	13	2.9	16	0.010	1.2	0.27	1.5
	Adult	0.085	1.6	1.4	3.1	0.008	0.15	0.13	0.29
PWR-5	Child	0.11	13	2.9	16	0.010	1.2	0.27	1.5
	Adult	0.085	1.6	1.4	3.1	0.008	0.15	0.13	0.29
PWR-6	Child	0.092	11	2.4	13	0.009	1.0	0.22	1.2
	Adult	0.070	1.3	1.1	2.5	0.006	0.12	0.11	0.23

a. The gaseous radwaste systems are defined in Table B-2

b. Because the values were rounded after adding, the total does not always equal the sum of the parts.

The capital cost for the equipment and installation, operating and maintenance (O&M) cost, and fixed cost were determined for each optional radwaste treatment system by using standard cost estimating techniques. Table B-10 presents a table of 1972 installed cost for equipment used in one or more of the various PWR radwaste treatment systems. Specific items are identified along with the direct and capital cost for each. Detailed estimate sheets for each radwaste treatment system option (case) were developed.

Fixed Charges

In addition to the costs of the installed equipment and operating and maintenance costs, certain fixed charges (such as taxes, interest, replacement cost, insurance, depreciation, etc.) also were included. The basis for the fixed cost for each of the PWR cases is presented in Figure B-9.

This is based on constant annual capacity factor. Variable capacity factor would give slightly different results, but the constant basis is recommended for simplicity. The fixed charge rate on depreciable capital, multiplied by the total depreciable capital investment, will give the annual dollar charges for capital and capital-related expenses. Annual operating and maintenance costs can then be added. The total, divided by the annual electrical production, will give the cost per unit of electricity. This procedure is consistent with the discounted cash flow method.

Liquid Radwaste Treatment Systems

Flow sheets were used to identify the kind and quantity of all components for each option. Figure B-10 is a schematic flow sheet for PWR liquid radwaste treatment system Case 2 (PWR L-2). The basic features of the candidate liquid radwaste treatment systems L-1 through L-4 are described in Figure B-3. PWR Case A, an optional system added after the initial evaluation, uses treatment equipment similar to PWR Case 2 but the subsystem provided to treat the dirty waste and turbine building drains has been replaced by subsystems from PWR Case 3. This resulted in better performance than Case 2 at little additional cost (and was found to be the optimum system of all those evaluated for PWRs located on sites using fresh water for coolant).

TABLE B-10. Installed 1972 Cost of Equipment for PWR Radwaste Treatment Systems

Item	No.	Cost Without Structures ($1000)	
		Direct[a]	Capital[b]
Surge tank, 610 ft^3, SS	1	16	28
Storage tank, 610 ft^3, SS clad	1	10	18
Compressor, 5 scfm	1	45	79
Recombiner	1	270	472
Charcoal delay bed (0.8-ton bed)	1	5.4	9.5
Cryogenic distillation (2 trains)	1	1,800	3,150
Selective absorption (2 trains)	1	1,620	2,840
Cover gas recycle	1	1,110	1,940
Clean steam for gland seals (each supplies two turbines)	2	1,230	2,150
Kidney	1	140	245
Building ventilation [c] (containment purge reactor and turbine building)	1	1,800	3,150
Liquid collection (L1 system)	1	140	245
Tank SS			
5,000 gal	1	13.3	23
20,000 gal	1	38	66
90,000 gal[d]	1	220	385
Filter, cartridge, SS			
10 gpm	1	2	3.5
100 gpm	1	7	12
Demineralizer, cartridge SS			
100 gpm	1	23	40
Evaporators			
10 gpm	1	260	455
20 gpm	1	295	516
30 gpm	1	315	551
Solid Waste			
Handling equipment	1	50	90
Centrifuge	1	45	80
Conveyor and mixer	1	60	105
Compactor	1	15	25
Silo	1	3.5	6

a. Costs for early 1972. Direct costs include equipment, site labor, and site materials.

b. Capital costs calculated by multiplying direct costs by 1.4 x 1.25 = 1.75. Capital costs - direct & indirect costs & interest during construction.

c. Includes structures

d. Field erected

Note, in Figure B-10, that for each equipment item there is an identification number and the number of units in the system. Table B-11 is a summary sheet indicating the identity and number of components of each of the four original liquid waste treatment systems and is used for determining the direct construction cost for the cases. Table B-12 presents the detailed cost summary, identifying the equipment, labor, material, and total direct cost for L-2. Table B-13 presents the O&M annual cost for L-2, including the O&M costs of the supporting solid radwaste system. Supplemental sheets frequently are used to cost individual components or sub-systems.

For example, Figure B-11 is a supplemental cost sheet used to estimate the installed cost for tanks of various sizes. Supplemental sheets detailing radwaste treatment subsystems and their cost were similarly developed. Table B-14 and Table B-15 detail the cost of the solid waste treatment system supporting L-2. The cost of the supporting solid waste system is carried as part of the liquid radwaste treatment system cost because the liquid radwaste treatment is the source of most of the solid waste. For example, Table B-16 indicates the estimated number of drums of solid wastes annually from the systems L-1 through L-4.

The fixed charge rate on depreciable capital is calculated for the reactor waste system using the POWERCO[a] Code. Basis for the calculation is given below using parameters typical of private ownership:

<u>Basis</u>

Debt fraction	56% at 7.5% per year
Equity fraction	44% at 13.5% per year after taxes
Life	30 years
Federal income tax	48%
State income tax	4%
Property tax	3.5% per year
Interim replacements	0.5% per year
Property damage insurance	0.3% per year

Federal income tax is calculated by the sum of the years' digits method with no investment credit. Property tax is based on linearly depreciated plant value. The above figures give a composite (weighted average) cost of money of 10.14% per year.

<u>Annual Fixed Charge Rate on Depreciable Capital</u>

Weighted average interest rate, %	10.14
Depreciation (sinking fund method), %0.59	
Federal income tax, %	2.31
State income tax, %	0.20
Property tax, %	2.55
Interim replacements, %	0.50
Property insurance, %	0.30
TOTAL	16.59

[a] The POWERCO reference can be found in AEC 1973 Vol. 1. Annex 3A.

FIGURE B-9. Fixed Charge Rate for Reactor Radwaste System

All costs for each radwaste option were annualized so that they could be used in conjunction with estimated annual collective dose to determine the option resulting in minimum total cost (optimization). Tables B-17 and B-18 present a summary of the liquid radwaste treatment subsystem total annual cost and annual quantity released for all cases considered. This summary demonstrates how subsystems can be varied to accomplish a variety of results.

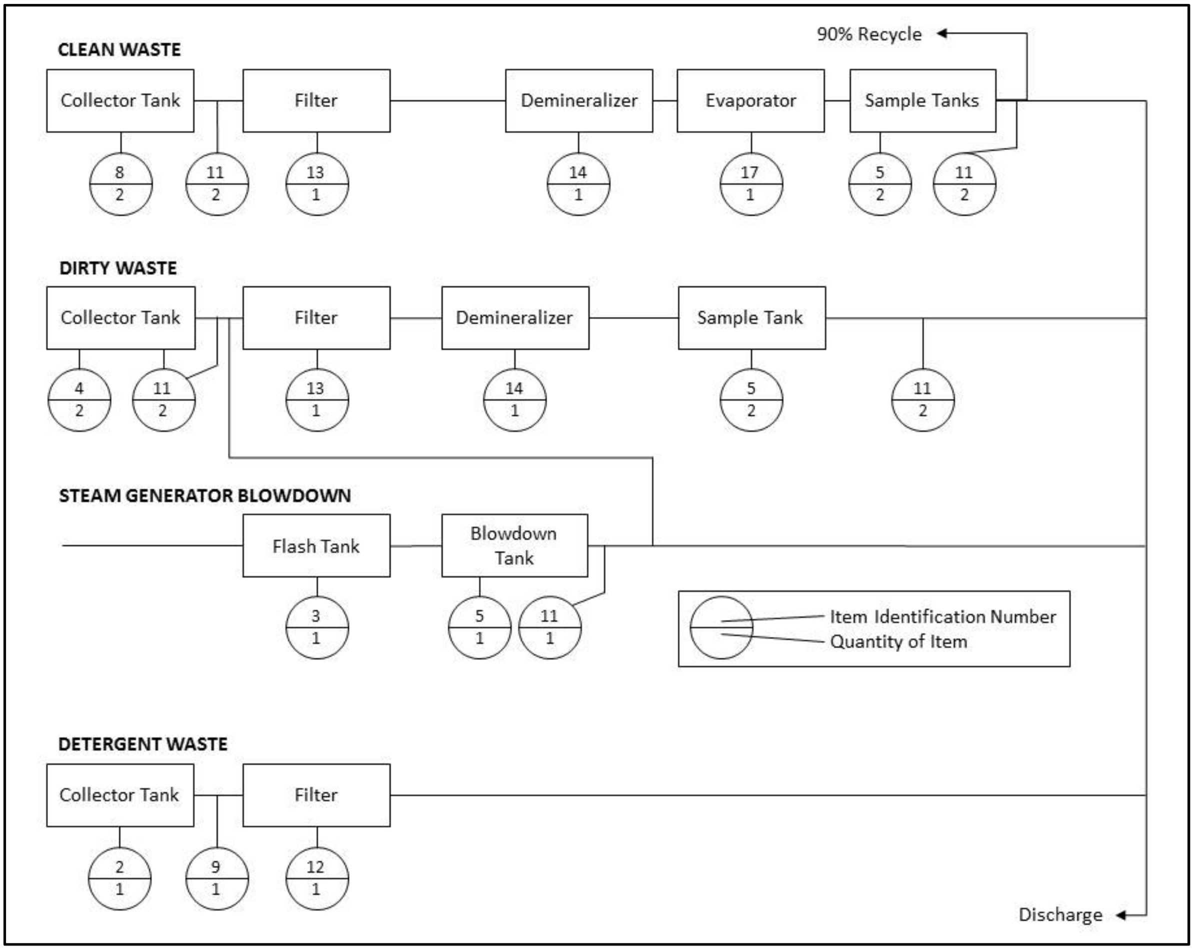


FIGURE B-10. PWR Liquid Case-2 Treatment Equipment - Two Reactor Plant

TABLE B-11. Major Liquid and Solid Treatment Equipment Items for PWR Plants Containing Two Reactors

Item[a]	Number of Items PWR Liquid Case			
	1	2	3	4
Tanks, SS				
300 gal	2	2	2	2
500 gal	1	2	2	2
900 gal		2	2	2
4,000 gal		1	3	4
5,000 gal	3	3	6	7
20,000 gal	2			
35,000 gal		2	2	2
90,000 gal		2	4	4
Pumps, centrifugal, SS				
10 gpm, 1 hp.	1	5	5	3
50 gpm, 3 hp.	4	6	9	10
100 gpm. 7.5 hp.	3	8	12	13
Filters, cartridge, SS				
10 gpm		1	1	1
100 gpm		4	4	4
Demineralizers, mixed-bed, SS				
100 gpm		11	12	14
Degassifiers, packed tower, including chiller and vacuum pump		2	2	2
Evaporators, SS				
10 gpm, vertical				1
20 gpm, vertical			2	4
30 gpm, vertical			1	2
Centrifuge, SS	1	1	1	1
Conveyer and Mixer	1	1	1	2
Cement Silo (700 ft^3)	1	1	1	1
Compactor	1	1	1	2

a. Remote instruments and controls are assumed for monitoring and controlling liquid levels, temperature, differential pressure, and pH. It is also assumed that there are adequate sample lines.

TABLE B-12. PWR Case L-2 Radwaste Direct Cost Estimate for a Two-Reactor 2400 Mw (e) PWR Plant - Early 1973 Start

ID. No.	Item Number	Item - Description	Quan.	Cost ($)				Cost Ref. No.
				Equipment	Labor	Material	Total	
2	1	Tanks 500g	1	900	500	200	1,600	PWR, L-1,1
3	2	1,000	1	1,300	700	200	2,200	”
4	3	5,000	2	8,000	2,000	600	10,600	”
5	4	10,000	5	30,000	15,000	4,000	49,000	”
8	5	90,000	2	60,000	6,600	6,600	73,200	”
9	6	Pump 10 gpm, 1 hp	1	1,500	300	200	2,000	BWR, L-1,7
	7							
11	8	100 gpm, 7.5 hp	9	6,300	4,500	1,050	11,850	BWR, L-1,7
12	9	Filters 10 gpm	1	1,500	300	200	2,000	Budget Est.
13	10	100 gpm	2	14,000	1,200	800	16,000	”
14	11	Demineralizer 100 gpm	2	30,000	6,000	4,000	40,000	”
17	12	Evaporator 20 gpm	1	210,000	25,000	15,000	250,000	”
	13	EQUIPMENT TOTAL		363,500	62,100	32,850	458,450	
	14	Piping	LOT	0	24,000	6,000	30,000	Allowance
	15	I&E	LOT	30,000	20,000	10,000	60,000	”
	16	Electric Services	LOT	40,000	20,000	10,000	70,000	”
	17			433,500	126,000	58,850	618,450	
	18	Structures	LOT	0	390,000	170,000	560,000	Allowance
	19							
	20							
	21	TOTAL DIRECTS		433,500	516,100	228,850	1,178,450	

TABLE B-13. Operating and Maintenance Costs (Two 1200 MW(e) PWR)

Liquids Case 2	**Notes**		**1973 $ Cost/yr**
1. Equipment - 11 tanks 10 pumps 3 filters 2 demin. 1 evap.	400,000@ 2%		8,000
2. Process Piping, etc.	160,000 @ 2%		3,200
3. Materials, etc. - Resins (2)(40)(100) Filters, see Case 1 Steam Allowance (500 hr @ 12,000 lb/hr) Allowance for other utilities and such like	8,000 4,000 6,000 2,000		20,000
		Liquids Total	31,200
Solids Associated with L-2			
1. S-1 System - Power and Equipment O&M Allowance			4,900
2. Collections per yr	ft^3	Drums	
Resins (2)(40)	80	26 @ 20	520
Sludges and other wet wastes	100	40 @ 20	800
Cement Binder (26 + 40)(7)(2)			770
Dry Waste Allowance		700 @ 15	10,500
		Solids Total	17,490

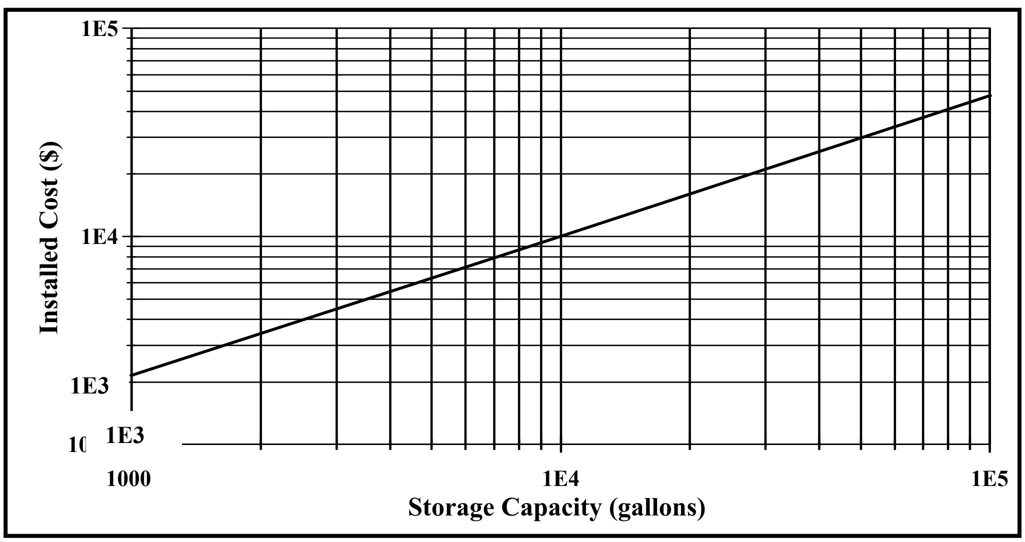


FIGURE B-11. Estimated Cost of Tanks Coated Carbon Steel 14.7psi

Discussion of PWR Liquid Radwaste Systems

Data from the final environmental impact statement (FEIS) (AEC, 1973) concerning PWR liquid radwaste systems and data for two additional alternate PWR liquid radwaste systems derived from information in the FEIS are presented in Table B-19. The doses associated with PWR stations using minimum treatment (PWR Case 1) liquid radwaste systems are much higher than doses used to define design objective release quantities. PWR stations featuring cooling towers result in calculated doses to individuals greater than those PWR stations featuring the once-through cooling mode. PWR stations featuring the once-through cooling mode and any of the PWR radwaste systems considered other than PWR Case 1 appear capable of reducing the calculated annual doses to individuals to less than 5 millirem at average river, lakeshore, and seashore sites but the total-body dose for individuals at the river and lakeshore sites is slightly in excess of the design objective values. If cooling towers are used in conjunction with a two-reactor PWR station using the PWR Case 2 liquid radwaste system some of the calculated annual doses to individuals are in excess of 5 millirem for all site regimes considered in this analysis. PWR stations with PWR Case 3 liquid radwaste systems and cooling towers at river and lakeshore sites also result in calculated annual doses to individuals in excess of 5 millirem. A two-reactor PWR station provided with PWR Case 4, 5, or 6 liquid radwaste systems appears capable of limiting doses to individuals to less than 5 millirem at all site regimes considered.

TABLE B-14. Solid Waste System Operating and Maintenance Costs (Two 1200 MW(e) PWR)

Liquid Case 1	Notes		1973 $ Cost/yr
1. Equipment - 9 tanks 8 pumps 3 filters 1 demin.	$110,200 $ 5,100 $ 15,500 $ 35,000 $165,800	O&M@2%=	3,320
2. Process Piping, I&C, Elec.	160,000	O&M at 2% =	3,200
3. Materials - Resins (40 x 100) and filters (4000)			8,000
4. Pumping power totals 45 hp; use factor 10%, [a] cost = (20)(0.746)(8760)(0.1)(0.0075) =			100
5. Allowance for other			1,900
		Liquids Total	16,500
Solids Associated with L-1			
4. Equipment O&M	2% on 235,200		4,700
5. Process Power Allowance			200
6. Collections per yr.	ft^3	Drums[b]	
1-100 gpm demin. Resins	36	13 @ 20/drum	260
Sludges and other wet waste[c]	50	20 @ 20	400
Cement binder = (13 + 20) (7)(2)			460
Dry Wastes[c]		350 @ 15	5,250
		Solids Total	11,270

a. Case 1 liquids/yr all systems is 6×10^5, 4×10^5, 2×10^5, 0 for clean, dirty, detergent, and s.g. blowdown response.

b. Drums = $(ft^3)(2.5)/(7) = (0.36)(ft3)$.

c. Allowance.

TABLE B-15. Radwaste Direct Cost Estimate for a Two -Reactor 2400 Mw(e) PWR Plant Early 1973 Start PQR Solids -- Case 1, 2, & 6

Item No.	Item - Description	Quan.	Equipment	Labor	Material	Total	Cost Ref No.
1	Spent Resin Storage Tank, 5000g	2	8,000	2,000	600	10,600	PWR, L-1, 1
2	Resin Batch Tanks, 300g	2	1,200	1,000	600	2,800	”
3	Pumps - 50 gpm	4	2,400	1,600	400	4,400	BWR, L-1, 7
4	Drumming Station						
5	Hydraulic Baler	1	12,000	3,000	1,000	16,000	Budget Est.
6	Capping & Transfer[a]	1	100,000	35,000	5,000	140,000	”
7							
8							
9	Cranes & Hoists	LOT	15,000	8,000	2,000	25,000	Allowance
10							
11							
12							
13	**EQUIPMENT TOTAL**		138,600	50,600	10,600	198,800	
14	Piping	LOT	0	15,000	5,000	20,000	Allowance
15	I&E	LOT	26,000	8,000	6,000	40,000	Allowance
16	Electric Service	LOT	24,000	12,000	4,000	40,000	Allowance
17	**PROCESS TOTAL**		188,600	85,600	25,600	298,800	
18	Structure	LOT	0	290,000	110,000	400,000	PWR S-1, 1
19							
20	**TOTAL DIRECTS**		$188,600	$375,600	$135,600	$698,800	

a. Including nitrogen cover gas system.

TABLE B-16. PWR Radwaste - Estimate Annual Number of Drums for Solid Waste (for Two Reactors)

Waste[a]	Case 1	Case 2	Case 3	Case 4
Resins, filter sludge, filters and evaporator bottoms, drums	54	160	470	630
Activity, Ci/drum	170	60	21	15
Dry and compacted waste, drums	700	900	1200	1400
Activity, Ci/yr	<5	<5	<5	<5

a. Decayed 180 days

TABLE B-17. PWR Liquid Radwaste Subsystem Annual Releases and Costs

Classification	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Clean Waste	Filter Demineralizer[a] 100% Discharge	Filter Demineralizer Evaporator 90% Recycle	Filter Demineralizer Evaporator Demineralizer 90% Recycle	Filter Demineralizer Evaporator Demineralizer 90% Recycle	Filter 2 Demineralizers Evaporator Demineralizer 90% Recycle	Filter 2 Demineralizers Evaporator Demineralizer 90% Recycle
Curies/Costs	164/157	0.0084/245	0.0018/271	0.0018/271	0.0017/	0.0017/
Dirty Waste	Filter 100% Discharge	Filter Demineralizer 100% Discharge	Filter 2 demineralizers[b] 100% Discharge	Filter Evaporator 90% Recycle	Filter Evaporator Demineralizer 90% Recycle	Filter Evaporator Demineralizer 90% Recycle
Curies/Costs	220/32	22/62	4.4/98	0.0014/166	0.0011/	0.0014/
Turbine Bldg. Drains	100% Discharge	100% Discharge	To Dirty Wastes	To Dirty Wastes	100% Discharge	To Dirty Wastes
Curies/Costs	0.084/0	0.084/0	0/0	0/0	0.052/0	0/0
Detergent Wastes	Filter 100% Discharge	Filter 100% Discharge	Filter Reverse Osmosis 100% Discharge	Filter 100% Discharge	Filter 100% Discharge	Filter Reverse Osmosis 100% Discharge
Curies/Costs	0.14/12	0.14/12	0.0046/38	0.14/12	0.14/12	0.0046/38
Steam Generator Blowdown	100% Discharge	Filter Demineralizer 100% Discharge	Filter Demineralizer Cation Demin. 100% Discharge	Filter Evaporator 100% Discharge	Regenerant Waste:[c] Demineralizer 90% Recycle	Filter Evaporator Demineralizer 90% Recycle
Curies/Costs	42/7	3.2/20	0.62/80	0.032/150	0.00004/	0.00032/
Solid Wastes						
Curies/Costs	0/195	0/202	0/259	0/258	0/258	0/209
Totals*						
Curies/Costs	420/403	24/541	10/746	0.2/857	0.2/899	0.2/862

a. Curie quantities released per year normalized (Appendix A, Section 18, Volume 2, WASH-1258). Costs in thousands of dollars per year.

b. Demineralizer refers to deep-bed, mixed bed demineralizer.

c. Demineralizers in series.

d. Once-through steam generator system and using condensate demineralizers in place of steam generator blowdown.

