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DOE STANDARD

APPLYING THE ALARA PROCESS FOR RADIATION PROTECTION OF THE PUBLIC AND ENVIRONMENTAL COMPLIANCE WITH 10 CFR PART 834 AND DOE 5400.5 ALARA PROGRAM REQUIREMENTS

-- VOLUME 2-- EXAMPLES AND CASE STUDIES

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BACKGROUND AND ILLUSTRATION OF ALARA PRINCIPLES

DOE Guidance on the Procedures in Applying the ALARA Process for Compliance with 10 CFR Part 834, Volume I, presents a discussion of the ALARA theory and the ALARA process by which the ALARA requirements of the rule may be achieved. Volume II provides some examples of how the theory and procedures have been applied in actual practices. The examples cover a broad spectrum of applications that also demonstrate the admonition that the technical effort should be commensurate with the potential impact on the public and workers.

Background

The admonition to keep exposures as low as is reasonably achievable (ALARA) has been the traditional position of the radiological protection community for several decades. The International Commission on Radiological Protection (ICRP) in Publication 26 (1977) recommended that ALARA be a formal procedure as part of a system of dose limitations which consisted of three parts:

(1) **Justification** No practice [causing exposures of persons to radiation] shall be adopted unless its introduction produces a positive net benefit (practices should not cause more harm than the do good);
(2) **Optimization** All exposures shall be kept as low as is reasonably achievable, economic and social factors being taken into account (practices should be implemented in a manner that is cost beneficial to society); and
(3) **Dose limits** The dose equivalent to individuals shall not exceed the limits recommended for the appropriate circumstances (individual equity: a practice that is beneficial to society should not disproportionately impact selected individuals).

The National Council on Radiation Protection and Measurements (NCRP) subsequently made similar recommendations. The ICRP system of dose limitations has been adopted almost universally and DOE has implemented the recommendations through Orders and regulations, e.g., DOE 5400.5, DOE 5480.11, 10 CFR Parts 834 and 835. The regulation 10 CFR Part 834, among other things, implements these ICRP/NCRP recommendations as applied to the general public and the environment.

In applying the 3 elements of the ICRP/NCRP radiation protection system, it may generally be assumed that an activity implemented by the Department has been reviewed by the appropriate government authorities and has been found to provide a net benefit, that is, the practice will do more good than harm. This is a finding of **justification** and is not be addressed further in this guidance. Exposures of individuals will be managed in a manner that will ensure compliance with the appropriate **dose limit** for all individuals, regardless of the cost for doing so. Identification and evaluations of alternative processes, radiation protection procedures, and other considerations are systematically brought together in applying the ALARA process to **optimize** radiological protection.

The records of ALARA process applications will provide proof of compliance with the ALARA requirements in 10 CFR Part 834 as well as providing a useful data base for cost, design, and performance information--particularly if follow-up data is added from operating experience. Such data is valuable to others with similar applications and should be shared among DOE contractors.

To assist in the practical application of the ALARA process, a number of example ALARA assessments are developed or reported in this appendix. The first example included in this section present a simple hypothetical situation that illustrates the classical evaluations that accompany an ALARA analysis. The remainder of the examples are derived from actual ALARA reviews. The summaries included and case studies presented should not necessarily be considered templets for ALARA analyses and documentation but are provided to DOE field and 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, some of these analyses may be too detailed and for others insufficient.

Example of ALARA Application

Input Data

The basic elements of optimization for radiation protection are demonstrated by the following example. 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 several other alternative processes that also could accomplish the same production goal, but each will have a different cost and each will result in different exposure conditions. The objective is to select the particular system from the several candidates systems that will maximize the benefits and minimize the costs. Consider the data in **Table 1**. **Tables and Figures are located at the end of each Section of text.**

Identity of the Optimum

As may be seen from the total cost column, the least cost is achieved by using system number 3. In this example, wherein the value of þ is assumed to be $2,000/person-rem, the same system (No. 3) would still be the optimum choice if the assumed value of þ were $1,000 or $3,000/person-rem. This demonstrates that the assumed value for þ generally is not a very sensitive parameter and the selection is quite definitive.

Graphical Illustration

This example of optimization is illustrated in the graphic presentation of the information on system performance in **Figure 1**. The cost (Y) and performance of each of five candidate systems is shown as ovals. The cost, in dollars, is on the y-axis and the performance, in person-rem, is on the x-axis. The data for each of the systems should be placed on linear graph paper to avoid distortion. 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 2**.