The approximate costs of the individual radwaste subsystems used in the separate full systems considered were derived from the detailed cost information presented in the FEIS. These subsystems are shown in Table B-17. All are defined in detail in the FEIS and were used to define three alternate PWR liquid radwaste systems (Cases A, B, and C) which provide capabilities nearly equivalent to some of the systems in Table B-17 but at slightly lower costs.

TABLE B-18. PWR Liquid Radwaste Subsystem Annual Releases and Costs

Classification	Case A	Case B	Case C
Clean Waste	Filter Demineralizer Evaporator 90% Recycle	Filter Demineralizer Evaporator 90% Recycle	Filter Demineralizer Evaporator 90% Recycle
Curies/Costs	0.0084/245	0.0084/245	0.0084/245
Dirty Waste	Filter 2 Demineralizers 100% Discharge	Filter 2 Demineralizers 100% Discharge	Filter Evaporator 90% Recycle
Curies/Costs	4.4/98	4.4/98	0.0014/166
Turbine Bldg. Drains	To Dirty Wastes	100% Discharge	100% Discharge
Curies/Costs	0/0	0.084/0	0.084/0
Detergent Wastes	Filter 100% Discharge	Filter 100% Discharge	Filter Reverse Osmosis 100% Discharge
Curies/Costs	0.14/12	0.14/12	0.0046/38
Steam Generator Blowdown	Filter Demineralizer 100% Discharge	Filter Demineralizer Cation Demin. 100% Discharge	Filter Evaporator 100% Discharge
Curies/Costs	3.2/20	0.62/80	0.032/150
Solid Wastes			
Curies/Costs	0/202	0/202	0/202
Totals*			
Curies/Costs	10/577	10/637	0.2/801

* Curie quantities released per year normalized (as shown in Appendix A, Section 18, Volume 2, WASH-1258). Costs in thousands of dollars per year.

These three additional liquid radwaste systems are described in Table B-18:

1. PWR Case A used treatment equipment similar to PWR Case 2 but the subsystems provided to treat the dirty waste and turbine building drains have been replaced by subsystems for PWR Case 3. The calculated cost of a PWR Case A liquid radwaste system is slightly higher than the cost for a PWR Case 2 system and lower than the cost for a PWR Case 3 system, but in Case A, the normalized radioactive material released in liquid effluents is the same as that from a PWR Case 3 system. Annual doses to populations and individuals were estimated for alternative radwaste cases. The collective doses from PWR stations with PWR Case A liquid radwaste systems were calculated to be 62 person-rem at a river site for the normalized annual release of 10 curies.

11. A PWR Case B system was also formulated but, because it has a normalized annual release of 10 curies with a higher annual cost than a PWR Case A system, the doses associated with a PWR Case B system are not given.

12. PWR Case C uses treatment equipment similar to a PWR Case A system, but the subsystem provided to treat the dirty waste has been replaced by one from a PWR Case 4 system. The calculated cost of a PWR Case C system is intermediate between that of a PWR Case 2 and a PWR Case 4 system, but the PWR Case C system reduces the

normalized annual release of radioactive material in liquid effluent to 0.2 curie. The collective doses were calculated in the same manner as described above for the PWR Case A liquid radwaste systems. Table B-20 presents the calculated costs of PWR Cases 1, 2, A, C, and 4 liquid radwaste systems and the calculated releases of radioactive materials in liquid effluent collective doses; incremental costs of the dose reductions achieved; and the calculated total annual cost which includes the annual cost of the treatment system plus a series of selected costs per person-rem received by the population in the vicinity of river, lakeshore, and seashore sites. The PWR liquid radwaste systems considered in this analysis illustrate the availability of treatment systems with low costs which appear capable of reducing the quantities of radioactive materials in liquid effluents to those specified in the Concluding Statement of Position of the Regulatory Staff Paragraph A.2 of Appendix I. The values of the lowest total calculated annual costs for each cost parameter selected for a given site are underlined in Table B-20.

TABLE B-19. PWR Liquid Radwaste Summary

Case No.		AC	Q	Once Through Cooling									Cooling Towers								
					Population Doses		$\frac{\Delta AC}{\Delta PR}$	Individual Doses						Collective Doses		$\frac{\Delta AC}{\Delta PR}$	Individual Doses				
				C	PR	PTR		Sk	TB	GI	Th	B	C	PR	PTR		Sk	TB	GI	Th	B
1	R	403	420	140	2200	2140	Base case	13	45	13	30	35	7000	2200	2140	Base case	14	290	24	72	210
	L				280	86		7.3	37	7.7	19	28		257	78		15	800	48	160	560
	S				48	400		7.3	7.4	7.4	45	7.0		44	366		15	41	42	1000	32
2	R	541	24	7.7	220	27	0.070	1.3	4.6	1.3	1.3	3.5	380	220	27	0.070	1.3	30	2.1	1.6	21
	L				29	3.7	0.55	0.73	3.8	0.74	0.72	2.8		26	3.4	0.60	1.5	82	4.1	2.4	57
	S				4.6	6.4	3.2	0.73	0.72	0.64	0.92	0.69		4.2	5.8	3.5	1.5	3.7	1.7	9.0	3.0
3	R	799	10	3.2	47	12	0.18	0.27	0.94	0.26	0.32	0.71	160	47	12	0.18	0.27	6.1	0.45	0.50	4.2
	L				5.9	0.90	1.4	0.15	0.77	0.15	0.18	0.57		5.4	0.82	1.6	0.30	17	0.88	0.90	12
	S				0.94	2.3	8.3	0.15	0.15	0.13	0.30	0.14		0.86	2.1	9.2	0.30	0.78	0.48	4.7	0.61
4	R	857	0.2	0.065	0.76	2.3	0.21	0.0008	0.0073	0.0031	0.021	0.0022	3.2	0.76	2.3	0.21	0.0009	0.024	0.0044	0.054	0.013
	L				0.022	0.048	1.6	0.0005	0.0048	0.0018	0.013	0.0018		0.020	0.044	1.8	0.0010	0.058	0.0073	0.13	0.035
	S				0.0063	0.31	9.4	0.0005	0.0008	0.0006	0.033	0.0005		0.0058	0.28	10.3	0.0010	0.010	0.0069	0.83	0.0037
5	R	899	0.2	0.065	0.71	0.77		0.0005	0.0062	0.0030	0.0063	0.0013	3.2	0.71	0.77		0.0005	0.016	0.0046	0.010	0.0078
	L				0.015	0.0096		0.0003	0.0039	0.0017	0.0036	0.0011		0.014	0.0088		0.0006	0.038	0.0082	0.018	0.021
	S				0.0047	0.030	b	0.0003	0.0005	0.0009	0.0032	0.0003		0.0043	0.027	b	0.0006	0.0079	0.018	0.077	0.0013
6	R	862	0.2	0.065	1.7	1.9	0.21	0.0085	0.027	0.0084	0.021	0.017	3.2	1.7	1.9	0.21	0.0065	0.15	0.013	0.045	0.10
	L				0.14	0.050	1.6	0.0036	0.021	0.0048	0.013	0.014		0.13	0.046	1.8	0.0072	0.40	0.022	0.096	0.28
	S				0.026	0.24	9.5	0.0036	0.0038	0.0033	0.026	0.0034		0.024	0.22	10.4	0.0002	0.025	0.012	0.60	0.016
A	R	577	10	3.2	62	9.3	0.081	0.36	1.2	0.34	0.41	0.94	160	62	9.3	0.081	0.36	8.0	0.59	0.65	5.5
	L				7.8	1.2	0.64	0.20	1.0	0.20	0.23	0.75		7.1	1.1	0.70	0.40	22	1.2	1.2	16
	S				1.2	3.0	3.7	0.20	0.20	0.17	0.39	0.18		1.1	2.7	4.1	0.40	1.0	0.63	6.1	0.80
C	R	801	0.2	0.065	0.62	2.8	0.18	0.0007	0.0060	0.0025	0.026	0.0018	3.2	0.62	2.8	0.18	0.0007	0.020	0.0036	0.066	0.011
	L				0.018	0.058	1.4	0.0004	0.0039	0.0015	0.016	0.0015		0.016	0.054	1.5	0.008	0.047	0.0060	0.16	0.029
	S				0.0051	0.38	8.3	0.0004	0.0007	0.0005	0.040	0.0004		0.0047	0.34	9.0	0.0008	0.0082	0.0056	1.0	0.0030
Tritium (all cases)		700	230	–	–	–	–	–	–	–	–	–	11700	–	–	–	–	–	–	–	–

AC - annual costs (thousands of dollars)
Q - curies per year for two reactors
C - concentration (pCi/l)
PR - person rem per year
PTR - person thyroid rem per year

$\frac{\Delta AC}{\Delta PR}$ and $\frac{\Delta AC}{\Delta PTR}$ = Thousands of dollars per year unit of dose reduction from base case.

R - river site L - lakeshore site S - seashore site

Sk - mrem/yr to skin
TB - mrem/yr to total body
GI - mrem/yr to GI tract
Th - mrem/yr to thyroid
B - mrem/yr to bone

b – once through steam generator not directly comparable to the other cases.

TABLE B-20. Total Annual Costs for PWR Liquid Radwaste Systems at River, Lakeshore and Seashore Sites (Minimum Total Annual Cost Values Underlined for Each Selected Cost Parameter)

RIVER SITE									
				ΔAC	Total Annual Costs				
Case No.	AC	Q1	PR	ΔPR	CP	0.1	0.2	0.5	1.0
1	403	420	2200	–		623	843	1503	2603
2	541	24	220	0.70		563	585	651	761
A	577	10	62	0.081		583	589	608	639
C	801	8	0.62	0.18		801	801	801	802
4	857	0.2	0.76	0.21		857	857	857	858
LAKESHORE SITE									
				ΔAC	Total Annual Costs				
Case No.	AC	Q1	PR	ΔPR	CP	0.5	1.0	2.0	4.0
1	403	420	280	–		543	683	963	1523
2	541	24	29	0.55		556	570	599	657
A	577	10	7.8	0.64		581	585	593	608
C	801	8	0.018	1.4		801	801	801	801
4	857	0.2	0.022	1.6		857	857	857	857
SEASHORE SITE									
				ΔAC	Total Annual Costs				
Case No.	AC	Q1	PR	ΔPR	CP	2	4	8	12
1	403	420	48	-		499	595	787	979
2	541	24	4.6	3.2		550	559	578	596
A	577	10	1.2	3.7		579	582	587	591
C	801	8	0.0051	8.3		801	801	801	801
4	857	0.2	0.0063	9.4		857	857	857	857

AC - thousands of dollars annual cost for radwaste system for 2 reactors.

Q1 - curies released per year for 2 reactors.

PR - person-rem per year remaining for radwaste system used.

ΔAC - thousands of dollars per person-rem dose reduction from base case.
ΔPR

CP - cost parameter, assumed societal cost in thousands of dollars/person-rem remaining for radwaste system used.

Total Annual Cost = AC + PR X CP

From Tables B-19 and B-20, it can be seen that there is a reasonable assurance that the design objective release quantities based on an annual dose of 5 millirem defined in the Paragraph A.1 of Section II of 10 CFR Part 50 Appendix I can be attained by a two-reactor PWR station using treatment systems similar to those defined in this analysis at river, lakeshore, and seashore sites.

For a two-reactor PWR station using once-through cooling, PWR Case 2 liquid radwaste system illustrates the lowest cost system capable of meeting the guidance of Section II, Paragraph A.1 of Appendix I. This system has a calculated annual cost of $541,000, and the costs per person-rem of collective dose reduction are approximately $70, $550, and $3,200 for river, lakeshore, and seashore sites, respectively. The calculated annual dose to an individual received from a two-reactor station using treatment systems similar to the PWR Case 2 liquid radwaste systems is 4.6 millirem. Annual doses to individuals near sites with more than two reactors were not specifically considered in the FEIS. While it is not expected that doses will be linearly related to the number of reactors at a site, use of a liquid radwaste treatment system similar to the PWR Case a system could permit as many as 7, 9, or 23 PWRs at a site on a river, lakeshore, or seashore, respectively.

For a PWR station featuring cooling towers, PWR Case C system provides the lowest cost liquid radwaste treatment which appears capable of meeting the design objectives of Appendix I at a seashore site. Calculated doses to individuals at river and lakeshore sites from liquid effluents from PWR Case C systems are greater than 5 millirem.

The calculated annual cost for the PWR Case C radwaste system is approximately $645,000 and the cost per person-rem of dose reduction attained is $5,680 for a two-reactor PWR station at a seashore site.

With PWR Case 4 liquid radwaste systems, a two-reactor PWR station at river, lakeshore, and seashore sites provides reasonable assurance of meeting design objective values. The calculated annual cost of a PWR Case 4 liquid radwaste system is $857,000 and cost per person-rem dose reduction is $210, $1600, and $9,400 for river, lakeshore, and seashore sites respectively. Based on this analysis, it would be possible to put at least 12 PWR reactors with PWR Case 4 liquid radwaste systems on a seashore site and considerably more on a river or lakeshore site without exceeding the design objective doses.

For the Cases considered, there is a reasonable assurance that the design guidance of Section II Paragraph A.2 of Appendix I can be met by PWR liquid radwaste systems except for systems similar to those used in PWR Cases 1 and 2.

If the cost parameter selected is in the range of $100 or $200 per person-rem of population annual dose, the lowest total calculated annual costs are attained for a two-reactor PWR station with a PWR Case 2 liquid radwaste system at a river site. This PWR station has calculated annual release of 24 curies (12 curies per reactor). If the cost parameter selected is in the range of $500 or $1,000 per person-rem, the lowest total calculated annual cost occurs for a PWR station on a river site with a PWR Case a liquid radwaste system which has a calculated annual release of 10 curies (5 curies per reactor). For a PWR station on a lakeshore site, the lowest total calculated annual cost occurs for a PWR station with a Case 2 liquid radwaste system if the cost parameter values selected are in the range of $500 and $1,000. A PWR Case A liquid radwaste system provides near-minimum total annual costs for a cost parameter of $1,000 and minimum total annual cost of the cost parameter values are $2,000 and $4,000. For a seashore site, the lowest total calculated annual cost occurs for the base Case (PWR Case 1) liquid radwaste system if the cost parameter value selected is $2,000. When the cost parameter value selected is in the range of $4,000 or $8,000, the lowest total calculated annual cost occurs with a Case 2 liquid radwaste system (12 curies per reactor). The lowest total calculated annual cost for an annual release of 10 curies (5 curies per reactor) occurs for a cost parameter value of $12,000 but near-minimum total annual costs occur with a cost parameter of $4,000.

Gaseous Radwaste Systems

Figure B-1 identifies the location of most sources of gaseous waste containing radioactive material from a PWR. Each of the sources may be treated by one or more processes, each with a unique efficiency in the removal of the radioactive contaminant and a corresponding cost. Various subsystems can be combined and evaluated to determine the optimum gaseous radwaste treatment system for whatever criterion is selected. For example, Tables B-21 and B-22 presents a summary of descriptive information to aid in identifying the radwaste systems that were evaluated, including the optional systems that accomplish the same objectives as the original system designs, but with different combinations of components and cost. Gaseous radwaste treatment systems for a PWR station with 2 reactors were defined and evaluated for 9 alternative designs and 6 additional variations. Tables B-21 and B-22 summarize the differences in features among the candidate gaseous waste treatment systems evaluated in this study and the cost to limit gases and iodine in the effluents. The major gas treatment equipment for each of the alternative designs were identified and costed in a manner similar to those described for the liquid treatment systems illustrated above. The various combinations of subsystems were selected to treat the several sources of radionuclides, particularly the radioiodine. That figure also contains the division of cost information for equipment to remove gases or to remove radioiodine. Note that if the effective dose had been used, rather than dose equivalent, there would be much less premium placed on radioiodine removal. Table B-23 shows the total annual cost for controlling iodine releases from gaseous waste treatment systems.

Discussion of PWR Gaseous Radwaste Systems

Summarized data concerning selected PWR gaseous radwaste systems plus similar data for a number of alternate systems are presented in Table B-24. The number of reactors that could be located on an average river site if the design objective dose guidance of Appendix I were to apply is shown by the number in parentheses below the thyroid dose for each of the distances indicated. Tables B-21 and 22 give a brief description of each of the subsystems for each of the PWR gaseous release cases considered in the FEIS, along with the calculated annual costs assigned to the treatment of noble gases and iodine. The additional alternate radwaste systems, made up from various combinations of the subsystems shown in Table B-21, are shown in Table B-22. All of the alternate PWR gaseous radwaste systems considered in this analysis include primary system gas holdup times of either 45 days or 60 days provided by pressurized storage tanks with HEPA filters. The FEIS cost analysis indicated that the primary gas holdup system used in the PWR Case 6 had equivalent holdup performance and was slightly less costly; however, because such a system was not in use or planned for use, it was not considered as an alternate system. Since no other radwaste subsystems appeared capable of further reducing the release of noble gases, the remaining discussion of alternate gaseous radwaste systems will concern only the iodine control aspects.

TABLE B-21. Summary of Annual Costs Applicable to the Control of Noble Gases and Iodine Emissions from the Gaseous Radwaste Treatment Systems

PWR	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9*
Primary System	7-day holdup pressurized storage tanks, HEPA filters	45-day holdup pressurized storage tanks, HEPA filters	45-day holdup pressurized storage tank, HEPA filters	60-day holdup pressurized storage tank, HEPA filters	Catalytic recombiner, Charcoal delay system, Pressurized storage tanks - Total holdup 60 days Xe, 31 days Kr	Catalytic recombiner, Cryogenic distillation, 90-day holdup pressurized storage tanks	45-day holdup pressurized storage tanks, HEPA filters	Cover gas recycle 90-day holdup pressurized storage tanks	60 day holdup pressurized storage tanks HEPA filters
Gases/Iodines[a]	135/0	148/0	148/0	163/0	133/0	131/0	148/0	352/0	163/0
Secondary System									
Condenser Air Ejector	No treatment	No treatment	Charcoal adsorber	Charcoal adsorber	Charcoal adsorber	Charcoal adsorber	No treatment	Charcoal adsorber	Charcoal adsorber
Gases/Iodines	0/0	0/0	0/54	0/54	0/54	0/54	0/0	0/54	0/54
Steam Generator Blowdown Tank	Vent to atmosphere	Vent thru condenser	Vent thru condenser	Vent thru condenser	Vent thru condenser	Vent to condenser	No blowdown (once-through steam generator)	Heat Exchanger, Blowdown Tank, Ion Exchange	Vent thru condenser
Gases/Iodines	0/0	0/11	0/11	0/11	0/11	0/6	0/0	0/14	0/11
Containment Purge									
Internal Cleanup	No treatment	4,000- cfm charcoal adsorber	20,000-cfm charcoal adsorber	20,000-cfm charcoal adsorber	20,000-cfm charcoal adsorber	No treatment	20,000-cfm charcoal adsorber	20,000-cfm charcoal adsorber	20,000-cfm charcoal adsorber
Gases/Iodines	0/0	0/20	0/81	0/81	0/81	0/0	0/81	0/81	0/81
Purge Vent	No treatment	No treatment	No treatment	Charcoal adsorber	Charcoal adsorber	Charcoal adsorber	Charcoal adsorber	Charcoal adsorber	Charcoal adsorber
Gases/Iodines	0/0	0/0	0/0	0/106	0/106	0/106	0/106	0/106	0/106
Auxiliary Building Ventilation	No treatment	No treatment	Charcoal adsorber	Charcoal adsorber	Charcoal adsorber	Charcoal adsorber	Charcoal adsorber	Charcoal adsorber	Charcoal adsorber
Gases/Iodines	0/0	0/0	0/192	0/192	0/192	0/192	0/192	0/192	0/192
Turbine Building Ventilation	No treatment	No treatment	No treatment	Clean steam on valves > 2.5" in diameter	No treatment	No treatment	No treatment	No treatment	Charcoal adsorber
Gases/Iodines	0/0	0/0	0/0	0/277	0/0	0/0	0/0	0/0	0/500
Stack	None	None	None	None	None	None	None	None	100-meter
Gases/Iodines	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	175/175
Totals Gases/Iodines	135/0	148/31	148/339	163/721	133/444	131/358	148/379	352/447	338/1119
Totals System	135	179	487	884	577	489	527	799	1457

a. ($ thousands for noble gases / $ thousands for iodines)

* Gaseous radwaste system with 100-meter stack

TABLE B-22. Summary of Annual Costs Applicable to the Control of Noble Gas and Iodine Emissions from the Gaseous Radwaste Treatment Systems

PWR	Case A*	Case B*	Case C*	Case D*	Case E	Case F
Primary System	45-day holdup pressurized storage tanks, HEPA filters	45-day holdup pressurized storage tanks, HEPA filters	45-day holdup pressurized storage tank, HEPA filters	60-day holdup pressurized storage tank, HEPA filters	60-day holdup pressurized storage tank, HEPA filters	60 day holdup pressurized storage tanks HEPA filters
Gases/Iodines[a]	148/0	148/0	148/0	163/0	163/0	163/0
Secondary System						
Condenser Air Ejector	No treatment	No treatment	No treatment	No treatment	Charcoal adsorber	Charcoal adsorber
Gases/Iodines	0/0	0/0	0/0	0/0	0/54	0/54
Steam Generator Blowdown Tank	Vent to atmosphere	Vent to condenser	Vent to condenser	Vent to condenser	Vent to condenser	Vent to condenser
Gases/Iodines	0/0	0/6	0/6	0/6	0/6	0/6
Containment Purge						
Internal Cleanup	No treatment	No treatment	4,000-cfm charcoal adsorber	20,000-cfm charcoal adsorber	20,000-cfm charcoal adsorber	20,000-cfm charcoal adsorber
Gases/Iodines	0/0	0/0	0/20	0/81	0/81	0/81
Purge Vent	No treatment	No treatment	No treatment	No treatment	Charcoal adsorber	Charcoal adsorber
Gases/Iodines	0/0	0/0	0/0	0/0	0/106	0/106
Auxiliary Building Ventilation	No treatment	No treatment	No treatment	No treatment	Charcoal adsorber	Charcoal adsorber
Gases/Iodines	0/0	0/0	0/0	0/0	0/192	0/192
Turbine Building Ventilation	No treatment	No treatment	No treatment	No treatment	No treatment	Charcoal adsorber
Gases/Iodines	0/0	0/0	0/0	0/0	0/0	0/500
Stack	100-meter	100-meter	100-meter	100-meter	None	None
Gases/Iodines	0/350	0/350	0/350	0/350	0/0	0/0
Totals Gases/Iodines	148/350	148/356	148/376	163/437	163/439	163/939
Total System	498	504	524	600	602	1102

a. thousands for noble gases / $ thousands for iodines

* gaseous radwaste system with 100-meter stack

TABLE B-23. Total Annual Costs for Iodine Releases from PWR Gaseous Systems

Case No.	AC_I	Q^1I	PTR	ΔAC / ΔPTR	TOTAL ANNUAL COSTS				
					CP	0.1	0.2	0.5	1.0
1	0	2.42	130	–		13	26	65	130
A*	0	2.42	130	–		13	26	65	130
B*	6	1.16	63	0.090		12	19	38	69
C*	26	0.66	36	0.28		30	33	44	62
D*	87	0.42	23	0.81		89	92	98	110
E	439	0.088	4.8	3.5		439	440	441	444
F	939	0.042	2.3	7.4		939	939	940	941

AC_I - thousands of dollars annual costs assigned to iodine control

$Q^1{}_I$ - annual quantities of iodine-131 released

PTR - annual person-thyroid-rem doses

ΔAC_I

ΔPTR - thousands of dollars per person-thyroid-rem removed

CP - cost parameter for the assumed societal cost in thousands of dollars per person-thyroid-rem remaining

Total annual cost = AC_I + CP x PTR

Annual costs, quantities, and doses are for sites with two reactors.

Minimum total annual cost values are underlined for each selected cost parameter.

TABLE B-24. Gaseous Radwaste Systems Summary for River Sites

Case No.	ACG	ACI	Gaseous Effluents		Population Doses		ΔACG / ΔPR	ΔAC1 / ΔPTR	Doses to Individuals for Selected Distances											
									500 m			1000 m			2000 m			5000 m		
			Q1G	$Q1_{131}$ / $Q1_{133}$	PR	PTR			TB	Sk	Th	TB	Sk	Th	TB	Sk	Th	TB	Sk	Th
1	135	0	92000	2.42/1.18	13	130	C	Base case	1.7	42	2400 (0)	0.90	17	800 (0)	0.34	6.0	300 (0)	0.11	1.9	68 (0)
4	163	721	7200	.060/.044	1.1	3.3	C	5.7	0.19	4.7	60 (0)	0.092	1.9	21 (1)	0.039	0.67	7.5 (4)	0.019	0.20	1.7 (17)
6	131	358	7000	.16/.070	1.1	8.5	Base case	2.9	0.19	4.7	160 (0)	0.092	1.9	55 (0)	0.039	0.67	19 (1)	0.019	0.20	4.3 (6)
7	148	379	7800	.011/.013	1.2	0.62	d	d	0.20	5.0	12 (2)	0.096	2.0	4.2 (7)	0.040	0.71	1.5 (20)	0.020	0.21	0.34 (88)
9*	338	1119	7200	.056/.044	0.30	3.0	259	8.8	0.017	0.06	0.36 (83)	0.012	0.042	0.26 (115)	0.0061	0.024	0.19 (157)	0.0025	0.010	0.16 (187)
A*	148	350	7800	2.42/1.18	0.32	132	b	c	0.019	0.064	15 (2)	0.013	0.045	11 (2)	0.0064	0.026	8 (3)	0.0026	0.011	7 (4)
B*	148	356	7800	1.16/.44	0.32	63	b	5.3	0.019	0.064	7.3 (4)	0.013	0.045	5.3 (5)	0.0064	0.026	3.8 (7)	0.0026	0.011	3.3 (9)
C*	148	376	7800	.66/.38	0.32	36	b	4.0	0.019	0.064	4.2 (7)	0.013	0.045	3.0 (10)	0.0064	0.026	2.2 (13)	0.0026	0.011	1.9 (15)
D*	163	437	7200	.42/.35	0.29	23	b	4.1	0.017	0.055	2.7 (11)	0.012	0.042	2.0 (15)	0.0061	0.024	1.4 (21)	0.0025	0.010	1.1 (27)
Case No.	ACG	ACI	Gaseous Effluents		Population Doses		ΔACG / ΔPR	ΔAC1 / ΔPTR	Doses to Individuals for Selected Distances											
									500 m			1000 m			2000 m			5000 m		
			Q1G	$Q1_{131}$ / $Q1_{133}$	PR	PTR			TB	Sk	Th	TB	Sk	Th	TB	Sk	Th	TB	Sk	Th
E	163	439	7200	.088/.061	1.1	4.8	b	3.5	0.19	4.7	92 (0)	0.092	1.9	32 (0)	0.039	0.67	11 (2)	0.019	0.20	3.0 (10)
F	163	939	7200	.042/.034	1.1	2.3	b	7.4	0.20	4.7	44 (0)	0.15	2.0	15 (2)	0.065	0.71	5.4 (5)	0.019	0.20	1.5 (20)

ACI - thousands of dollars annual costs assigned to iodine control

Q1I - annual quantities of iodine-131 released

PTR - annual person-thyroid-rem doses

ΔAC_I

ΔPTR - thousands of dollars per person-thyroid-rem removed

CP - cost parameter for the assumed societal cost in thousands of dollars per person-thyroid-rem remaining

Total annual cost = AC_I + CP x PTR

Annual costs, quantities, and doses are for sites with two reactors.

Minimum total annual cost values are underlined for each selected cost parameter.

The alternate radwaste cases identified in the order of decreasing calculated quantities of iodine released have been selected by introducing individual radwaste subsystems in a stepwise procedure to reduce the iodine releases from the various waste streams. The PWR gaseous radwaste systems are as follows (an asterisk (*) after a PWR Case number indicates a radwaste system with 100-meter stack for all effluent):

1. Case A* [the 4000-cfm system would be inadequate to provide as low as practicable in-plant occupational exposures, which have not been considered in this analysis, uses a 45-day holdup system for noble gases.] A stack is provided to reduce the thyroid dose for individuals in the vicinity of the reactor. The stack has essentially no effect on the population thyroid dose and its annual cost, which is estimated to be $350,000, should be considered only for the reduction of doses to individuals. The annual thyroid dose calculated for the 500-meter distance is 15 millirem. The population thyroid dose is 130 person-thyroid-rem.

    13. Case B* uses a 45-day holdup system for the noble gases and includes a 100-meter stack and also includes treatment for the steam generator blowdown tank effluent to be vented to the main condenser thereby eliminating a major source of iodine release for Case A*. The individual annual thyroid dose is reduced to 7.3 millirem for the 500-meter distance, and the population thyroid dose is a 63 person-thyroid-rem. The calculated annual cost for iodine removal is $356,000.

    14. Case C* includes treatment systems similar to those used in Case B* and also provides a small 4000-cfm containment internal cleaning system (charcoal absorber) which reduces the containment effluent release to 0.24 curie of iodine-131 and 0.044 curie of iodine-133 per year. Total calculated releases are 1.16 curies of iodine-131 and 0.44 curie of iodine-133 per year. The individual annual thyroid dose is 4.2 millirem, and the population annual dose is 36 person-thyroid-rem. The calculated annual cost for iodine control is $376,000.

    15. Case D* uses a 60-day holdup system for the noble gases and is otherwise like Case B* except that it includes a 20,000-cfm internal containment cleanup system (charcoal absorber) which reduces the release from the containment to 0.0090 curie of iodine-131 and 0.0084 curie of iodine-133 per year. The total releases are 0.42 curie of iodine-131 and 0.35 curie of iodine-133 per year. The calculated individual annual thyroid dose is 2.7 millirem at a distance of 500 meters, and the population annual dose is 23 person-thyroid-rem. The calculated annual cost for iodine control is $437,000.

    16. Case E is an improved radwaste treatment system without a stack. It uses a 60-day holdup system for the noble gases and includes the features of Case D* (except the stack) and in addition provides charcoal absorbers for the effluent from the condenser air ejector, the purge vent, and the auxiliary building ventilation. The total iodine releases are reduced to 0.088 curie of iodine-131 and 0.061 curie of iodine-133 per year. The population annual dose is reduced to 4.8 person-thyroid-rem, and the individual annual thyroid doses are 92 millirem for 500 meters, 32 millirem for 1000 meters, 22 millirem for 2000 meters, and 3.0 millirem for 500 meters. The calculated annual cost for iodine control is $439,000.

    17. Case F has all the treatment systems of Case E and in addition includes charcoal absorbers for the turbine building ventilation the total iodine release is reduced to 0.042

curie of iodine-131 and 0.034 curie of iodine-133 per year. The population annual dose is reduced to 2.3 person-thyroid-rem and the calculated individual doses for the distances 500, 1000, 2000, and 5,000 meters are 44, 15, 5.4, and 1.5 millirem, respectively.

The total calculated annual costs for the lowest-cost PWR gaseous radwaste systems which appear capable of attaining various population annual doses were calculated. Data for the noble gas annual releases are limited essentially to Cases A*, B*, C*, and the 7-day holdup used for Case 1, and 45-day holdup system used with stackless Cases 2, 3, and 7 and the systems with stack which includes Cases A*, B*, and C*. The 60-day holdup system is used with stackless Cases 4, E, and F, and with Case D*, which has a stack. The costs of all of the systems are similar and the collective doses are very low except for those for Case 1. The lowest total annual costs are associated with Case 1 for cost parameters up to $1,000 per person-rem. For a cost parameter of $1,500 per person-rem, the lowest total annual costs occur with the use of the 45-day holdup system. Table B-24 shows five stackless radwaste systems (Cases 4, 6, 7, E and F) which for distances of 500 meters or more are capable of limiting annual doses to total body and skin below the design objective doses of paragraph b.3 of Section II of Appendix I. The Case 1 system can attain this release level for receptor distances greater than 2,000 meters from the release point.

The values of the total annual costs for the iodine control subsystem were calculated without including the annual costs for the 100-meter stack. The data for the iodine cases selected are presented in Table B-23. The cases are arranged in order of increasing annual cost and decreasing iodine release quantities. The lowest total annual costs for the cases considered are attained with a Case B* for cost parameter values of $100, $200, and $500 per person-thyroid-rem and with Case C* system for a cost parameter value of $1,000 per person-thyroid-rem.

One of the stackless systems (Case 7) appears capable of limiting the calculated annual release quantities to meet the requirements of subparagraph C.1 of the Concluding Statement of Position of the Regulatory Staff at distances of 500 meters or greater. PWR stations with Case E systems appear capable of meeting this guidance for a distance of 2,000 meters, and Case F systems appear capable of meeting this guidance for a distance of 2,000 meters. All of the PWR gaseous radwaste systems with stacks (Cases A*, B*, C*, and D*) provide reasonable assurance of meeting this guidance for distances of 500 meters or greater. Except for the Case 1 system, the annual releases of iodine-131 from all of the radwaste systems considered appear capable of meeting the guidance provided by subparagraph c.2.

There was reasonable assurance that the air dose from either the gamma radiation or the beta radiation in effluents for PWR stations could be no more than 5 millirem per year.

On the basis of Tables B-23 and B-24 and the discussion in the previous paragraphs, it can be seen that there is reasonable assurance that the proposed design objective release quantities of paragraph B of the Concluding Statement of Position of the Regulatory Staff and subparagraphs C.1 and C.2 can be met by the use of one of several PWR gaseous radwaste systems which have been analyzed. The lowest cost radwaste system which appears capable of meeting these objectives at all distances greater than 500 meters is a PWR Case A* system, and use of this system would allow a two-reactor PWR station (2,400 MWe) to operate on a site. More reactors can be accommodated by the use of the slightly more costly radwaste systems of PWR Cases B*, C*, and D* which can provide for 4, 7, and 11 reactors at a site, respectively, if the distance to the location where the dose guidance is to be applied is 500 meters or greater.

Monetary Equivalent per Unit of Collective Dose

A quantitative cost-benefit analysis for the various radwaste options requires that the collective doses resulting from the operation of the LWR be compared to the cost of the radwaste options. Since the annual collective dose is expressed in units of person-rem, a monetary equivalent per unit of collective dose (e.g., $ per person rem) is needed to permit comparisons of terms with a common denominator. The monetary equivalent per unit of collective dose is the “alpha” term in the equation:

Total annual cost = annual cost of system operation+ alpha x collective dose + other cost considerations reflecting releases (beta).

The value for alpha is intended to apply to collective dose where the individual doses are in the range where only “stochastic” effects such as radiation-induced cancer (as opposed to deterministic effects) are assumed to occur. For radiation protection purposes, it is assumed that the radiation-induced health effects are linearly related to the dose. Deterministic effects are assumed to occur only after a threshold dose has been received. In this application, it has generally been assumed that the value for the monetary equivalent per unit of collective dose is independent of dose or dose rate so long as it is applied to doses below the appropriate dose limit.[28] A partial search of the literature revealed several suggested values ranging from "a few pounds Sterling" per person rem to about $1,000 per person rem. No two studies were found to use the same rationale as the basis and varied widely. Since 1973, several additional values have been suggested, making the range even greater (by more than an order of magnitude) than had been found previously. There is no specific value for alpha that has been adopted by any Federal agency or authoritative radiological protection organization in the United States. A value of $1,000 per person rem was used in the cited AEC rulemaking to demonstrate optimization and to consider back-fitting operating LWRs. However, the study also investigated the sensitivity of the value selected for alpha and concluded that for LWR radwaste systems, optimization was not affected by values of alpha ranging a factor of two above or below $1,000 per person rem. As noted elsewhere, the NRC recommends $2,000 per person-rem while DOE recommends a range from $1,000 to $6,000 per person-rem value for alpha.

The “beta” term is a cost that reflects the monetary value associated with other impacts (generally societal) that are not necessarily directly related to either individual or collective dose and that generally are quantified rather arbitrarily. Optimization is the identification of the optimal system, selected from several, that provides an acceptable dose to the MEI and results in the minimum total annual cost.

[28] It is of interest to note that the National Radiation Protection Board (NRPB) of the United Kingdom, for radiation protection purposes, has applied a variable value for alpha. The NRPB values are selected for each three ranges of individual dose, depending on how close the dose range is to the appropriate dose limit.

Evaluation

The basic information important to the analysis is summarized in tabular form in Tables B-19 and B-21 for liquid and gaseous radwaste treatment systems, respectively. It contains the annual cost and annual total body and organ doses to individuals and the collective (population) for PWRs with once- through and PWRs with cooling towers. The tables present the information for PWRs on river, lake, and sea shore sites to demonstrate the magnitude of the variations that might be anticipated for that parameter. The collective total body doses are shown, graphically, as a function of annual cost for selected treatment systems in Figures B-12 and B-13 for liquid and gaseous radwaste treatment systems, respectively. Notice that the graph is presented using semi-log scales because of the substantial ranges of source terms (and consequently, doses) for the several treatment systems evaluated.

The total annual costs, including a range of monetary values assumed for a unit of collective dose, were evaluated for selected Cases. The results are presented in Tables B-20 and B-24 for liquid and gaseous treatment systems, respectively. As may be seen in these figures, the results are not sensitive to the assumed monetary value per unit of collective dose. This appears to be true in many optimization analyses.

Conclusions

In this example, it was demonstrated that PWRs can be designed and operated in a manner that will limit the radioactive material in effluents to a small fraction of that from natural background radiation. In the actual study, duplicate information was generated for BWRs with similar results. The procedures used in the optimization are described in detail so that it they may be repeated for other applications. This example demonstrated the importance of identifying as many alternative treatment subsystems as possible, evaluating their probable performance and cost, and combining the subsystems to provide the best performance at the least cost – including the cost assumed per unit of dose. It was also demonstrated that the design selected is not sensitive to the monetary value assumed per unit of collective dose.

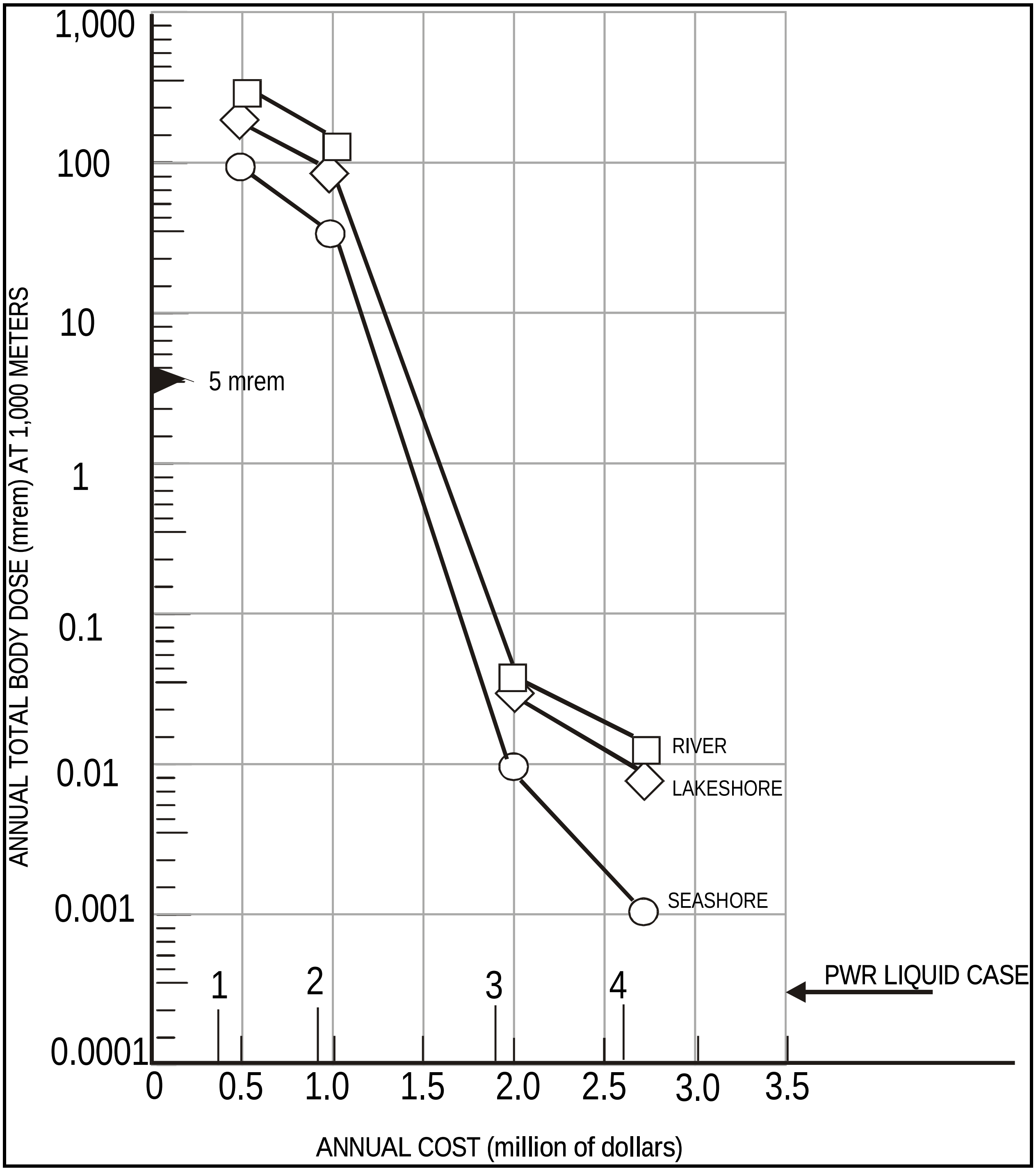


FIGURE B-12. Annual Average Total Body Dose from Liquid Effluent from a PWR Station

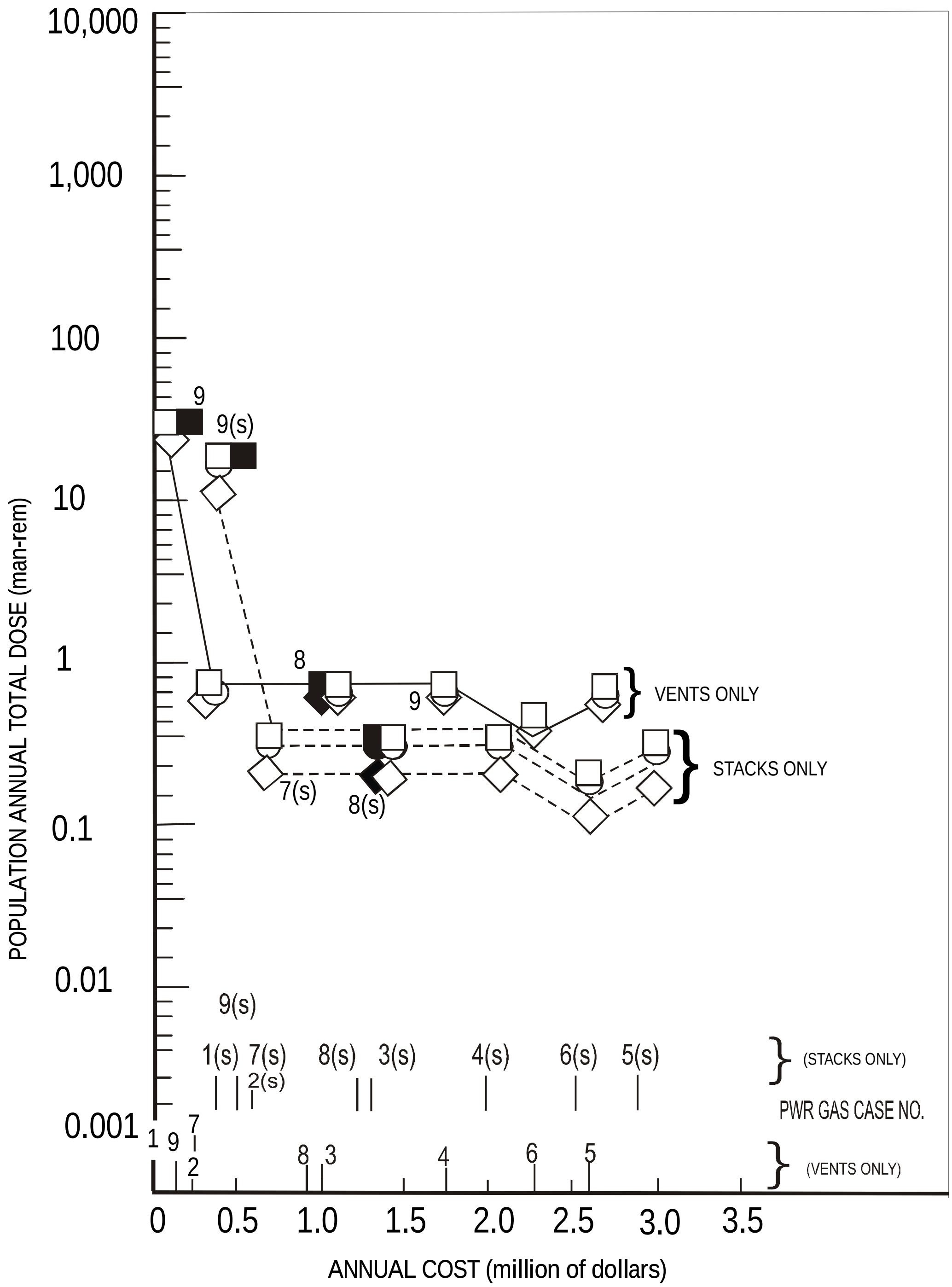


FIGURE B-13. Annual Total Body Dose from Gaseous Effluent to the Year 2000 Population Near a Site of a PWR Station

APPENDIX C.