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

The value of þ, 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 þ is discussed in Section E.3.) The straight line with a slope of þ 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, þ, is taken to be $2,000/person-rem. In **Figure 3**, the ovals are the data points for each of the optional systems, their locations determined by the cost and collective dose of each system, the rectangles are 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, has the minimum cost for the optional systems that were evaluated.

The same data for the system costs and collective dose are presented in **Figure 4**. A straight-line with a slope -þ has been drawn near the origin. While retaining the slope þ, if the line (with slope -þ) 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 system No. 3. In **Figure 5**, two other lines are shown intersecting the same point, one with a slope of þ = $1,000/person-rem and the other with a slope þ = $3,000/person-rem. This illustrates the fact that the selection of the optimum generally is not very sensitive to the assumed value of þ, in this case an indication of the robustness in the selection process.

Notice that the dose (S) in the figures is **collective** dose. The primary dose limit for an individual is 100 mrem 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 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 maximally exposed individual 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 maximally exposed individual 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 are generally based on analytical modes derived from limited measurements under specific parametric conditions. Referring again to the figure, in practice, 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 2**.) The same principles apply to these data as described in the first example. 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 must also be considered.

Other Considerations

Clearly, the many factors and considerations entering the ß-factors in the equation may defy quantitative evaluation. Techniques other than quantitative cost-benefit analysis are generally 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. (These factors are discussed in Sections E.) Optimization means determining the alternative that has the minimum total cost (where costs is a measure of all negative factors or attributes considered). This also infers 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 following sections provide some examples of ALARA Process applications: recycle; rulemaking; and remediation decisions.

TABLE 1 Cost and Collective Dose Data for Illustration of Alara Principles.

Options System No.	System Cost, $	Collective Dose, S (person-rem)	H-Detriment Cost, þ S $	Total Cost* $
1	80,000	250	500,000	580,000
2	120,000	60	120,000	240,000
3	160,000	15	30,000	190,000
4	200,000	4	8,000	208,000
5	240,000	1	2,000	242,000

* In this example, the cost and collective dose 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.

Figure 1 Graphical Illustration of the Data Demonstrating ALARA Process. Cost and Performance of Control Options.

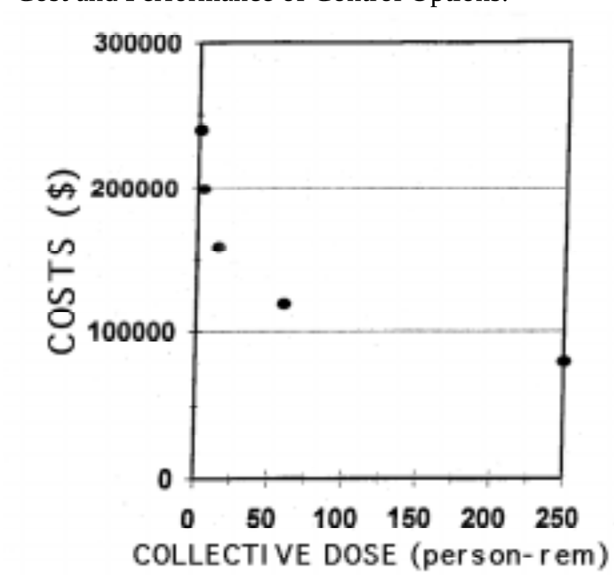


Figure 2 Illustration of Cost and Collective Dose for a Variety of Candidate Systems.