REMEDIATION OF THE WELDON SPRING CHEMICAL PLANT AND SELECTION OF TREATMENT METHOD FOR THE CONTAMINATED QUARRY WASTE WATER

This example of an ALARA application summarizes the effort to remediate the Weldon Spring facility. The implementation of the ALARA requirements of DOE Order 5400.5 is fully adequate, and no criticism of the project is intended. The analysis at the end of this section is a post-decision assessment of the data reviewed and is provided to assist others in the conduct of similar ALARA assessments and risk-management decisions and to identify information that is useful to consider and document during the process.

This application is of interest for several reasons:

- It is an application where a large site complex is being remediated.
- The majority of radioactive and chemically hazardous waste generated by site cleanup is not related to the incremental amounts of site soil that would result from different cleanup criteria for soil.
- The bulk of the waste is associated with other media, principally the raffinate pit sludge, structural debris, and waste from the quarry.
- The soil contamination is quite localized, that is, on a small fraction of the total site soil. (Non-homogeneous distributions are commonly found at most sites with contaminated soil.)
- The site contains a variety of structures and several contaminants.
- The site provides a glimpse of the real-world, wherein decisions included consideration of the total detriment, that is, potential health-effects and actual non-health (societal) considerations.
- The project was conducted consistent with and in compliance with DOE requirements but is being planned and implemented under CERCLA regulations.
- The potential risks from residual contamination related to both radionuclides and chemical risks, as well as radiation dose, were considered in the comparison of alternatives.

Background

In 1941, the U.S. Army acquired about 17,000 acres of land 30 miles (48 km) west of St Louis, Missouri, to construct the Weldon Spring Ordnance Works for the manufacture of explosives. The location of the Weldon Spring site is shown in Figure C-1.

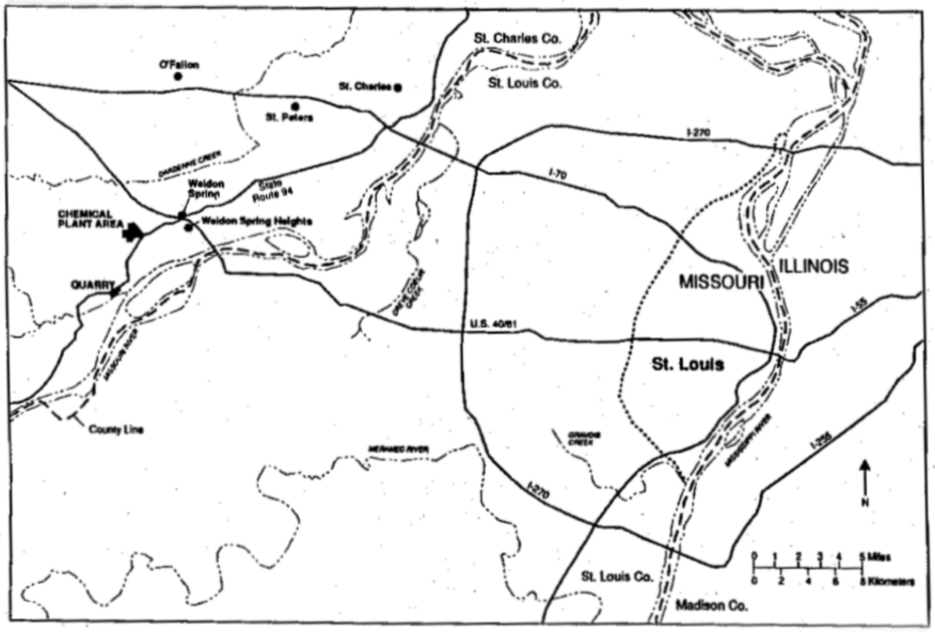


FIGURE C-1. Location of Weldon Spring Site

In 1955, the AEC acquired 217 acres of the property to construct a uranium feed materials plant. Uranium and thorium ore concentrates were processed in the plant from 1957 to 1966. The plant operations generated several chemical and radioactive waste streams, including raffinates from the refinery and washed slag from the uranium recovery process. Waste slurries were piped to the raffinate pits, where the solids settled to the bottom and the supernatant liquids were decanted to the plant process sewer; this sewer drained off-site to the Missouri River via a 1.5-mile (2.4 km) natural drainage channel. Some solid wastes were disposed on-site and the quarry was used by the Army to dispose of chemicals and by the AEC to dispose of radioactively contaminated material (uranium and thorium residues, building rubble, and processing equipment) through 1969. For decontamination purposes, the AEC (now DOE) site is divided into two areas; the chemical plant area (217-acres), and the quarry area (9-acres). Adjacent to the Weldon Spring Site are two wildlife areas (recreational areas including small lakes and streams), and an Army Reserve/National Guard Training Area. The Busch and Weldon Spring wildlife areas comprise 14,000 acres, compared to the 217 acres of the Chemical Plant area. Figure C-2 identifies features of the areas within a few km of the Weldon Spring site.

The nearest communities are Weldon Spring and Weldon Spring Heights, about two miles (3.2 km) east of the site with a combined population of about 850. St. Charles, about 15 miles (24 km) to the northeast, has a population of about 50,000. There are about 10,700 persons living within 3.1 miles (5 km) of the site and less than 3,000,000 persons within 50 miles (80 km).

The Weldon Spring site, a former uranium and thorium processing facility, has been cleaned in compliance with the CERCLA and NEPA. Refer to the third example given in Appendix A of this Handbook that discusses the Weldon Spring Site Remedial Action Project for a discussion of work performed to complete the closure of the site.

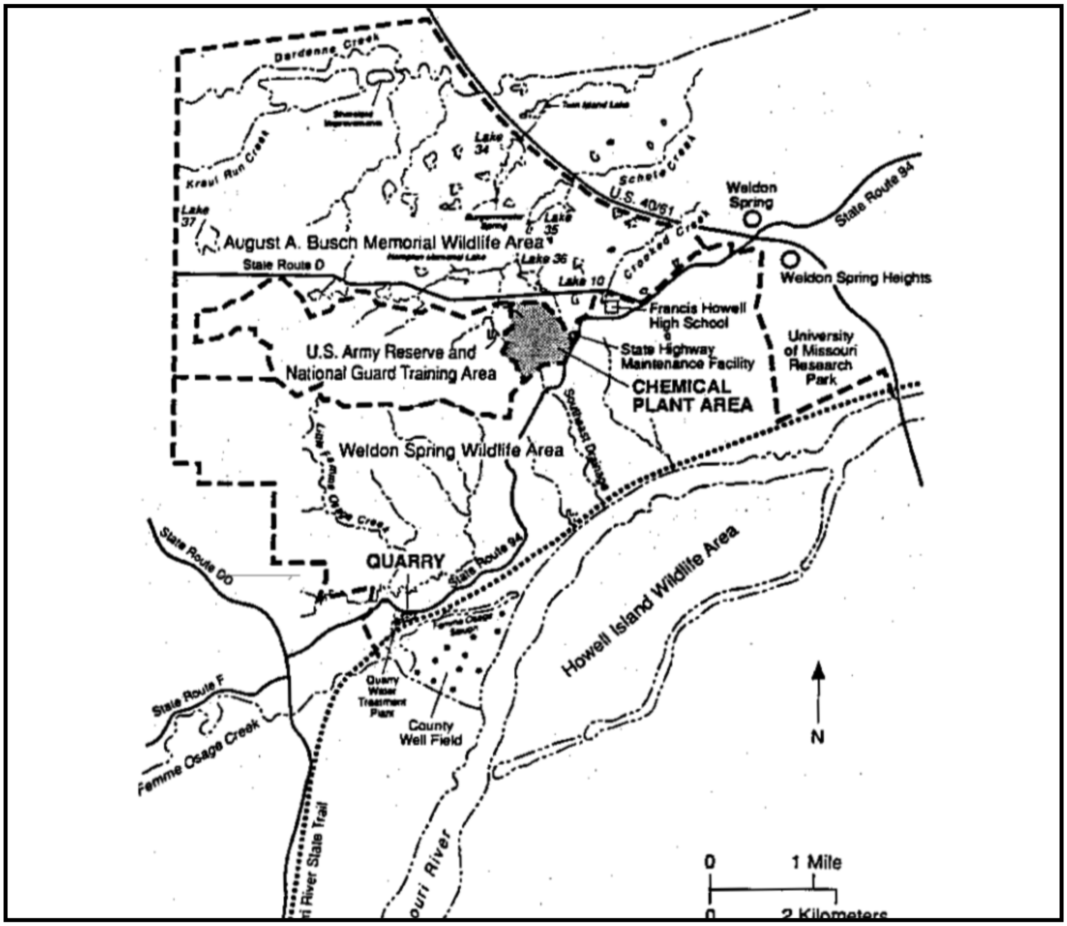


FIGURE C-2. Surface Features near the Weldon Spring Site

The location of the principal contaminated media and source areas at the Weldon Spring site is indicated in Figure C-3.

Radioactive contaminants at the Weldon Spring site are U-238, Th-232, and U-235 and their decay series, principally Ac-227, Pb-210, Pr-231, Ra-226, Ra-228, Rn-220, Rn-222, and Th-230. The contamination of the soil is very heterogeneous; there being relatively few locations with relatively high contaminations in soil and low concentrations over most of the site. Chemical contaminants include metals and inorganic anions as well as organic compounds such as PCBs, PAHs, and nitroaromic compounds. There are about 883,000 cubic yards of contaminated sludge, sediment, soil, structural material, process chemicals, and vegetation. (Analyses indicate that the chemical contaminants constitute less potential risks than the radioactive contaminants. Consequently, the chemical contaminants will not be addressed in this example, but they were evaluated and considered in the decisions for remediation.)

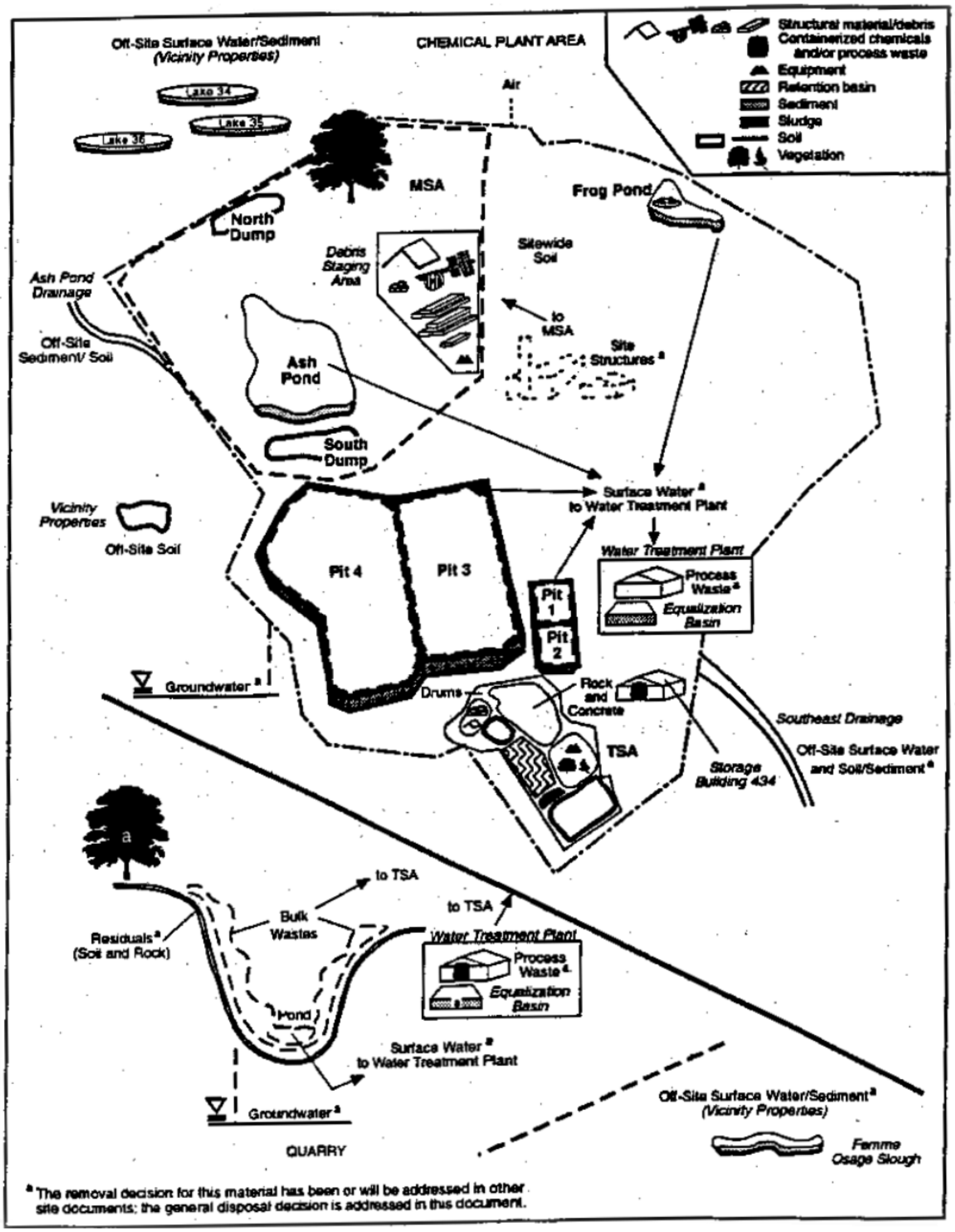


FIGURE C-3. Contaminated Media and Source Areas at Weldon Spring Site

1. Remediation

Objectives

The overall objectives of the remedial action at the Weldon Spring site were to: (1) protect human health and the environment by developing actions that address the radioactive and chemical contaminants in various media at the site and control related exposures; (2) implement the actions in a manner that would ensure compliance with applicable environmental requirements; and (3) release, to the extent practicable, at least a portion of the property for unrestricted use.

Initially, four determinations were needed:

- Selection of residual or "cleanup" levels for soil and other solid debris;
- Selection of methods for collecting and disposing of the solid material contaminated above the cleanup level;
- Selection of methods for removing, treating, and disposing of contaminated water impounded at the quarry and chemical plant areas; and
- Choosing between discharging the quarry water to the Missouri River via the Femme Osage Creek or via a pipe that would bypass the creek.

Doses and Risks

EPA (1989a) selected a risk coefficient of 600 cancer-induction effects per 1 million person-rem (6.0 E-7 per person-mrem[29]) and a risk factor of 260 per 1 million person-rem for genetic effects. The EPA risk factor was used for deriving soil cleanup levels. All doses from intakes of radionuclides were 50-year committed dose equivalent and all doses were assumed to be effective dose equivalent (EDE).

Basis for Remediation Goal Selection

Although the project cleanup criteria (authorized limits) were developed consistent with DOE requirements, they were being developed and implemented through CERCLA regulations. Two main factors were used to evaluate the appropriate cleanup options for the site: (1) long-term protection of human health and the environment--as indicated by results of site-specific risk assessments, and (2) compliance with environmental requirements such as "applicable or relevant and appropriate requirements" (ARARs) and "to be considered requirements" (TBCs). The ARARs and TBCs serve as a starting point for selecting cleanup levels for the site-specific data provide a basis for selecting the remediation goals. For contaminated debris from structures, the NRC guidance for the release of decommissioned nuclear sites, which was incorporated in DOE Order 5400.5, was adopted. Cleanup criteria for soil (including sludge) was developed independently.

To implement the Uranium Mill Tailings Radiation Control Act (UMTRCA) and the National Oil and Hazardous Substances Pollution Contingency Plan (NCP), EPA has promulgated

[29] A TEDE dose-to-risk conversion factor was used in this example to estimate risk, but if risk is being used to support ALARA analyses or, for that matter, any assessment of health risk, factors that convert intake of radionuclides or exposure to radiation directly to risk also may be used. In many cases, differences are within a factor of two or so and there is little impact on the decisions, but for some radionuclides difference can be significant. EPA provides slope factors and other information for converting radionuclide intake to risk in documents such as "Health Effects Assessment Summary Tables." The computer codes such as the RESRAD computer code for assessing the impacts of residual radioactive material in soil also includes an option to compute individual risk as well as dose. RESRAD calculations are consistent with the EPA methodology.

standards (40 CFR Part 192 and 40 CFR 300.430) for Ra-226 and its daughters, Th-230, and the Th-232 decay series. DOE has established guidelines for Ra-226, Ra-228, Th-230, and Th-232 in soil for areas with unrestricted access and address nonsecular equilibrium conditions between Th-232 and Ra-228 and between Th-230 and Ra-226. No Federal or State standards are available for uranium in soil. The State of Missouri has a standard for Rn-222 and Rn-220 in uncontrolled areas and DOE has similar guidance for the same isotopes. EPA has dose standards for airborne emissions for radionuclides other than Rn-222, and dose limits for the management of uranium and thorium by-product material. DOE Order 5400.5 requires use of the ALARA process to consider reducing potential doses below the applicable standards. Ra-226 and its progeny are the primary contaminants of importance because they contribute the most to potential doses through external exposures and inhalation of radon.

Risk-based remediation goals and site-specific estimates of potential doses were used to select cleanup criteria for soil. To judge the “acceptability” of risk, the study cites the EPA “target range” for incremental risk used to limit the probability that an individual could develop a fatal cancer from exposures to residual contaminants at a National Priority List (NPL) site. The principal concern, at that time, was anthropogenetic chemicals. These chemicals are generated by man and do not occur in nature, and thus, truly constitute incremental risks. In contrast, the principal contributors to risk at the Weldon Spring site also occur naturally in soil. ALARA analysis was applied to determine how far below the current levels they could be reduced, considering technical practicability. The top of the EPA target range is 1.0 E-4 (incremental lifetime risk for exposure from a given site) and the bottom of the range, referred to as the “point of departure,” is 1.0 E-6.

Evaluations of potential doses were obtained using site-specific exposure modeling, supplemented with the RESRAD and CAP-88-PC computer programs and the methods given in *Risk Assessment Guidance for Superfund* (EPA 1989b). The RESRAD program permits evaluations of doses from several exposure pathways from multiple radionuclides over selected time intervals. It also permits including the effects of soil erosion and infiltration of ground water. The CAP88-PC program was used to evaluate collective doses off-site from airborne releases of radioactive material. Joint wind speed/frequency/stability class data were collected for the 16 sectors. The population distribution was determined for each of the 16 sectors for 10 radial distances to 80 km (50 miles) of the site.

2. The Chemical Plant

The chemical plant once consisted of about 40 buildings, four disposal (raffinate) pits for process waste, two ponds, and two dump areas. There are about 679,000 m^3 of contaminated media, excluding water, on the site.

Selection of Cleanup Levels

The first ALARA consideration for the chemical plant was to select levels for the cleanup of soil. The EPA target range (1.0 E-6 to 1.0 E-4) was used to select clean-up levels for the contaminated soil. Interim cleanup levels from the NRC decommissioning guidance and DOE Order 5400.5 were applied to debris from buildings and other structures. The results of a source term analysis indicated the need for soil cleanup criteria for U-238, Th-232, Th-230, Ra-228, and

Ra-226. Hypothetical receptor parameters, exposure conditions, and durations for calculating potential doses (e.g., for a recreational visitor, a trespasser, a resident, and a wildlife area ranger) are described in the section on Potential Exposures. The potential risks to hypothetical receptors were estimated for exposure to the various radionuclides in soil and "target" risk values, that is, associated with ALARA levels to minimize risks for the principal radionuclides, are presented in Table C-1. Note that the concentrations are linearly related to the potential risk for each receptor, but the importance of the specific isotopes varies among the receptors, being dependent upon their exposure modes and durations.

TABLE C-1. Soil Concentrations of Radionuclides Associated with Target Levels for Risk for Selected Hypothetical Receptors

Receptor/ Radionuclide[a]	Soil conc. (pCi/g) for risk[b] of 1.0 E-4	Soil conc. (pCi/g) for risk[b] of 1.0 E-5	Soil conc. (pCi/g) for risk[b] of 1.0 E-6
Recreational Visitor			
Ra-226	23	2.3	0.23
Ra-228	46	4.6	0.46
Th-230	2,100	210	21
Th-232	430	43	4.3
U-238	810	81	8.1
Ranger			
Ra-226	0.81	0.081	0.0081
Ra-228	2.6	0.26	0.026
Th-230	160	16	1.6
Th-232	31	3.1	0.31
U-238	95	9.5	0.95
Resident			
Ra-226	0.075	0.0075	0.00075
Ra-228	0.62	0.062	0.0062
Th-230	81	8.1	0.81
Th-232	16	1.6	0.16
U-238	23	2.3	0.23

a. The values in this table are applicable for the selected scenarios and locations and would not be applicable for the site as a whole.

b. Risk for Ra-226 includes that for Rn-222 and Pb-210; the risk from U-238 includes that from U-235, Pr-231, and Ac-227.

[Note that since the natural background for Ra-226 in soil in the Weldon Spring area is about 1.2 pCi Ra-226/g soil, and the risk to a resident of 1.0 E-4 is associated with a concentration of 0.075 (pCi/g), it would be impossible to measure remediated soil with a risk potential of 1 x 10^{-4} above background, e.g., to verify a level of 1.275 pCi/g. Normally, radon is not included in the risk assessment, but is considered separately. In such cases Ra-226 concentrations would be limited to provide a reasonable expectation of limiting indoor concentrations to less than 4 pCi/L (0.02 WL) and outdoor concentrations, where people reside or work, to less than 0.5pCi/L above background.]

A site-specific analytical model was developed locally to estimate the potential incremental radiological risks to a hypothetical resident at the chemical plant site in the absence of remedial action and it was found to range from about 1.0 E-6 to 9.0 E-2, with a median of 2.0 E-4. This was due largely to inhalation of Rn-222 decay products and external irradiation from Ra-226. The estimated risk from the same sources at a "background" location is 3.0 E-3. (This is about 30 times the upper limit of the EPA "target" range.) Since the local soil would be used as backfill, the EPA risk target of 1.0 E-4 could not be met for Ra and Rn, and the issue was to select cleanup levels based on other considerations. The lowest level that Ra-226 in soil could reasonably be measured in the field was about 5 pCi/g, including background, or 4 pCi/g net residual Ra-226. Based on practicality of measurements and being able to achieve them, 5 pCi/g (including background) was selected for the Ra-226 "ALARA" cleanup level.

A cost-benefit analysis was performed to select the Ra-226 ALARA cleanup level. However, one important factor was the observation that the site contamination was very uneven, with higher concentrations located in a few specific locations, namely, raffinate pits, ponds, some chemical plant buildings and support structures, former dump areas, and storage areas, and the remainder of the site subject to generally low level (near background) contamination. For example, the location of the 30 pCi U-238/g soil isopleths in the top 2 feet of soil is presented in Figures C-4 and C-5. EPA has selected 4 pCi/L as an acceptable level for Rn in indoor air and this appears to be feasible at all site locations based on measurements of contaminants in soil.

Initially, the RESRAD program was used to evaluate potential doses from uranium in soil at concentrations of 190, 120, 60, 30, and 15 pCi/g; subsequently, site-specific modeling was conducted to assess impacts across the site. Table C-2 presents the estimated potential annual doses, volume of soil to be excavated, and cost to achieve the soil concentrations. The CAP-88-PC computer program was used to estimate population exposures off-site from airborne emissions during remediation actions. The 190 pCi U-238/g soil concentration level, without backfill, could result in maximum annual doses of 42 mrem (0.42 mSv) – within the 100 mrem (1 mSv)-annual dose limit for members of the general public, but slightly above the 30 mrem (0.03 mSv) in a year dose constraint used for DOE sources. External irradiation, inhalation, and ingestion of locally grown produce, and milk, meat, and soil are estimated to cause 60%, 16%, 12% and <15% of this potential dose, respectively.

The 120 pCi/g level for U-238, without backfill, was selected as the "target-level." This level would ensure that potential doses were less than 25 mrem (0.25 mSv) in a year without taking credit for clean cover material. This value was applied to Radium and Thorium too (that is, U, Ra, and Th combined, as required by the State of Missouri and EPA Region VII). However, considering the feasible net reductions in dose, additional cost, and technical limitations associated with further reducing the residual level (for instance, measurements of 15 pCi/g requires laboratory analysis and greatly increases the cost), a site-specific "ALARA" goal of 30 pCi/g was selected. This would reduce potential residual dose to less than 7 mrem (0.07 mSv) in a year without considering clean cover or less than 2 mrem (0.02 mSv) in a year when credit for the cover is assumed. Collective dose was not specifically addressed in this process. However, collective doses at the target levels would be small. For example, a screening assessment of residual collective doses at the target level, given the conservative scenario that the remediated areas were used for residential purposes (20 families with 4 persons each) would suggest that doses would be less than one person-rem over 200 years.

Table C-3 and Table C-4 present the estimated risks and doses, respectively, associated with the derived cleanup target, ALARA goal, and background levels for the principal contaminants for three hypothetical receptors: (1) a recreational visitor; (2) a ranger; and (3) a resident. Note that the risks (and, assuming the risk coefficient of 6.0 E-7 health effects per person-mrem, the doses to the hypothetical individuals) presented in these tables are not annual risks, but lifetime risks for the exposure conditions and durations described in the section on "Potential Exposures" below.

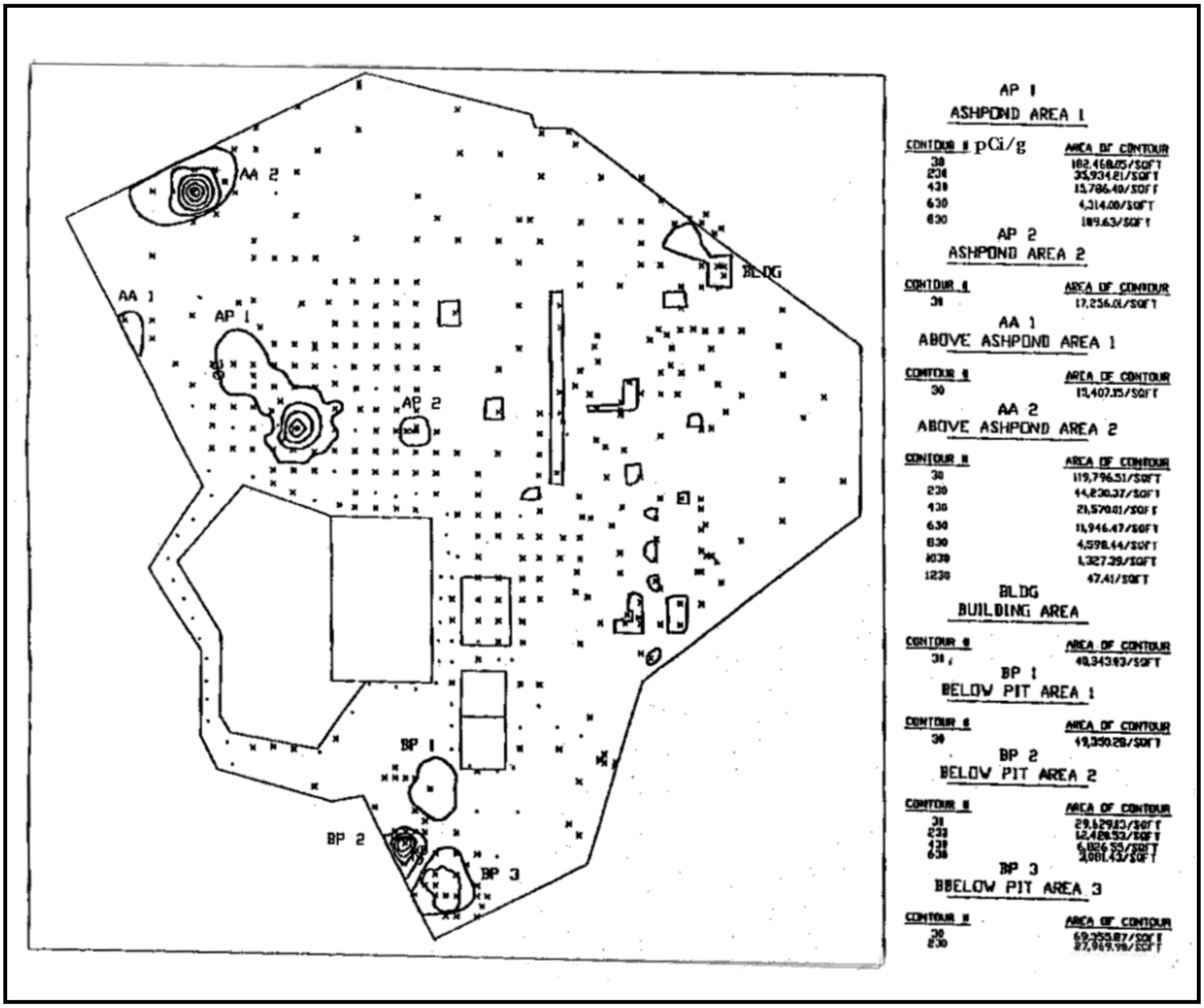


FIGURE C-4. Uranium-238 in Surface Soil (0.0 to 1.0 feet)

Although information for this selection included limited cost and feasibility considerations, it did not include a detailed cost-benefit analysis or evaluation of collective doses either within or beyond the site boundary, during or subsequent to the remediation effort. Because the relatively highly contaminated areas are small, the incremental cost and risk from contaminated soil are small – essentially insignificant – compared to those associated with raffinate sludge and other sources.

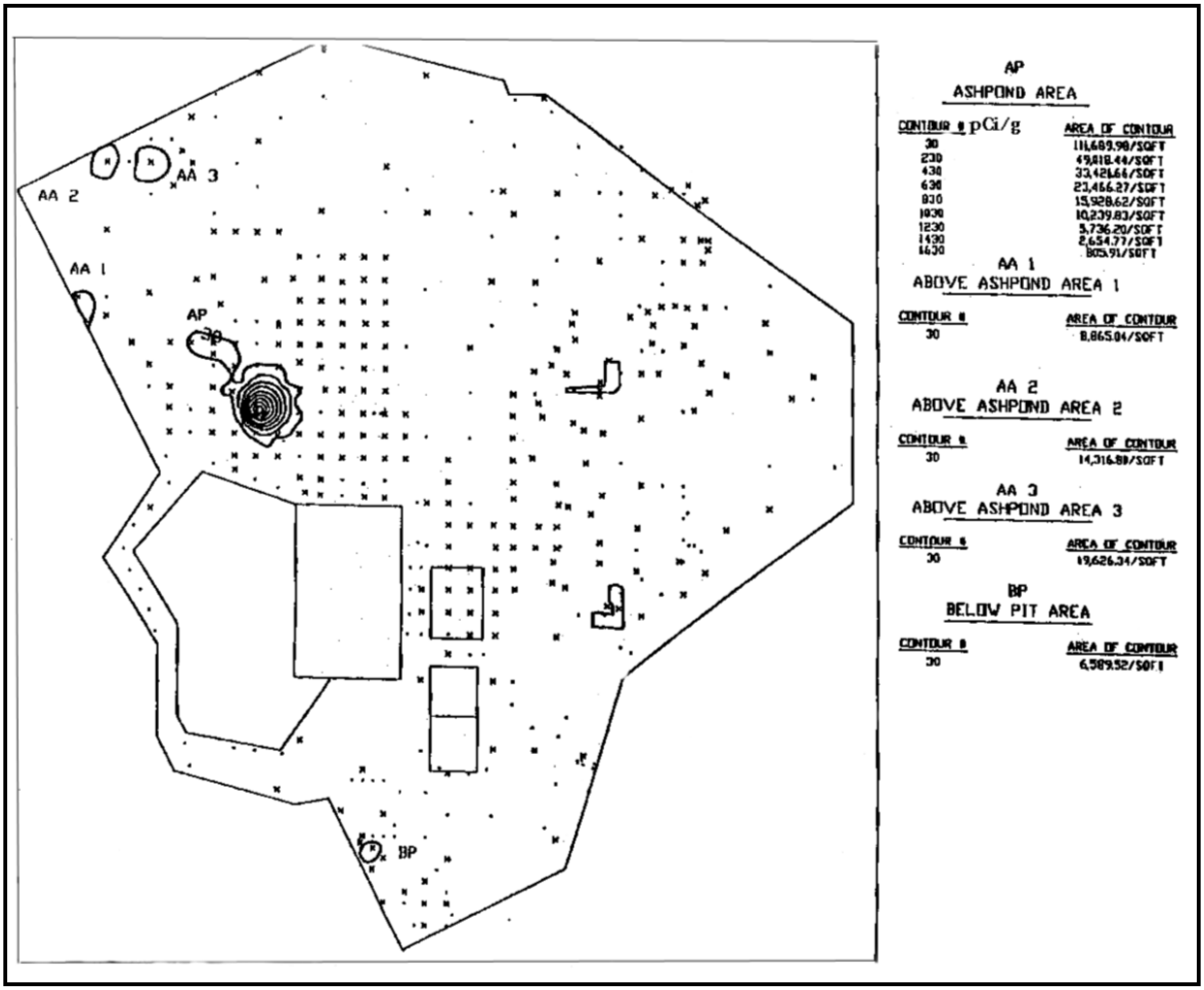


FIGURE C-5. Uranium-238 Subsurface (1.0 to 2.0 feet)

TABLE C-2. Potential Annual Individual Doses to a Farmer and Excavation Cost for Various Concentrations of U-238 in Soil

Concentration Level (pCi U-238/g soil)	Potential Annual Dose to Farmer (mrem/y)	Excavation Soil Volume (m^3)	Cost of Excavation/ disposal (x $1,000)
190+[a]	42	0	0
120	25 (present) 20[b](@ 400 y)	8,100	-- 580
60	12 (present) 6.7[b](@ 800 y)	20,000	-- 1,400
30	6.7 (present) 1.5[b](@ 10,000 y)	28,000	-- 2,000
15	0.38[b](@ 10,000 y)	42,000	3,000

a. Average concentration of U-238/g soil for a hypothetical farm located in the surface (6") soil at the Ash Pond area – one of the more contaminated areas. Thickness is 6 inches.

b. With backfill (provides indicated delay time: 6" soil -> 400 y; 12" soil -> 800 y; 24"soil -> 10,000+y). It is assumed that when contaminated soil is excavated, the soil will be replaced with uncontaminated backfill.

TABLE C-3. Estimated Risks* for Individual Hypothetical Receptorsa Associated with Target Cleanup Criteria and ALARA Goals

Radionuclide Criterion	Soil Concentration[b] (pCi/g)	Recreational Visitor (risk)	Ranger (risk)	Resident (risk)
Ra-226[c]				
Cleanup target	6.2	5.0 E-5	8.0 E-4	2.0 E-2
ALARA goal	5.0	4.0 E-5	6.0 E-4	8.0 E-3
Background	1.2	9.0 E-6	2.0 E-4	2.0 E-3
Ra-228				
Cleanup target	6.2	2.0 E-5	2.0 E-4	1.0 E-3
ALARA goal	5.0	1.0 E-5	2.0 E-4	8.0 E-4
Background	1.2	3.0 E-6	5.0 E-5	2.0 E-4
Th-230				
Cleanup target	6.2	3.0 E-7	4.0 E-4	8.0 E-6
ALARA goal	5.0	2.0 E-7	3.0 E-4	6.0 E-6
Background	1.2	6.0 E-8	8.0 E-5	2.0 E-6
Th-232				
Cleanup target	6.2	2.0 E-6	2.0 E-4	4.0 E-5
ALARA goal	5.0	1.0 E-6	2.0 E-4	3.0 E-5
Background	1.2	3.0 E-7	4.0 E-5	7.0 E-6
U-238				
Cleanup target	120	2.0 E-5	2.0 E-4	5.0 E-4
ALARA goal	30	4.0 E-6	5.0 E-5	1.0 E-4
Background	1.2	2.0 E-7	3.0 E-6	8.0 E-6

*Lifetime risks based on exposure assumptions in Table C-5.

a. The values in this table are for selected scenarios and locations and would not be applicable for the site as a whole.

b. Cleanup and ALARA values include background. For Ra and Th, the sub-surface concentration commitment, including background, is 16.2 pCi/g.

c. Risk for Ra-226 includes contributions for Rn-222, and Pb-210; the risk from U-238 includes contributions from U-235, Pr-231, and Ac-227.

Selection of Treatment

Having selected the soil cleanup levels, a decision needed to be made on the disposition of the contaminated soil. Potential applicable technologies for treating the contaminated residues (soil and debris) were identified, evaluated, and incorporated into seven preliminary alternatives and several variations including in-situ and removal containment, treatment, stabilization, and vitrification. These alternatives were screened on the basis of the nine criteria in the NCP:

- Overall protection of human health and the environment;
- Compliance with ARARs;
- Long term effectiveness and performance;
- Reduction of contaminant toxicity, mobility, or volume through treatment;
- Short-term effectiveness;
- Implementability;
- Cost; and
- State and community acceptance.

TABLE C-4. Estimated Lifetime Doses* for Individual Hypothetical Receptors Associated with Target Cleanup Criteria and ALARA Goals

Radionuclide/ Criterion	Soil Concentration[b] pCi/g	Recreational Visitor (mrem)	Ranger (mrem)	Resident (mrem)
Ra-226[c]				
Cleanup target	6.2	8.0 E+1	1.3 E+3	3.0 E+4
ALARA goal	5.0	7.0 E+1	1.0 E+3	1.3 E+4
Background	1.2	1.5 E+1	3.0 E+2	3.0 E+3
Ra-228				
Cleanup target	6.2	3.0 E+1	3.0 E+2	1.7 E+3
ALARA goal	5.0	1.7 E+1	3.0 E+2	1.3 E+3
Background	1.2	5.0 E+0	8.0 E+1	3.0 E+2
Th-230				
Cleanup target	6.2	5.0 E-1	7.0 E+2	1.3 E+1
ALARA goal	5.0	3.0 E-1	5.0 E+2	1.0 E+1
Background	1.2	1.0 E+0	1.3 E+2	3.0 E+0
Th-232				
Cleanup target	6.2	3.0 E+0	3.0 E+2	7.0 E+1
ALARA goal	5.0	1.7 E+0	3.0 E+2	5.0 E+1
Background	1.2	5.0 E-1	7.0 E+1	1.2 E+1
U-238				
Cleanup target	120	3.0 E+1	3.0 E+2	8.0 E+2
ALARA goal	30	7.0 E+0	8.0 E+1	1.7 E+2
Background	1.2	3.0 E-1	5.0 E+0	1.3 E+1

* Total dose to individual over a lifetime based on exposure assumptions in Table C-5.

a. The values in this table are for selected scenarios and locations and would <u>not</u> be applicable for the site as a whole.

b. Cleanup and ALARA values include background. For Ra and Th, the sub-surface concentration commitment, including background, is 16.2 pCi/g.

c. Doses for Ra-226 includes contributions for Rn-222, and Pb-210; the dose from U-238 includes contributions from U-235, Pr-231, and Ac-227.

The final alternatives subject to detailed evaluation were:

- Alternative No.1: No action;
- Alternative No.2: Removal, chemical stabilization/solidification, and disposal on-site;
- Alternative No.3: Removal, vitrification, and disposal on-site;
- Alternative No.4: Removal, vitrification, and disposal at the Envirocare facility (Utah); and
- Alternative No.5: Removal, vitrification, and disposal at the Hanford (Washington) facility.

The "No-action" alternative assumes:

- The bulk waste excavated from the quarry would be in short-term storage;
- The water treatment plants at the quarry and the chemical plant area would be operational;

- The building and other structures would be dismantled and the resulting material would be in short-term storage; and
- The containerized chemicals would be in storage.

Contaminated soil, sludge, and sediment would remain, with continued potential for release. DOE site ownership, access restrictions, and monitoring would continue into the foreseeable future. Annual costs to maintain the site under the “no action” alternative were estimated to be $1.2M for 10 years operation and 30 years maintenance, with increases likely to address contamination that might be released in the absence of further source control or mitigation control measures. The total costs of the other alternatives are presented in Table C-5.

TABLE C-5. Comparative Costs for Removal, Treatment, and Disposal Activities for the Chemical Plant[a]

Alternative Activity	No. 1 Cost (x $1M)	No. 2 Cost (x $1M)	No. 3 Cost (x $1M)	No. 4 Cost (x $1M)	No. 5 Cost (x $1M)
Removal	26.8	24.0	26.5	26.3	26.3
Treatment	--	30.0	64.4	64.0	64.0
Transport and Disposal	--	55.7	44.7	214	143
Other	--	47.2	46.8	46.5	70.4
Total	26.8	157	182	351	304

a. The incremental cost of removal, treatment, and disposal of the soil is a relatively insignificant component, compared to the total cost of remediation.

Potential Exposures

The hypothetical receptors (exposure location, mode, time, frequency, and duration) were identified to characterize potential individual doses. These are presented in Table C-6. Nearby communities were assumed to be exposed during the remedial action period (7 years exposure) but not exposed otherwise.

The Busch and Weldon Spring wildlife areas were anticipated to have as many as 2 million recreational visitors annually by 1994 and about 7,000 troops train (mostly on weekends) in the area annually. A small fraction (~0.015) of the total wildlife area is occupied by the Chemical Plant and only about 20% of the site surface soil is sufficiently contaminated to require remediation (i.e., >30 pCi/g soil). The annual number of recreational visitors in the remediated area is likely to be less than 6,000 persons if the area were to be used for that purpose. Exposure modes evaluated were: direct (external) exposure to gamma radiation; dermal contact; ingestion of surface and ground waters; ingestion of flora and fauna; direct contact with the water; and inhalation of dust and gases.

TABLE C-6. Baseline Calculated Doses (EDE) to Individual Receptors from Various Exposure Pathways (Lifetime dose associated with scenario)

Receptor[a] Pathway	Worker (mrem)	Trespasser (mrem)	Recreational Visitor[b] (mrem)
Site soil[c]: external gamma; ingestion	46 94	0.14 0.78	6.8 14
Near-site soil[c]: external gamma; ingestion	--	--	0 to 510 0.55 to 67
Raffinate Pit: water ingestion; sludge[c] ingest	-- --	13 250	160 4,600
Off-site surface water: ingestion; sludge[c] ingest.	-- --	-- --	8 to 18 4.4 to 340
Site aerosols: inhalation	31	0.15	4.5
Building 403: external gamma; inhalation; ingestion	--	-- 51	-- 1,700

a. Exposure time, frequency, and duration differ among receptor scenarios.

b. Visitor evaluated for uncontrolled access.

c. Ingestion of sludge and soil is incidental.

The potential doses to hypothetical receptors at various locations and from various pathways are presented in Table C-7 and Table C-8, respectively. Recall that the each type of receptor is assumed to be subjected to typical exposure conditions. Individual, but not collective, doses also were projected for the period after remediation. Since it is likely that the remediated site will again be used for recreational purposes, the collective dose to this group is of interest. The "recreational visitor" receptor was assumed to visit the site 20 times per year over a 30-year period for a total of 600 visits. The recreational visitor receptor was estimated to receive a total of D mrem over the 30-year period. Thus the postulated 6,000 recreational visitors per year would be the equivalent of 6,000 visitor-days/y x 20 days/y per receptor x D_{rec} mrem/30 y = 10 x D_{rec} person-mrem annually. Similarly, one can postulate that the remediated site could be used for farming, in which case, the annual collective dose could be 40 (remediated) acres/10-acre per farm x 4 persons per farm x D_{farm} mrem/ 30 years = 0.5xD_{farm} person-rem annually. The annual collective dose for residents living on the remediated site can be estimated by: 40 acres/0.3 acres per residence x 4 persons/residence x D_{res} mrem/30y = 2 x D_{res} person-mrem/y, where D is the median integral dose per receptor and the subscripts indicate the type of receptor.

TABLE C-7. Potential Individual Lifetime Doses to Various Receptors on Site (After Remediation)

Receptor Pathway	Recreational Visitor (mrem)	Ranger (mrem)	Resident (mrem)	Farmer (mrem)
External gamma	7	(70 to 10,00)[a] 80	(0 to 10,000) 330	50
Inhalation	83	(830 to 17,000) 830	(1 to 130,000) 33	17,000
Ingestion of soil	10	-- 150	(1 to 5,000) 17	670+1,200[b]
Total dose	100	(1,000 to 17,000) 1,160	(2 to 130,000) 380	17,000

a. Dose ranges are indicated in (), single value is median of range.

b. Dose from eating locally grown food.