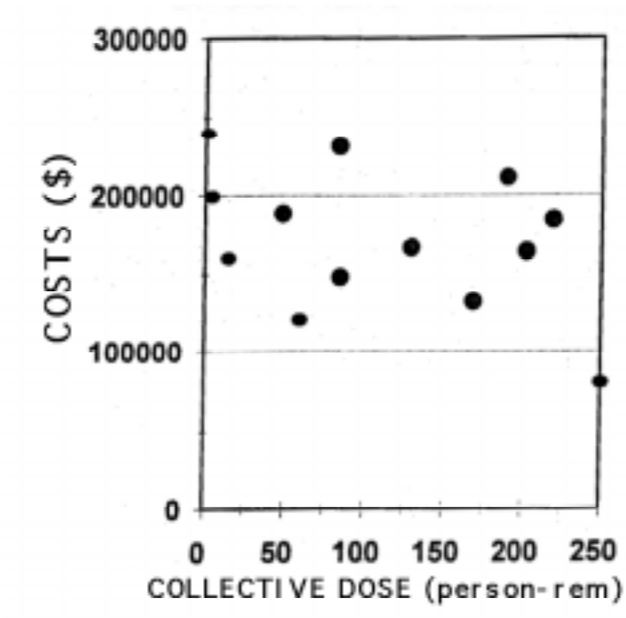


Figure 3 System and Total Cost for Candidate Systems with þ = $2,000

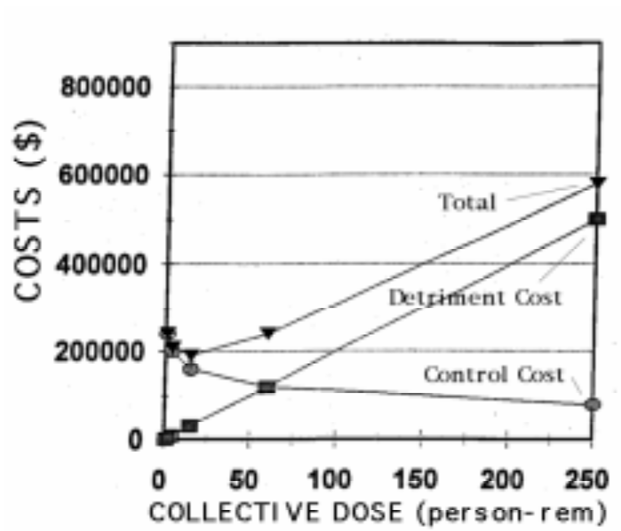


Figure 4 Graphical Method for Selection of Optimum System

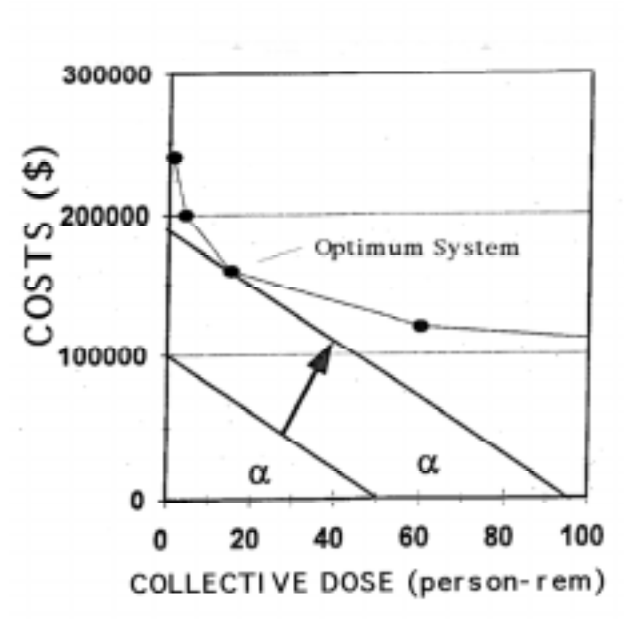
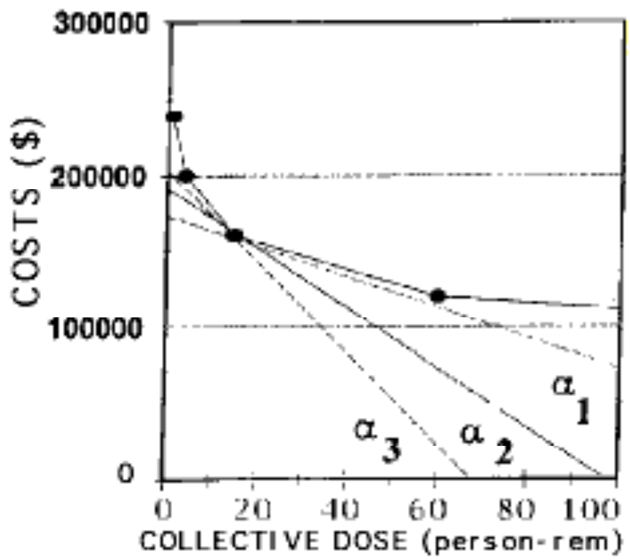


Figure 5 Illustration of the Effects of Three Values of þ on Optimization



A. RECYCLE APPLICATIONS

1. Recycle of Copper

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

This action was supported by an environmental assessment (EA). The data in the ALARA summary was 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 and the most highly contaminated portions were removed and disposed 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 the recycle of the copper. Had the more highly contaminated copper not been already disposed, 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 the following 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 deciding on a course of action and illustrates the principle that the ALARA effort should be commensurate with the potential detriment associated with of the activity.

<u>Background</u>

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 outdoor 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 Department of Health has approved burial of the copper as ordinary waste, without regard 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 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.

Contaminants

The high-purity (99.99%) copper has an average activity, principally 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 in 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 at 1 ft from the source would be about 5.5 mrem/hr. About 1.5 pCi/g of Ni-63 (half-life 92 years, beta emitter) is also present, but it is of little radiological importance.

Proposed Action and Alternatives

The laboratory proposed to recycle the copper by selling it to a local scrap metal dealer. Several local dealers are interested and the nearest is located within 10 miles of the warehouse. 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 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 [China is 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 is 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].

Radiological Impact

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 population dose of 0.072 person-rem was estimated from the reuse of the copper as jewelry. An additional 0.000003 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 0.00004 given the exposed population. This is essentially zero cancers (no chance of an additional fatal cancer) and in any case, is insignificant considering that the normal incidence of cancer among individuals in the United Sates is about 1 cancer per 3 persons, about half of the cancers are fatal.

Radiation workers

Transporting and recycling the copper were estimated to cause a collective doses of 0.0004 and 0.04 person-mrem, respectively, to workers. Potential fatal cancers would be 2×10^{-10} and 2×10^{-8}, respectively. Workers in the warehouse, for the storage option, would receive 0.0001 person-rem, with an associated fatal cancer incidence of 6×10^{-8}.

Dose and Cost/Benefit Summary

A summary of the cost and doses for the alternative copper disposal actions are presented in the **Table 3-1**. The collective dose is so small that the choice of alternatives would not change if $10,000 per person-rem were to be assumed (as was the case in the actual EA). This value is slightly higher than the DOE suggested range for þ ($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.

Other Considerations

Additional benefits of the proposed recycling action would include:

1. 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;

2. Valuable, and expensive, low-level radioactive waste burial space for material that is actually classified as radioactive waste would be preserved;

3. Valuable sanitary landfill space would be preserved;

4. Currently used storage space would be released;

5. Compliance with the DOE waste minimization and pollution prevention policy would be achieved; and

6. 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 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 radioactive material in the subject material are too low to be of any concern. Furthermore, the relatively short half-life of Co-60 (5.2 years) ensures that there is no concern for buildup of this material in the metals pool.

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 "additional benefits," listed above. 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 3-1 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
Recycle @ SEG	a	0.14	323	323
Sale/gift-foreign	a	0.047	30	30
Disp./ Hanford	3 x 10^{-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 value of þ = $2,000/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.

2. Recycle of High Explosives

This example discusses the ALARA analysis supporting the establishment of authorized limits to recycle high explosives containing residual tritium. An ALARA assessment should normally 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 determine 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.

Background

The primary mission of 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 main-charges. 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 on site by regulated open burning/open detonation. The recycled HE would be sold to industrial users in the mining industry. Consideration was given to recycling into the (public) market about 50,000 pounds of high explosives (HE) per year for several years. The recycled HE was estimated worth about $15 per pound in the open market.

Alternatives Considered

Two options were considered for the disposition of high explosive (HE) main-charges. The current method used involved removing the HE part and treating the HE through open burning/open detonation 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.

OPEN BURNING/OPEN DETONATION

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 "Burning Ground" is being 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 (NO_x), fluorides (F^{-1}), chlorides (Cl^{-1}), and airborne tritium in the form of HTO. All releases of CO, CO_2, NO_x, 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 Title 40 Code of Federal Regulations (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 of by OB/OD during 1993.

It was estimated that this practice resulted in a maximum individual dose of 6×10^{-5} mrem in a year. Collective doses were projected to be less than 1×10^{-4} person-rem in a year.

RECYCLING OPTION

The second alternative was to dispose of all HE below a specified bulk tritium contamination of 2×10^{-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 4×10^{-5} mrem in a year and to members of the public on the order of 5×10^{-5} mrem in a year. Collective doses were estimated to be about 1.5×10^{-6} person-rem in a year.

<u>Analysis</u>

The final dose analysis supporting this ALARA analysis examined 2 scenarios: (1) worst-case and (2) realistic case. Both cases representative conservative assessments of the potential exposures but the assumptions used in the "realistic case" were less conservative. It is necessary for dose assessments supporting ALARA evaluations to be as realistic as possible (without substantially under estimating 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 general 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), one cannot justify committing more than about $1 to $7 per year for dose reduction (i.e., reducing dose to zero), based on health risk considerations.