TABLE C-8. Summary of Potential Doses and Costs for the Disposal Alternatives

Receptor	Baseline	(6a)	(7a)	(7b)	(7c)
Dose to member of public on/near site, (mrem[a]/y)	Baseln 1700 Mod.150,000 Env. 500	4.0 E-3 to 2.0 E-1	6.0 E-3 to 3.0 E-1	0.4	0.4
Collective dose,[b] worker (person-rem)	--	150	260 --	260 4.4	260 5.8
Collective dose,[c] public-50mi (person-rem)	--	34	32	4.4	5.8
Cost of alternative (x $1M)	--	157	182	351	304
Total cost[d] incl.coll.dose (x $1M)	--	157.2	182.3	351.3	304.3
dCost/dDose[e] ($/person-rem)	--		25/2= 13M	47/1.4=34M	122/26=5M

a. Dose estimates are from inhalation the entire exposure period (10 to 30 years). Baseline (baseln) dose is to recreational visitor, modified (mod.) site configuration dose is to farmer, environment (env.) dose is from soil near the site and Rn-222 daughters.

b. (1 WLM = 1 rem).

c. Number of workers: 200 offices; 80 for 6a; 110 for 7a; 160 for 7b and 7c.

d. Number of receptors: 0 to 3 miles = 10,700 persons; 0 to 50 miles = 3 x 10^6 persons.

e. Total cost includes $1,000/person-rem for workers and for public collective dose.

These collective doses could be too high if they are based on the dose estimates for the MEI because the contaminated areas are small compared to the rest of the site and hiking trails and other target areas are not in the contaminated area. The same is true for the farm scenario. In both cases, site- and location-specific evaluations would be needed. Following soil cleanup to 5 pCi/g for Ra-226, Ra-228, Th-230, and Th-232 and 30 pCi/g for U-238, the estimated median risk (and assuming 6.0 E-7 x dose [mrem] = risk) to the onsite resident would be 8.0 E-6 (13 mrem) and a maximum of 6.0 E-3 (1.0 E+4 mrem). The minimum dose could be zero. The estimated risk for a recreational visitor is 7.0 E-6 (12 mrem), and for a ranger the maximum risk is 2.0 E-4 (300 mrem) and the median is 2.0 E-5 (30 mrem).] Again, the minimum dose could be zero. Four water treatment plants are located within 86 km (50 miles) and they supply water to about 2 million persons who are assumed to ingest 820 million liters/y. The annual consumption of local fish is assumed to be 116,000 kg.

Results of Analyses

Based on the results of the analyses, final Alternative 2 – Removal, chemical stabilization/ solidification, and disposal on-site, was selected as the proposed action. Under this alternative, material would be removed from the contaminated areas and treated as appropriate; material with the highest contamination would be stabilized chemically and stored in an on-site disposal cell designed to retain its integrity for at least 200 and up to 1,000 years. The cell would be monitored and maintained for the long term. Because this alternative would meet the nine criteria stated in the NCP, it was selected for the proposed remedial action on the basis that it is the least costly of the acceptable options evaluated.

With respect to guidance on ALARA, the ICRP in Publication 26 (1977) recommends managing doses as low as reasonably achievable within the dose limits appropriate for the exposed individuals. When exposure of the public is involved, the appropriate dose limit is 100 mrem (1.0 mSv) in a year from all sources. To ensure that the total dose from DOE and non-DOE sources is within the limit, DOE has established a dose constraint for DOE only sources of 25 mrem (0.25 mSv) in a year. When selecting cleanup levels for soil the EPA "target range" for acceptable risk was also considered. The upper limit for the range, 1.0 E-4 serious health effects per person, was used with the EPA risk coefficient of 6.0 E-7 per person mrem. Given that an individual might be exposed for a period from 10 to 30 years suggests that annual doses less than 20 mrem (0.2 mSv) in a year would be in the target range and would be below the DOE dose constraint. Further, the collective doses were sufficiently low that their inclusion in a cost benefit analysis was not necessary. Notice that the total costs (including collective doses evaluated at $2,000 per person rem) for all options were essentially the same as the cost without the collective dose consideration when data were presented within two significant figures.

3. The Quarry

The quarry at Weldon Spring is located in the southern part of the site about one mile (1.6 km) from the Missouri River and about 14.5 miles (23 km) from the Mississippi River. Drainage from the quarry to the Missouri River is through the Femme Osage Creek. The quarry covers about 9 acres, is about 300 m long, has a floor of about 2 acres, and holds about 11,000 m^3 of water when full. It has an average depth of 6.1 m. Drainage to the quarry is from direct precipitation or subsurface flow only. Drainage from the quarry is to the ground water.

The average concentration of uranium in the quarry pond is about 2,300 pCi/L, which exceeds the DOE criteria for triggering Best Available Technology considerations of 550 pCi/L for discharge to uncontrolled areas derived per discharge requirements of DOE Order 5400.5. The sources of mixed-waste contamination of the quarry water are stated in the "Background" section.

Alternative Remedial Actions

The general technologies were screened and the following preliminary alternatives were identified for further evaluation:

- Alternative 1: No action;
- Alternative 2: Access restrictions, for example, improvement of existing controls;
- Alternative 3: Access restrictions with in-situ containment, such as using a grout system;
- Alternative 4: Access restrictions; pumping and treatment, with temporary storage of process wastes at the quarry; and discharge of the treated water to Femme Osage Creek;
- Alternative 5: Access restrictions; pumping and treatment, with temporary storage of process wastes at the quarry; and discharge of the treated water to Missouri River; and
- Alternative 6: Access restrictions; pumping and treatment, with temporary storage of process wastes at the quarry; and discharge of the treated water on land at the quarry, through spray irrigation or evaporation pond.

Following initial evaluations, Alternatives 1, 2, and 3 were rejected because there was considerable uncertainty regarding the ability to provide protection of the public and environment over the long term. Potential contamination of the ground water was an important consideration. Alternatives 4, 5, and 6 were subject to further detailed evaluation. The contaminated water could be treated to attain a concentration of less than 550 pCi/L (derived for total uranium) by the following conventional processes:

- Alternative A: Chemical (lime) addition; granular media filtration; and adsorption onto both activated alumina and granular activated carbon;
- Alternative B: Adding an ion-exchange process could reliably attain 100 pCi/L; and
- Alternative C: A vapor recompression/distillation system could be used, rather than the multi-stage treatment process, to reliably attain a concentration of 30 pCi/L. (This option was eliminated due to an ALARA analysis.)

Treatment System Costs and Doses

Table C-9 presents a summary of the costs and doses for the three alternative system designs for treating the quarry water. DOE Order 5400.5 requires that discharges of contaminated liquid to surface waters be managed such that the concentration being discharged does not exceed the derived concentration guide (DCG) values prior to dilution, that is, 550 pCi/L (derived for total uranium). Alternative A will meet this requirement operating at about one-third of capacity. The "design safety factor" of the plant is 2.5 and would compensate primarily for increased flows: (1) the potential for large temporary increases in storm runoff; (2) uncertainty with respect to groundwater inflow over time; and (3) the capacity for follow-on surface water/ground water treatment, if necessary. (Note: The documentation does not make it clear why the ion-exchange is necessary given the design safety factor built into the initial system that – if fully used – might reduce the concentrations to about 100pCi/L without the ion-exchange. It is also not clear why the design safety factor is needed for concentrations higher *and* lower than the design concentration. Ideally the documentation could more fully discuss the basis for adding the process.)

If the impact on the environment is acceptable, the discharge concentration constraint, that is, a concentration less than DCG, can be satisfied by simply diluting the untreated quarry water with river water at a ratio of 4 parts river water to 1 part quarry water prior to release and dilution in the natural waterway. This has been added to the other options in Table C-9 and constitutes the base case. While dilution might not be an attractive alternative philosophically, it could be attractive from the economic point of view and should be presented to clearly define alternatives and illustrate costs and benefits.

Chemical Plant

Consideration of candidate clean-up guidance for the Weldon Spring site started with consideration of ARARs for Ra and Th and then evaluated several increments of risk values for concentrations of U-238, Ra, and Th in soil. Rather than starting with the EPA risk value of 10^{-4} to derive the soil cleanup concentration, the evaluation might have been done for several more incremental values than those presented in Table C-3 and the appropriate individual and collective doses calculated for each. The total cost, including collective dose monetary equivalents, might then indicate the optimum alternative, that is, the option with the minimum total cost, where benefits are expressed as negative costs. Notice, in Table C-2, that the dose for a concentration of 190 pCi U-238/gm of soil is 42 mrem (0.42 mSv) in a year for the resident farmer scenario and lower still for the other scenarios. These doses are well below the 100 mrem-annual dose limit for members of the public and most are within the 30 mrem (0.30 mSv) in a year DOE dose constraint – and that is with no excavation. However, the contributions from Ra and Th must also be considered. The table also indicates how the cost for excavation is related to the soil concentrations. Similarly, the ALARA concentrations for the other nuclides in soil were not chosen based on cost-analysis information. In other words, for our ideal case, the ALARA levels for soil cleanup were selected too early in the process. They should have been selected only after more complete analyses of doses and costs were available. The summary used in this example is based on incomplete information.

TABLE C-9. Summary of Cost and Dose Information on the Alternative Treatment Systems for Quarry Water

Alternative treatment system	Uranium in effluent (pCi/L)	System cost ($M)	Collective public dose (person-rem)	dCost/dDose ($/person-rem)
No treatment (base)	2,300	b	35	base case
No. A Chemical/filter/adsorp.	550[a]	1.27	8.25	1,270K ------ = 47K 26.75
No. B above + ion exchange	100	1.44	1.5	170K ----- = 25K 6.75
No. C Vapor recompression/ distillation	30	2.15	0.5	710K ----- = 710K 1.0

a. Assumes operation of the facility 100 days per year for 10 years.

b. Assumes that untreated quarry water could be released directly to the Femme Osage Creek or to the Missouri River after diluting it by about 4:1 with river water. There would be some cost for the pumping station, but it would be small compared to the water treatment station.

Quarry Water Treatment

The concentration of uranium in the quarry water is about 2300 pCi/L. Discharge of the quarry water without treatment could result in an estimated dose to the MEI and collective dose to the population of about 1.8 mrem (0.018 mSv) and 35 person-rem respectively, after 10 years of operation. DOE Order 5400.5 contains a requirement (Chapter II, Section 3.a.1) that liquid effluent cannot be discharged to a surface waterway if the concentration at the point of discharge exceeds the DCG value (550 pCi/L) without being treated by the best available technology. However, discharging at 500 pCi/L, the dose to the MEI from ingestion of water and local fish would be about 0.0014 mrem (1.4 E-5 mSv) in a year (a very small fraction of the 100 mrem (1.0 mSv) per year dose limit or the 25 mrem (0.25 mSv) in a year dose constraint for DOE only sources). With Alternative A, the concentration will be reduced to less than 550 pCi/L, for example, 500 pCi/L, (the system would have a design safety factor of about 3), and consequently, discharge of effluent from the basic water treatment system could be permitted by DOE Order 5400.5. It appears feasible to attain this same discharge concentration at a lesser cost by accounting for dilution of the untreated quarry with river water. Assuming that the effluent from the quarry with alternative treatment system A is 500 pCi/L, the dose to the maximally exposed individual and the collective dose to the population would be about 0.014 mrem (1.4 E-4 mSv) and 7.5 person-rem respectively after the 10 year operation of the facility. The cost of reducing the collective dose would be about $47K/person-rem if the Alternative A treatment system waswere used. However, this alternative would likely not have been acceptable to EPA or the State of Missouri.

Treatment Alternative B for the quarry water was selected because the incremental cost ($170K) was judged to be modest compared to the cost of the conventional system ($1.27M) and the monetary equivalent per unit of collective dose ($64,000/person-rem), although greater than the $1,000 to $6,000/person-rem range, was judged to be acceptable. Nevertheless, in view of the low potential individual dose and collective dose, the ion-exchange unit cannot be justified on health considerations. Because the cost greatly exceeds that justified by health detriment considerations, it is another example of the non-health detriment, that is, societal factors – usually referred to as the beta factor.

Discharge Mode

Another consideration was whether to discharge the effluent to the Femme Osage Creek or to the Missouri River. Using treatment system Alternative A or B, the calculated annual dose to the MEI and annual collective dose to the exposed population from ingesting water containing 7.0 E-4 pCi/L of uranium from the Missouri River would be about 7.7 E-5 mrem (7.7 E-7 mSv) per year and 0.15 person-rem/y, respectively for the 10 years of operation. Ingestion of fish, assumed to be caught in an area where the concentration is 100 times greater, would result in a dose commitment of 2.0 E-4 mrem (2.0 E-6 mSv) per year. The collective dose from fish consumption would be about 4.4 E-5 person-rem/y. The collective dose to the population from operation of the quarry treatment system over a period of 10 years is about 1.5 person-rem (population risk about 9.0 E-4). The advantage of piping the quarry effluent to the Missouri River, rather than to the Femme Osage Creek is that it eliminates the possible accidental inadvertent drinking of the water by persons passing through the area. It also would reduce the need for monitoring the effluent en route to the ultimate discharge point. However, in the unlikely event that a hiker or hunter was to drink 1 liter of the untreated and undiluted effluent from the Femme Osage Creek, the dose commitment to the individual would be only about 0.03 mrem (3.0 E-4 mSv). Therefore, the cost of construction of the one mile (1.6 km) of piping to the Missouri River, that is $106K, to avoid that potential occasional dose to individuals, is not justified on the basis of health consideration.

Some decisions at this site were based on the total detriment (that is, including non-health considerations) and the site analysts did not believe that many of the adopted features were justified through cost-benefit considerations. However, in coordinating with the State of Missouri and to some degree EPA (Region VII) it was determined that the choices were necessary in order to receive the support of the agencies – that was critical for the success of the project. This is an example of the non-health (ß) factor. These considerations should be documented in the ALARA records. Recording this additional information would help DOE track all factors – including the assumed scenarios incorporated in the cleanup decisions.

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APPENDIX D.

CLEANUP OF CONTAMINATED SOILS AT THE NEVADA TEST SITE

This case study used the report *Cost/Risk Benefit Analysis of Alternative Cleanup Requirements for Plutonium-Contaminated Soils on and near the Nevada Test Site* (DOE/NV-399, 1995) as its basis and includes a brief summary of the findings of the report. This case study demonstrates the value of the output of the ALARA process with respect to decision-making.

The case study looks at cost and risk (to members of the public, workers, and biota). The impacts of the EPA cleanup criteria on the population risks and cost are discussed and evaluated. The overall summary for this case study is that the remediation activities being considered would be very costly and would avoid little public risk.

Background

EPA has published several documents related to cleanup of Federal facilities contaminated with radioactive material. These include issues papers and radiation site cleanup regulations. For NTS and adjacent areas, EPA considered a two-tiered cleanup criteria for remediating the plutonium contaminated areas: (1) areas to be released without control, cleanup areas until the projected dose from residual Pu is 15 mrem (0.15 mSv) per year above background to the reasonably maximally exposed individual(s) (RME) for 1,000 years after cleanup without active control measures; and (2) where active controls are in place, cleanup the areas until the projected dose from residual Pu is 75 mrem (0.75 mSv) per yr above background to the RME. DOE undertook a cost-benefit analysis to better understand the issues and evaluate a range of alternative cleanup levels.

Figure D-1 shows the location of the NTS and nearby areas (totaling about 6,000 square miles). There are several locations within the areas where measurable depositions of plutonium (Pu) are located from atmospheric explosions and safety tests.

Figure D-2 indicates the isopleths of depositions in excess of 10 pCi/g. The total area within the isopleths is about 37,000 hectares (50 square miles). Areas with various contamination levels at one of the typical locations are shown in Figure D-3. A summary of the areas in NTS contaminated at specified contamination levels is presented in Table D-1. Contamination in areas near the NTS are presented in Table D-2. The variation of concentration with depth is assumed to be described by an exponential function. Uncertainties in the estimated relationship between surface concentrations and areas within isopleths were estimated. Table D-3 and Table D-4 present factors used in projections and the results. The estimates are characterized as "realistic," "optimistic," and "pessimistic" projections.

Cost

Cost elements included consideration of excavation, area and volume of soil remediated, cost of processing soil and no processing, remediation strategy selection (volume reduction, disposal location) construction of facilities, site locations, transportation (building roads, hauling distances), surveys, and re-vegetation. Fixed cost components and estimates and area driven activities and cost are presented in Table D-5 and Table D-6, respectively.

Risk

Members of the Public

Radiological risks to individuals and to the population, remediation workers and the public, who may inhabit portions of the NTS in the future, were estimated. The estimates were based on alternative exposure scenarios affecting intake of Pu from soil by inhalation and ingestion (land use and exposure pathways); predictions of Pu concentrations in indoor and outdoor air, dust, and soil; population and its distribution; and conversions of intake to risk. Scenarios considered include land use for residential, commercial/industrial, and agricultural/ranching. Pathway exposure factors for inhalation and ingestion were rationalized and applied. The exposure duration was based on U.S. Bureau of the Census (1991) findings that the mean residence time is 10 years, with 5 and 95 percentiles of 0.4 and 36 years. For farm/rural locations, the mean residence time is about 20 years. For industrial workers, the mean time at a location was assumed to be 6 years, with a standard deviation of 1.74. Population densities were taken to range from that of the current least and most populated counties in Nevada, being limited by water availability. The risk coefficients used in this study were not substantially different from that recommended in this document, that is, 400 to 500 fatal health effects per million person-rem, despite the different bases for their selection.

Workers

The factors used for exposure to risk conversion are based on a combination of ICRP (Publication 67), EPA, and other sources. Non-nuclear accidents were also evaluated for the worker activities supporting the remediation. Results of the risk evaluation indicated that the risk to workers from traffic accidents would be an order of magnitude greater than those from industrial activities (operation of heavy equipment) and two orders of magnitude greater than that from radiological considerations.

Biota

Risks of remediation activities, that is, mechanical disturbances and scraping, on the NTS environs would be substantial for plants, animals, and micro-organisms important in the nutrient cycle over the total area of about 17,000 to 220,000 hectares that might require scraping and removal of the surface layers and adjacent areas. Restoration of a vegetation cover could require a long time interval, such as 100 years, if it can be done at all. Revegetation was estimated to cost about $40,000 per hectare. The study indicates that there has been little impact of the Pu contamination on the biota without remediation and that remediation can have devastating impacts that may be irreversible.

Impact of the EPA Cleanup Criteria

Population Risks

Figure D-4 illustrates the main components of the integration model used to estimate costs, risks, and benefits. Considering the provisions for active controls for (smaller) areas of higher concentration and release for unrestricted use for those (larger) areas, the strategy that minimizes the remediation necessary is shown in Figure D-5. However, the EPA paper defined the RME as the exposure dose at the 95% percentile. Figure D-6 illustrates the applicable exposure distribution. To reduce the likelihood that future remediation would be necessary, a safety margin of 10% was also considered desirable.

Individual risk was estimated for a location where the Pu concentration is as high as permitted by the suggested standard, that is, RME results in a dose of 75 mrem (0.75 mSv) per year (about 844 pCi/g). The risk is about 7×10^{-5}. Consequences of the population exposures were estimated using various discount rates and for a finite exposure duration of 1,000 years. Both approaches are acceptable cost-benefit methods.

Figure D-6 shows the "expected" risk over all time is about 100 (or less) fatal cancers for a wide range of alternative concentration limits. The risk is not strongly dependent on the cleanup concentration levels because much of the risk is due to the 10 pCi/g area. Similar risk values are obtained for alternative annual dose limits. Although not consistent with the recommendations in Section 6.5 of this document, the risks averted due to various cleanup levels at this site were integrated over more than 100,000 years. There is almost a three-orders of magnitude spread between the ± 90% confidence bounds.

Costs

Two components of costs were identified: (1) fixed costs (that are independent of the cleanup levels) and (2) variable costs (that are dependent on the cleanup levels). The fixed component includes the cost of building and maintaining roads and other support functions. The variable component is strongly dependent on the volume of soil that requires excavation and the location of the disposal site. Total expected and ± 90% confidence bounds of the cost are presented in Figure D-7 as a function of Pu concentration in soil [also note that 169 pCi/g is associated with 15 mrem (0.15 mSv) per year].

Worker Risk

The risk to workers from the remediation is almost entirely due to industrial accidents from operating heavy equipment (non-radiological). Even so, the total risk to workers is less than one fatality.

Summary of Results

Figure D-8 presents an "influence diagram" that indicates how the various decisions and factors considered in the remediation activity are interrelated. Table D-7 provides a summary of the key results of the study.

Inferred Cost to Avert a Projected Cancer

The data may be interpreted as inferring a value of life or, more appropriately, cost for preventing a hypothetical cancer, that is, the value that is placed on a fatality (cancer) to justify the various cleanup criteria. The cost for a member of the public would vary from about $200M to about $10M for 10 pCi/g to 1000 pCi/g and in this particular case, essentially independent of the cost of protecting a worker life.

The graphic effect of discounting is demonstrated in Figure D-9, which presents the inferred cost of protection for various dose limits and 0%, 1%, and 5% discount rates. The values range from about $7M for the 100 mrem (1.0 mSv) per year level with no discounting to almost $40 Trillion for 10 mrem (0.10 mSv) per year with a 5% discount rate. If the effects are limited to 1,000 years, the value of public life needed to justify the remediation is $240M for a 75 mrem (0.75 mSv) per year cleanup level, $390M for a 15 mrem (0.15 mSv) per year level, and $970M for a 5 mrem (0.05 mSv) per year level. Considering the effects of uncertainties, the study concluded that if the cleanup level were to be set at 75 mrem (0.75 mSv) per year, or less, it would be very worthwhile to more definitively and precisely determine the contamination distribution, the cost of excavation and disposal, and the cost of public health protection.

Conclusions

The data indicates that the contemplated remediation efforts would be very costly and would avoid little public risk. There is little incentive to undertake the remediation in the near future, there being no need for commercial development or public housing at this time. Cleanup criteria based on dose rate, rather than soil concentration, permits more flexibility.

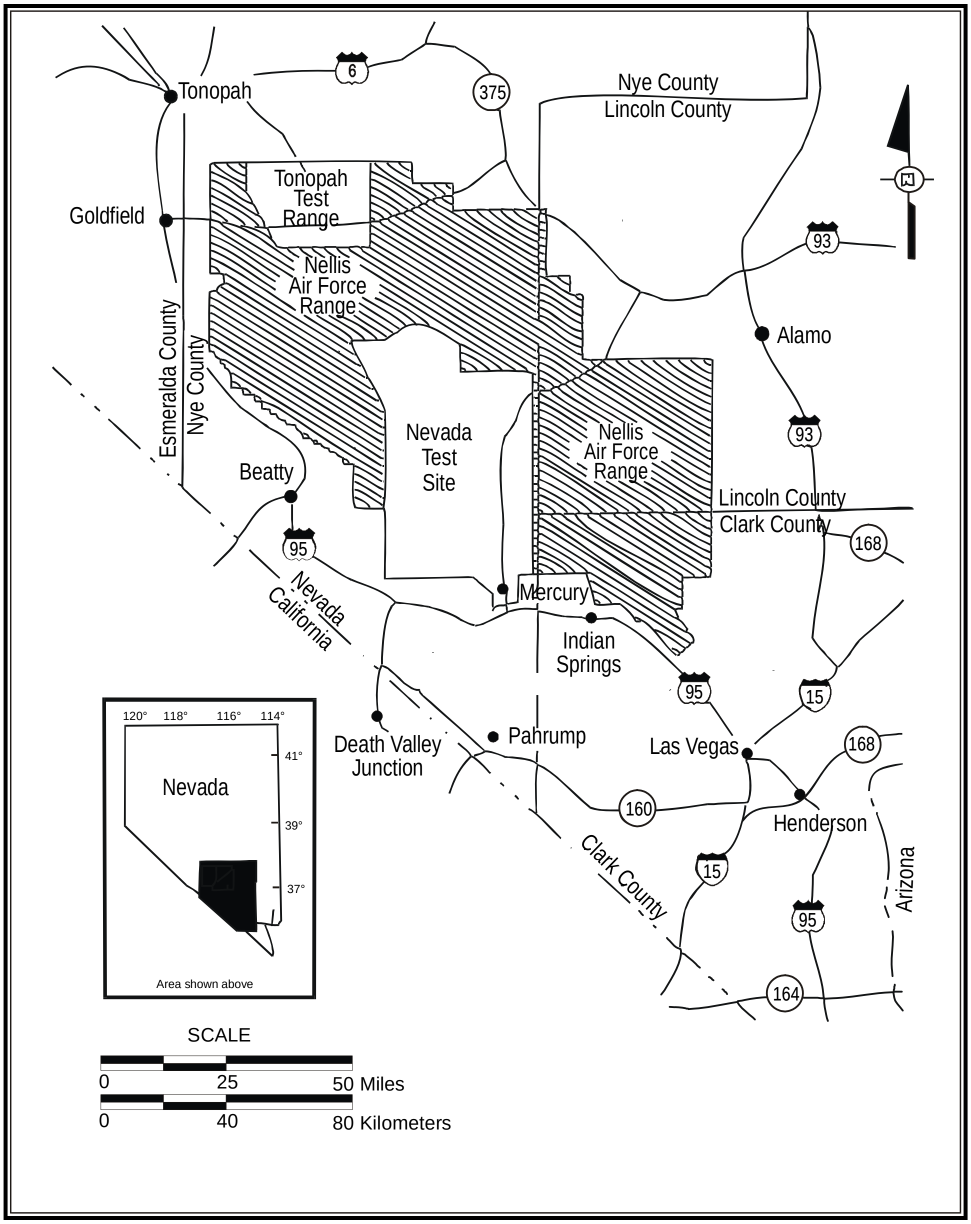

FIGURE D-1. Location of the Nevada Test Site

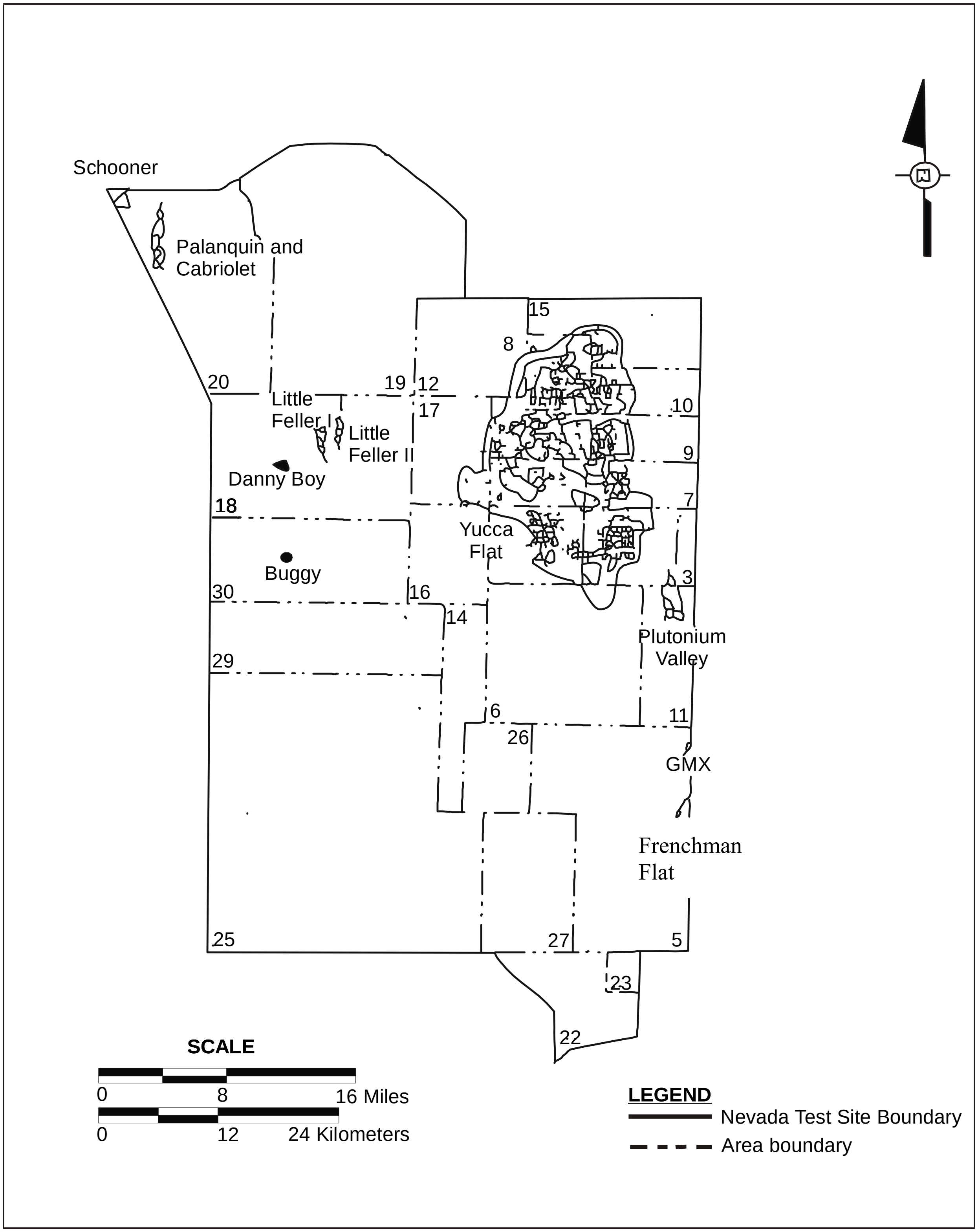

FIGURE D-2. Sites of Plutonium Contamination Exceeding 10 pCi/g at the Nevada Test Site

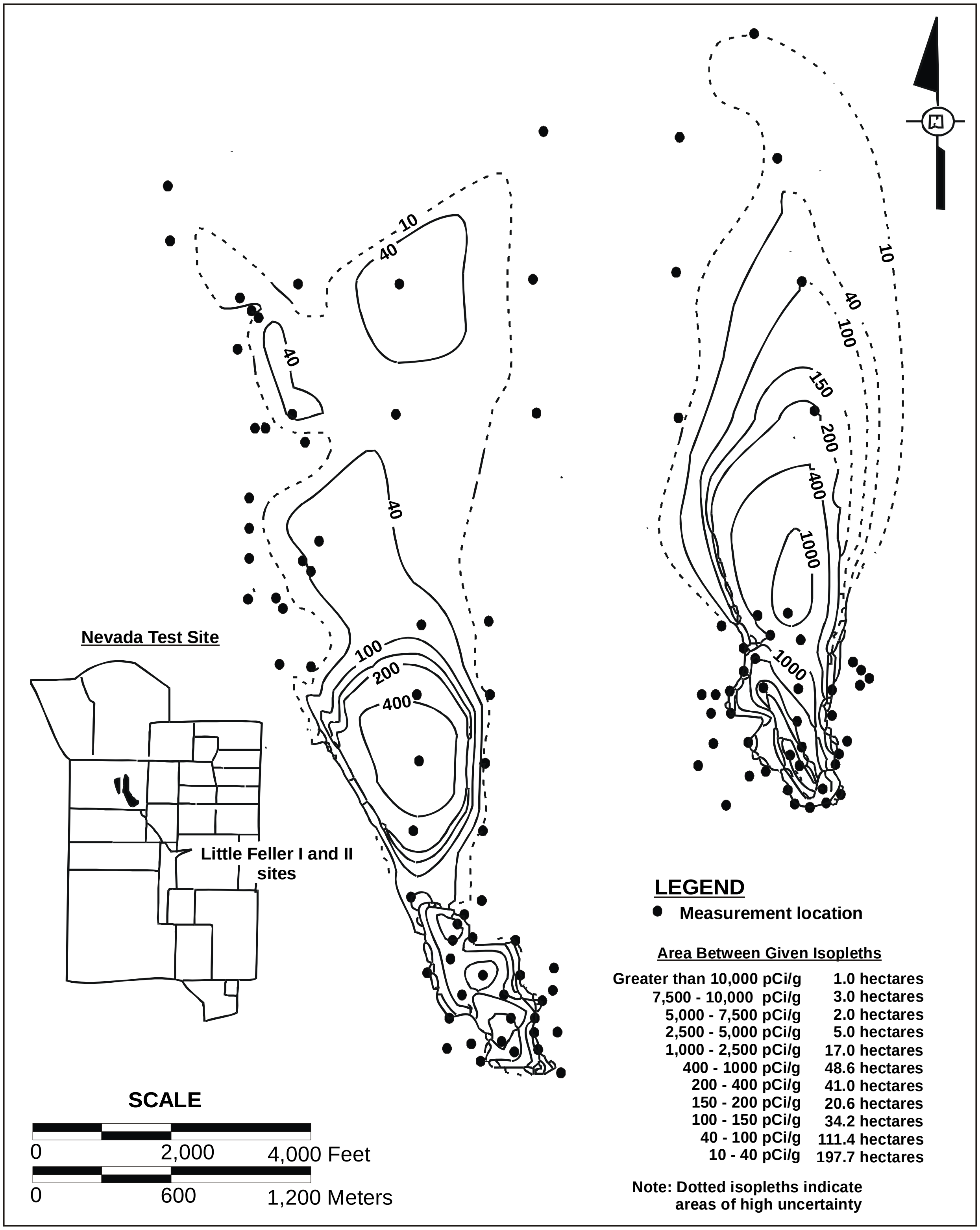

FIGURE D-3. Approximate Areas of Plutonium Contamination – Little Feller I and II Sites

TABLE D-1. Estimated Areas (in Hectares) Exceeding Specified Concentrations of Plutonium on the Nevada Test Site

Site	Pu Concentration (pCi/g)										
	>10,000	>7,500	>5,000	>2,500	>1,000	>400	>200	>150	>100	>40	>10
Yucca Flat	4	11	19	29	73	230	470	730	1,600	7,800	26,000
Schooner	0	0	0	0	0	0	0	8	35	77	230
Palanquin/Cabriolet	0	1	3	8	18	30	68	83	120	220	580
Little Feller I & II	1	4	6	11	28	77	120	140	170	280	480
Danny Boy	0	0	0	1	2	5	10	13	17	29	51
Buggy	0	0	0	<1	5	14	19	22	25	35	51
Plutonium Valley	0	0	0	<1	13	28	73	110	210	580	820
GMX	0	0	0	<1	1	2	3	4	6	16	82
Frenchman Flat	0	0	0	0	0	0	1	1	3	16	91
Total	5	16	28	49	140	400	760	1,100	2,200	9,100	28,000

TABLE D-2. Estimated Areas (in Hectares) Exceeding Specified Concentrations of Plutonium Near the Nevada Test Site

Site	Pu Concentration (pCi/g)										
	>10,000	>7,500	>5,000	>2,500	>1,000	>400	>200	>150	>100	>40	>10
Clean Slate 1	<1	<1	<1	<1	<1	<1	6	8	15	81	690
Clean Slate 2	<1	<1	<1	<1	4	17	26	39	77	170	280
Clean Slate 3	<1	<1	<1	<1	4	17	49	57	79	180	470
Double Tracks	<1	<1	<1	<1	1	1	3	4	7	8	11
Area 13	1	2	4	7	18	40	67	82	130	260	370
Smallboy Plume	0	0	0	0	12	130	400	670	940	2,100	6,200
TOTAL	1	2	4	7	39	200	550	860	1,200	2,800	8,000

TABLE D-3. Factors Used to Compute Optimistic and Pessimistic Bounds on Area Estimates

	pCi/g Range	Optimistic	Pessimistic
NTS Sites	>40	0.5	2
	10-40	0.5	5
Clean Slates	>40	0.5	2
	10-40	0.3	10
Double TracksArea 13	>40	0.3	3
	10-40	0.3	20
Small Boy Plume	>1,000	0.3	3
	400-1,000	0.4	2.5
	100-400	0.3	3
	40-100	0.4	2.5
	10-40	0.3	20

TABLE D-4. Estimated Areas Exceeding Specified Concentrations of Plutonium

Pu(pCi/g)	Area (hectares)		
	Optimistic	Realistic	Pessimistic
10,000	2	6	13
7,500	9	18	38
5,000	16	32	68
2,500	27	56	125
1,000	83	180	390
400	280	600	1,300
200	580	1,300	3,100
150	850	2,000	4,600
100	1,500	3,400	7,800
40	5,600	12,000	26,000
10	17,000	37,000	220,000

TABLE D-5. Values for Fixed Cost Components

Item	Optimistic Cost*	Realistic Cost*	Pessimistic Cost*
Processing Plants	0.72	2.33	7.50
Roads Connecting TTR and Area 12	33.48	44.27	62.27
Build Waste Disposal Site on TTR	6.44	8.58	14.30
Upgrade Roads on NTS	1.00	1.45	2.10
Mobilization/Demobilization	0.86	0.86	1.02
Survey Support	0.14	0.15	0.17
Clean-up	0.14	0.15	0.16
Ram Compactor	0.08	0.08	0.08

*In millions of dollars.

TABLE D-6. Summary of Areas Driven Cost Components[a]

Item	Optimistic Cost[b]	Realistic Cost[b]	Pessimistic Cost[b]
Survey and Certification, Pu > 35 pCi/g	1,134	1,297	1,698
Survey and Certification, 10 < Pu < 35 pCi/g	5,041	5,189	13,590
Revegetation[c]	15,000	30,000	40,000
Total. Pu > 35 pCi/g	16,134	31,297	41,698
Total. 10 < Pu < 35 pCi/g	20,041	35,189	53,590

a. As many significant digits as possible were carried throughout the calculations. It should not be inferred that all digits are meaningful.

b. Dollars per hectare.

c. See Appendix C of DOE/NV-399, for explanation of rounding.

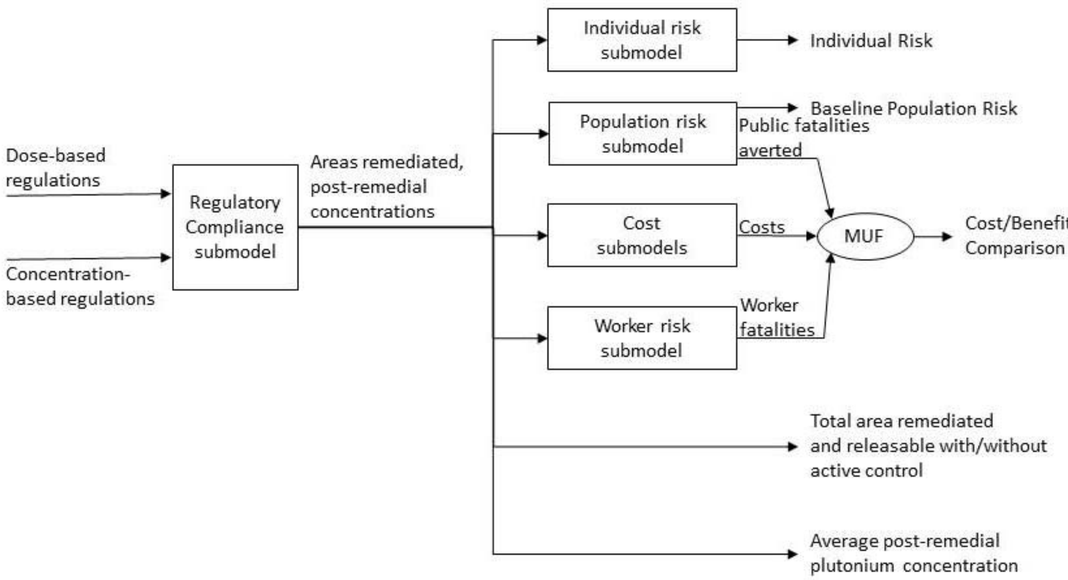

FIGURE D-4. The Integration Model Expressed in Flowchart Form

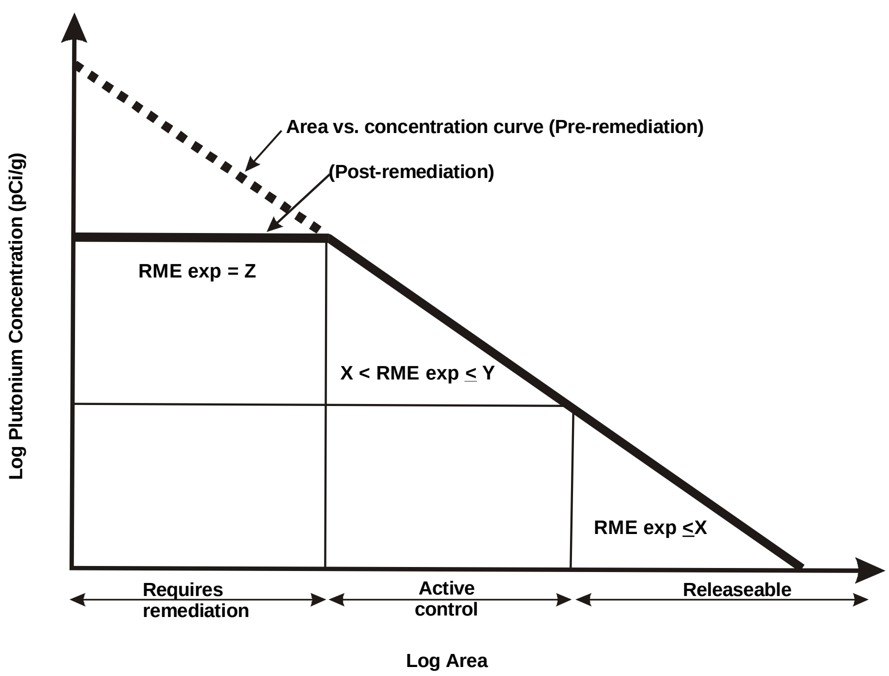

FIGURE D-5. The Inverse Area vs. Concentration and Minimal Remediation under the Two-Tiered Dose Limit

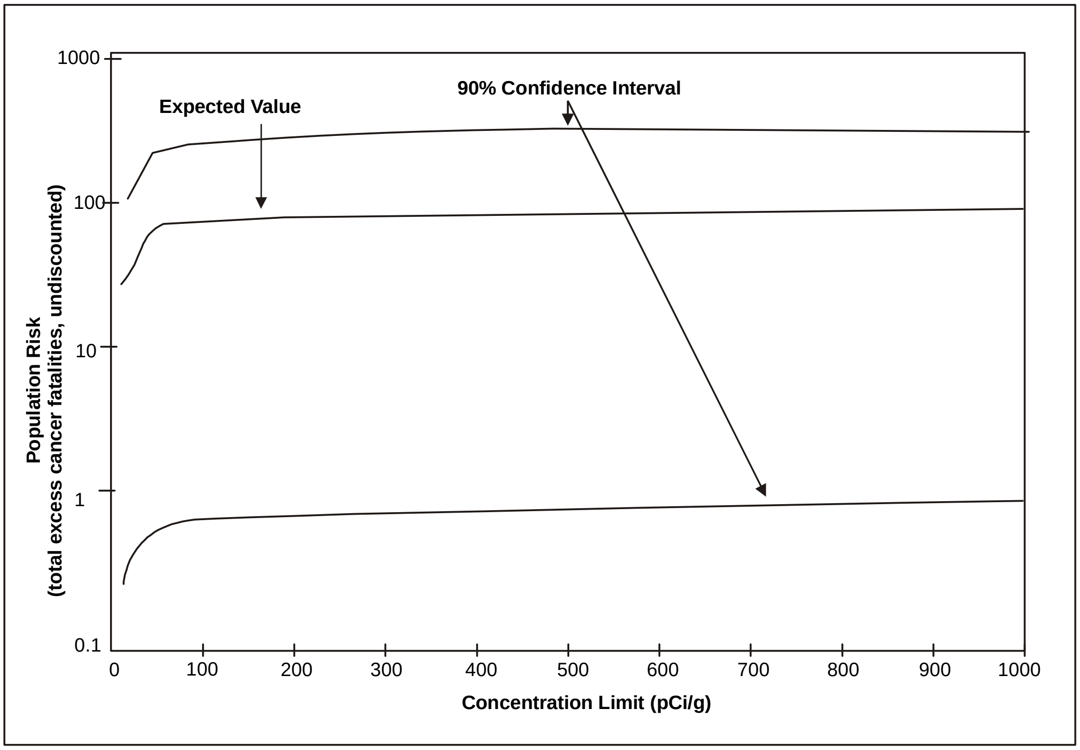

FIGURE D-6. Total Numbers of Excess Public Cancer Fatalities under Alternative Concentration-based Regulations

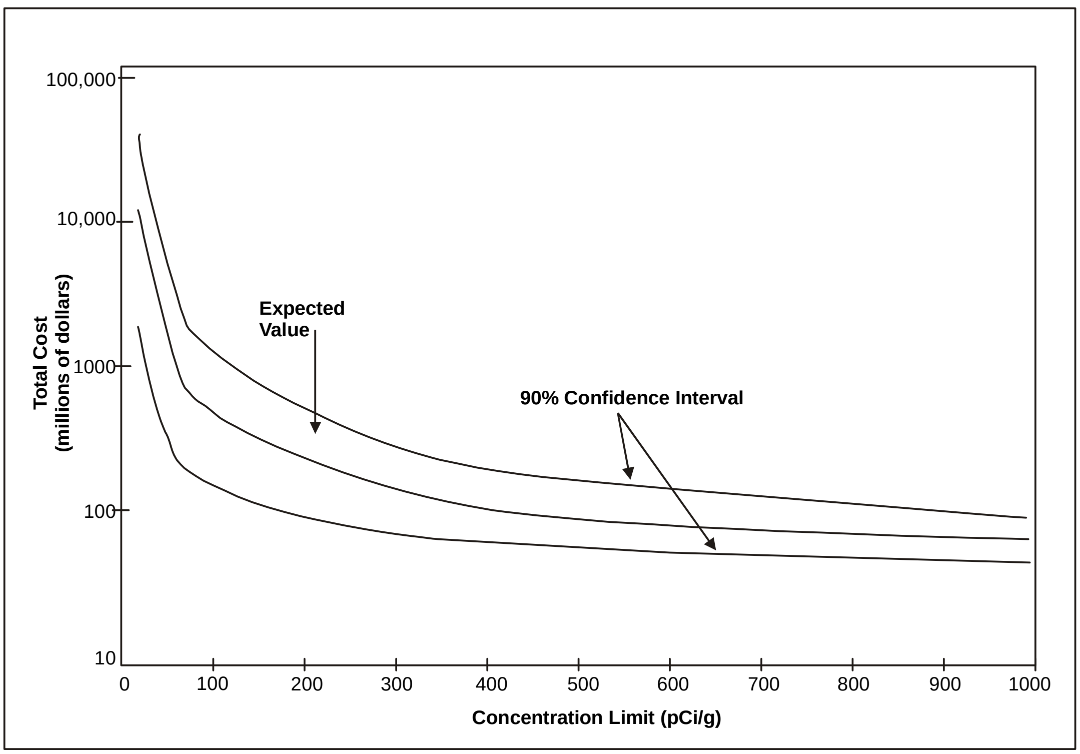

FIGURE D-7. Total Cost under Alternative Concentration-based Regulations if Disposal on Tonopah Test Range is Not Allowed

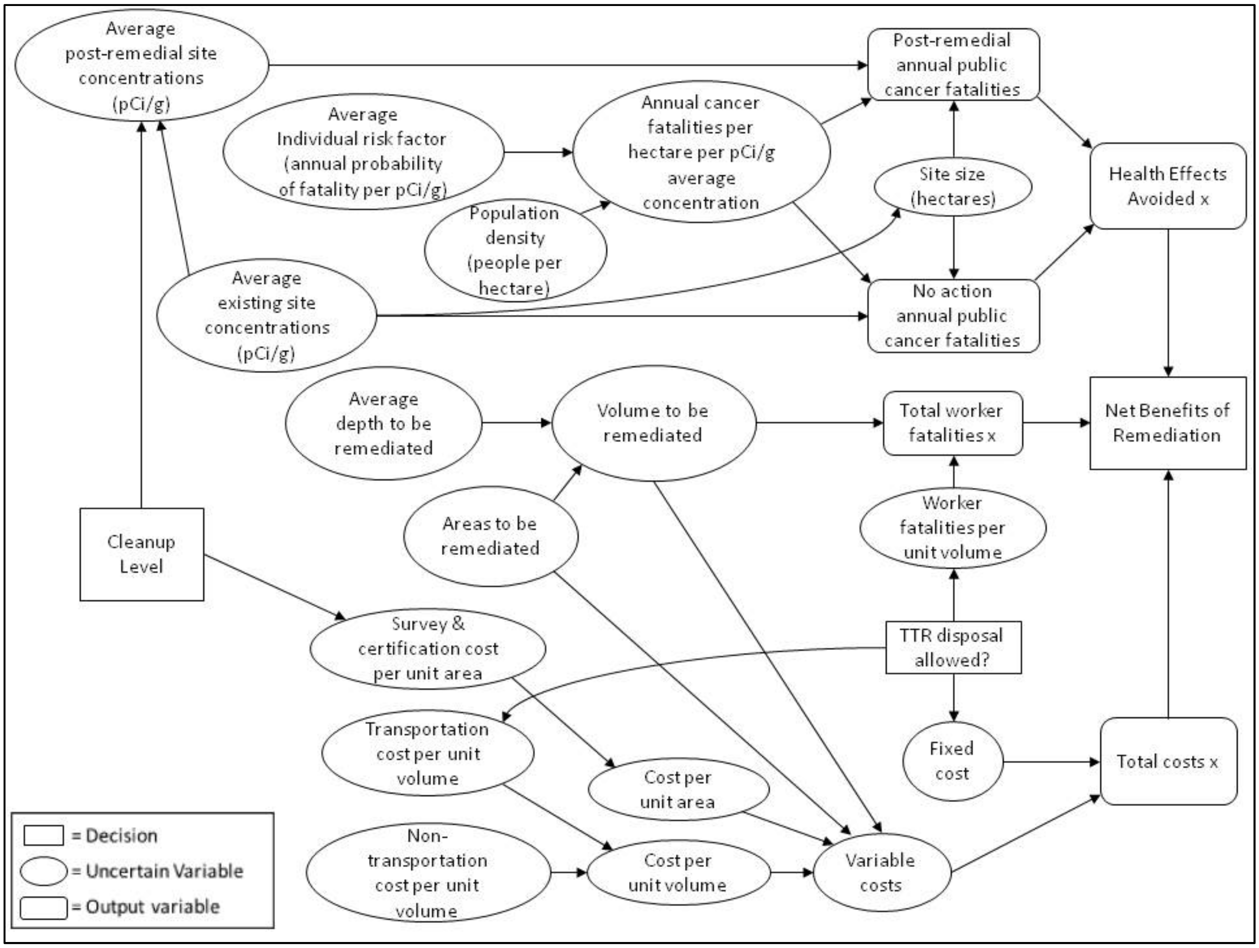

FIGURE D-8. The Integration Model Expressed as an Influence Diagram

TABLE D-7. Summary of Key Results

Expected Values	Dose-Based Regulations (without active control /with active control, mrem/yr)				
	1/5	**3/15**	**5/25**	**15/75**	**20/100**
Individual Risk - Nuclear	4.3 E-6	1.3 E-5	2.2 E-5	6.5 E-5	8.6 E-5
Individual Risk - Safety Test	3.5 E-6	1.1 E-5	1.8 E-5	5.3 E-5	7.1 E-5
Pre-Remed Population Risk - 1,000 years	2.9	2.9	2.9	2.9	2.9
Post-Remedial Population Risk - 1,000 years	1.8	2.2	2.3	2.6	2.6
Population Risk Reduction - 1,000 years	1.1	0.7	0.6	0.3	0.3
Total Cost (millions of dollars)[a]	$1,060	$282	$171	$82	$73
if TTR disposal allowed ($ millions)	$1,003	$240	$131	$44	$35
Worker Risk	0.86	0.19	0.097	0.0248	0.0179
if TTR disposal allowed	0.56	0.12	0.64	0.0166	0.0118
Area Releasable (hectares)[b]	13,813	71,724	80,929	87,711	88,282
Area Under Action Control (hectares)	67,116	15,987	7,765	1,772	1,214
Area Remediated (hectares)	8,831	2,048	1,065	276	197
Post Remedial Avg. Conc. (PCi/g)	23	29	31	35	36
	Concentration-Based Regulations (pCi/g)				
	10	**40**	**100**	**400**	**1000**
Individual Risk - Nuclear	7.6 E-7	3.1 E-6	7.6 E-6	3.1 E-5	7.6 E-5
Individual Risk - Safety Test	1.5 E-6	6.1 E-6	1.5 E-5	6.1 E-5	1.5 E-4
Pre-Remed. Population Risk - 1,000 years	2.9	2.9	2.9	2.9	2.9
Post-Remedial. Population Risk - 1,000 years	0.9	1.7	2.1	2.5	2.6
Population Risk Reduction - 1,000 years	2.0	1.2	0.8	0.4	0.3
Total Cost (millions of Dollars)	$10,543	$1,349	$417	$110	$70
if TTR disposal allowed $ millions)	$10,442	$1,303	$376	$72	$32
Worker Risk	8.2	0.93	0.25	0.040	0.0129
if TTR disposal allowed	7.1	0.80	0.21	0.033	0.0106
Area Remediated (hectares)	89,694	11,606	3,276	530	168
Post Remedial Av. Conc. (PCi/g)	10	21	27	33	36

a. Total cost under minimum remediation strategy (cleanup to higher close level in the two-tiered dose-based regulation)

b. Area releasable without active control is determined by the lower dose level in the two-tiered dose-based regulation. Expected total site area (area contaminated above 50 pCi/g) is 90,000 hectares.

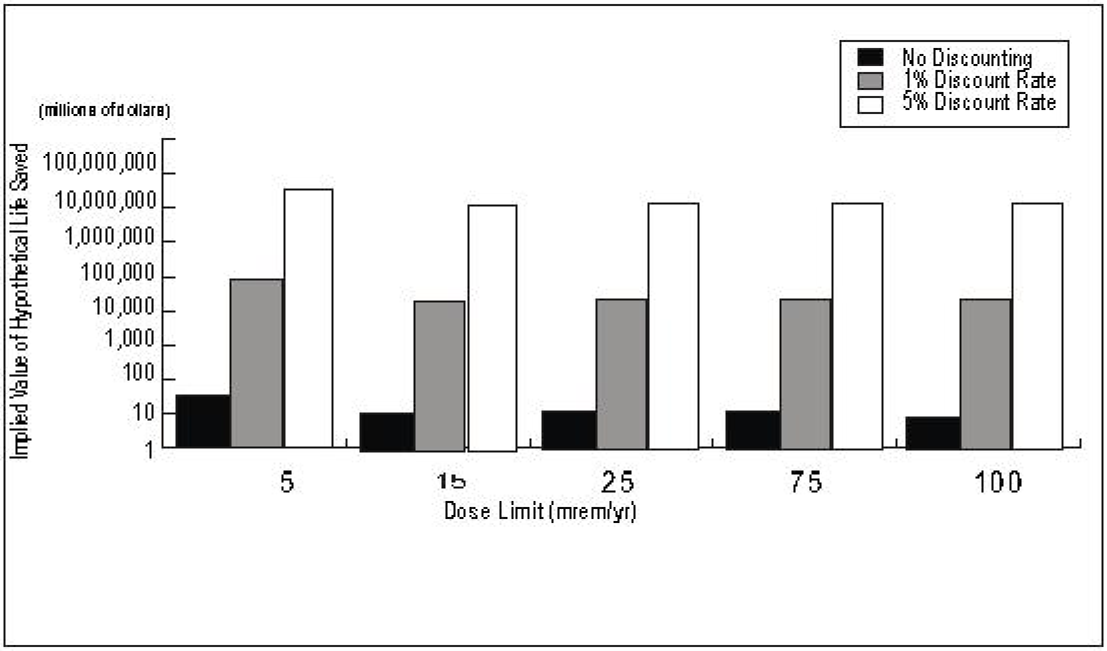

FIGURE D-9. Implied Value of Hypothetical Life Saved (Cancer Averted) Required to Justify Alternative Dose-based Regulations

References

DOE. 1995, Cost/Risk Benefit Analysis of Alternative Cleanup Requirements for Plutonium-Contaminated Soils on and Near the Nevada Test Site. DOE/NV-399, UC700.

APPENDIX E.

BNL's HAZARDOUS WASTE MANAGEMENT FACILITY (HWMF)

The following case study is a summary of a Brookhaven National Laboratory (BNL) Informal Report entitled *A Risk Assessment and Optimization (ALARA) Analysis for the Environmental Remediation of Brookhaven National Laboratory's Hazardous Waste Management Facility* (BNL-65339, March 1998).[30] This action provided a case study to demonstrate the value of the results of an ALARA analysis when making a decision on selecting the best remedial action.

Dose assessments were made for members of the public and workers to determine the risk to be averted from the remedial action using the risk based remediation goals of 1, 15, 25, 75, and the 100 mrem (0.01, 0.15, 0.25, 0.75 and 1.0 mSv) per year public dose limit. In addition, a risk optimization analysis was performed to determine the cost savings from the remedial action, the life cycle costs for the remedial action, the value of the net dose avoided, and the value of other avoided risks and damages.

Background

Extensive measurements of radiological contamination in soil and ground water were made at BNL's Hazardous Waste Management Facility (HWMF) as part of a CERCLA remediation process.

The HWMF is a fenced, 12-acre (4.8 ha) lot, located in the southeastern quadrant of the BNL site. The Army (Camp Upton) originally used this restricted-access area as a munitions storage area and livery stable during and after World War I. Since 1947, BNL has used this site as the central receiving facility for processing, limited treatment, and storage of hazardous and radioactive waste. BNL terminated operations in 1998 and a work plan was developed for decommissioning the facility and remediation of the environment.

A feasibility study was conducted in 1996 and a draft report prepared (CDM 1996b). The remedy selected was large-scale excavation with off-site disposal. This involved excavating 30,800 yd^3 (24,000 m^3) of soil to achieve the preliminary remediation goal of 67 pCi/g for Cs-137. This cleanup goal was based on a 15 mrem (0.15 mSv) per year dose goal using a commercial industrial scenario and 50 years of Federal control.

This ALARA or risk optimization analysis was undertaken in accordance with applicable requirements (DOE 1991b and EPA 1988b) and DOE guidance (DOE 1991a and 1997). It also was consistent, to the extent possible, with the relevant and appropriate requirements in 10 CFR Part 20, Subpart E.

[30] The report and its appendices contain the scenarios, assumptions, input parameters, calculations, spreadsheets, and computer printouts for the risk assessments and optimization analysis used in this study.

Soil Contamination and Future Land Use

Approximately one fourth of the 12-acre lot is paved or covered with temporary storage buildings. Approximately 5 acres of the surface is contaminated with mixed fission-products and activation products from previous site operations. About 8,000 to 78,000 cubic yards of soil predominately contaminated with Cs-137 and Sr-90 will require treatment or excavation/disposal depending on the derived concentration guideline levels (DCGL) that is selected. Other radionuclides that are present include H-3, Am-241, Pu-238/-239/-241, U-235/-238, Co-60, and Cu-242. None of these other isotopes were detected at concentrations that exceeded the DCGL for an undeveloped recreational area (undeveloped open-space scenario) during the remedial-investigation sampling program.

This parcel of property was designated for commercial/industrial use. Several public meetings were held to discuss various land-use options. It was agreed that when operations cease at BNL, the HWMF would be converted from commercial/industrial use to open space.

Cost Estimates for Large Scale Excavation and Disposal

The costs for implementing the remedial alternative, e.g., design and engineering, equipment procurement, fabrication, installation or construction labor, operation, maintenance, associated training and procedure, additional chemicals, additional consumables, special tools, additional radioactive waste, as well as the costs to decontaminate, decommission, dispose of, and then restore the environment during facility/system closure were also estimated. The periodic operating and maintenance expenses were included in this total and were converted to worth in 1997 dollars using a 3% discount rate (NRC, 1995). The present worth for long-term radiological environmental and ecological monitoring programs/reports, the CERCLA/RCRA post-closure monitoring program/reports, and HWMF site maintenance and security inspections was $457,640. Table E-1 lists the total cost to remediate to the various risk-base remediation goals/limit.

Results of Risk Assessments

Dose assessments were made for workers and the public to determine the risk to be averted from this proposed remedial action using the risk-based remediation goals of 1, 15, 25, 75, and the 100 mrem (0.01, 0.15, 0.25, 0.75 and 1.0 mSv) per year limit. These goals and limit translated into the DCGLs listed in Table E-2. These DCGLs were based on an undeveloped open-space scenario and 50 years of Federal control. The clean-up of soil to these DCGL levels required that the following soil volumes be excavated: 78,000 yd^3 (60,000 m^3); 26,000 yd^3 (20,000 m^3); 20,000 yd^3 (15,000 m^3); 9,000 yd^3 (7,000 m^3); and 8,000 (6,100 m^3) yd^3, respectively.

TABLE E-1. Cost to Remediate at Various Remediation Goals/Limit

Risk-Based Remediation Goals/Limit (mrem/yr)	Remediation Costs (1997 Dollars)
1	64,728,000
15	28,650,000
25	24,826,000
75	17,102,000

100	16,420,000

TABLE E-2. Derived Concentration Guideline Limits (DCGL) for the Undeveloped Open-Space Scenario after 50 Years of Federal Control

Risk-Based Remediation Goals/Limit (mrem/yr)	DCGL Cs-137 (pCi/g)	DCGL Sr-90 (pCi/g)
1	15	390
15	230	5,800
25	380	10,000
75	1,140	29,000
100	1,500	39,000

Radiological risk assessments were performed for the following:

- Present workers;
- Future members of the public;
- A basement resident assuming the failure of active controls; and
- A resident drinking ground water.

The estimated range of collective doses for present workers, over the remediation goal/limit range of 1 to 100 mrem (0.01 to 1.0 mSv) per year, is summarized below. The potential radiation doses to workers resulting from excavation and off-site disposal (collective dose impacts) would be extremely large in comparison to the potential radiation dose that would be saved by present workers as a result of remediation (collective dose savings).

- Worker collective dose savings from remediation: 4.1 to 3.8 person-rem
- Worker collective dose impacts from remediation: - 223 to - 212 person-rem
- Net collective dose to workers: -219 to -208 person-rem

The estimated range of collective doses for the future public, over the remediation goal/limit range of 1 to 100 mrem (0.01 to 1.0 mSv) per year, is summarized below. The potential radiation doses to the public resulting from excavation and off-site disposal (collective dose impacts) would be about three times greater than the potential radiation dose that would be avoided by remediation (net collective dose). The radiological impacts to the public from the remediation (dose impacts from remediation) would be comparable to the dose that would be saved (dose savings from remediation). Workers would receive about 100 times more collective dose than what would be averted to the public.

- Public collective dose savings from remediation: 8.5 to 8.1 person-rem
- Public collective dose impacts from remediation: - 6.7 to - 6.3 person-rem
- Net collective dose to public: 1.8 to 1.8 person-rem

Table E-3 summarizes the hypothetical fatalities for workers and public from radiological causes, as well as those that could result from construction and transportation at the various remediation goals. They show that the net risk of fatalities associated with remediation range from 15 in 100 to 9 in 100 for the remediation goal/limit of 1 and 100 mrem (0.01 to 1.0 mSv) per year, respectively. Therefore, the probability for a hypothetical fatality resulting from the remedial actions (0.09 to 0.15 hypothetical fatalities) is higher than that for the no-action alternative (0.0001 to 0.0043 hypothetical fatalities).

TABLE E-3. Estimated Hypothetical Fatalities Associated with Remediation

Risk-based Remediation Goals/Limit (mrem/yr)	Net Worker Radiation Fatalities	Net Public Radiation Fatalities	Worker Construction Fatalities	Transport Fatalities	Net Hypothetical Fatalities
1	0.0876	-0.00093	0.0040	0.0600	0.1506
15	0.0856	-0.00097	0.0010	0.0200	0.1056
25	0.0856	-0.00097	0.0010	0.0160	0.1016
75	0.0836	-0.00096	0.0005	0.0080	0.0912
100	0.0832	-0.00093	0.0004	0.0070	0.0897

Results of Optimization Analysis

A risk optimization analysis was performed to determine the cost savings from the remedial action, the life cycle costs for the remedial action, the value of the net dose avoided, and the value of other avoided risks and damages. The purpose of this was to select the optimum radionuclide concentration for the risk-based remediation goal. The risk-based remediation goals used to assess these costs and benefits were 1, 15, 25, 75, and the 100 mrem (0.01, 0.15, 0.25, 0.75 and 1.0 mSv) per year limit. The optimization (ALARA) analysis produced the following results for each: cost savings from the remediation; cost to remediate, package, ship, and dispose of the contaminated soil; value of the radiation dose averted to the workers, visitors, and public; value of other risks and damages avoided by remediation; net benefit analysis; and qualitative factor analysis.

The results for the net-benefit analysis using the 15 mrem (0.15 mSv) per year remediation goal were as follows:

- Cost of excavation and disposal $ - 28,650,000
- Benefits from reduced well sampling and potential real-estate sale $ 819,000
- Value of collective dose averted or expended (negative) $ - 424,000
- Value of avoided risks and damages $ 27,000
- Net Benefit or Cost (negative) $ - 28,227,000

Table E-4 lists the net benefits for the various remediation goals/limits. Based on risk avoidance and economic factors alone, it was concluded that none of these goals were reasonably achievable since no net benefit would be achieved below 100 mrem (1.0 mSv) per year.

TABLE E-4. Net Benefit at Various Remediation Goals/Limit

Risk-based Remediation Goals/Limit (mrem/yr)	Net Benefit/Cost (1997 Dollars)
1	- 64,486,000
15	- 28,227,000
25	- 24,386,000
75	- 16,618,000
100	- 15,930,000

However, compliance with the applicable Federal regulations and guidelines must be achieved. The DOE's public radiation dose limit in DOE Order 5400.5 (and now DOE O 458.1) of 100 mrem (1.0 mSv) per year must be met. Also, since the HWMF exceeded EPA's regulatory risk range in CERCLA (or Superfund Act) of 0.0001 to 0.000001, remediation must be performed. Therefore, whatever costs are needed to comply with these Federal rules must be expended. The decision makers need to decide what level below these regulatory levels is reasonable based on the net benefit and other factors.

Other factors considered for the selection of the optimal level for BNL's HWMF remediation included:

- Relocation of the habitat for an endangered species;
- Workers and community concerns;
- Public policy factors;
- Regulatory fines, enforcement actions and administrative orders; and
- Potential liabilities from civil suits.

Conclusions

The ALARA level selected for this analysis was the level at which the costs to remediate the area and the net fatalities begin to increase dramatically. This occurred at the 15 mrem (0.15 mSv) per year level for the soil concentration distribution at BNL's Hazardous Waste Management Facility; it corresponded to 230 pCi/g for Cs-137 assuming an open-space land use and the agreed-upon 50 years of Federal control at BNL. The preliminary remediation guideline that DOE proposed to State and Federal regulators was 67 pCi/g (Cs-137). This guideline was based on a commercial industrial land use and 50 years of control. Therefore, the 67 pCi/g preliminary remediation guideline for the HWMF was more protective for the hypothetical future user than the level derived using risk-based decision techniques.

Selecting a risk-based remediation goal just below the 100 mrem (1.0 mSv) per year limit involves cleaning up a relatively small volume of soil, while, at the same time, there is a relatively small chance for a fatality. As the soil-remediation goal was made more stringent i.e., decrease in the DCGL, the volume of soil to be removed increased rapidly, while the chance for a fatality being avoided decreased, or, in other words, the probability for a fatality increased rapidly. Since there is no clear optimum remediation level (differential cost to risk ratio of zero), the traditional optimum risk level cannot be defined. Instead, the optimum (ALARA) level will be defined as the value of the risk-based remediation goal where costs and the number of deaths caused by remediation begins to increase dramatically. This ALARA level also corresponds to the point where the volume of contaminated soil to be remediated begins to increase dramatically. The final remediation level selected by the decision-makers also would factor in some of the qualitative factors listed above.