Because all projected doses are extremely low and although the propose action indicated slightly lower collective doses, the details of the dose estimates are moot in this specific application and the decision was made primarily based on economic benefits. The highest dose to an individual is about 0.005 person-rem per year and the collective dose to workers and the public was estimated to be 1.5 x 10^{-6} person-rem per year for the recycle case. The present disposal method is estimated to result in a collective dose of 0.0001 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 to alternative disposal methods, given the low doses associated with the action, these need not be addressed in the quantitative assessment. Normally 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 significantly effect doses. 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.

B. OPTIMIZATION OF THE DESIGN OF LWR-RADWASTE TREATMENT SYSTEMS BY COST-BENEFIT ANALYSIS

This example of an ALARA application is quite comprehensive because it applied to a rulemaking wherein 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. There was very little information available on the cost and operational data from the operation of LWR rad-waste systems. The specific cost and equipment data may not be not current, but the methods are still valid. They are presented here to provide a procedure and workable format for contemporary applications.

It is also noted that because this case study is based on a 1972 analysis, doses are presented in terms of dose equivalent rather than total effective dose equivalent(TEDE). The case study was presented in this manner because of the difficulty in converting the older data to TEDE. Current analyses would in most cases use TEDE not dose equivalent.

Background

In 1971, the Atomic Energy Commission (AEC) published for comment "Proposed Numerical Guides for Design Objectives and Limiting Conditions for Operation to Meet the Criterion 'As Low As Practicable[1]' 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

1 The phrase "A Low As Practicable" (ALAP), as used in the early 70's, is identical in meaning to the phrase "As Low As [is] Reasonably Achievable" (ALARA), that is commonly used today.

operation of LWRs by which licensees could demonstrate compliance with the requirement in 10 CFR Part 50 that releases of radioactive material in effluents from those facilities be "as low as practicable." This requirement had been added as a revision to 10 CFR Part 50 in December 1970. The proposed guides were subject of a rule making (Docket No. RM-50-2) which was one of the first to be subject to 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 February 20, 1974. 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 maximally exposed individual would be unlikely to receive more than 5 mrem in a year during normal operation. The determination of practicability was based on estimated performance and a cost-benefit analyses of several candidate radwaste system designs.

The following example of a quantitative cost-benefit analyses is based on the information developed for that rule making. While some of the specific parametric values selected for the study might be changed if the study were to be repeated today, the principles of the application remain valid. The evaluation would now be termed an "optimization" analysis. **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 rule making 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 data base 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 rule making application was very similar to that described in the text of this guidance for applying the ALARA process. All proposed and licensed light-water cooled nuclear power reactors (LWR), comprised of boiling-water reactors (BWR) and pressurized-water reactors (PWR), and their sites were used to obtain a data base 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[2] at the minimum total cost; and

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2 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

(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 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 order to simplify this example in some detail.

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 (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 2 reactors. A computer code was developed to calculate the source terms in effluents using appropriate parametric values.

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

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general public. The effective dose equivalent (EDE) 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 for this study might be somewhat higher or lower for a variety of reasons. Doses would be expressed in terms of EDE. The cost also would be greater than those presented here.

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, that 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.

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. Figure B-3 presents a summary of liquid radwaste treatment systems for L-1 through L-4 to illustrate the type of variations evaluated. **Figure B-4** 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 current (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.

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 **Figure B-5**.

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 **Figures B-6 and B-7** 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-8 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). The 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 sites out to 5 miles is presented in **Figure B-9**, and between 5 and 50 miles is presented in **Figure B-10**.

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.

Dispersion in each of the waterways (river, lake, and ocean) were also 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. **Figure B-11** 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. **Figure B-12** presents the pathway parameters used to calculate the doses from liquid effluent at a typical river site. **Figure B-13** presents additional parameters used in pathway evaluations. The potential doses to the thyroid was of special interest in the study and **Figure B-14** presents the parameters used to calculate the thyroid doses from inhalation and ingestion.

"KRONIC," a computer program, was used to calculate annual average doses[3] 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;
the release path phenomena from fuel to atmosphere;
the climatology for the site;
the time-dependance of fission product concentrations;
the energy and number of photons and beta particles emitted from the nuclides; and
the 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 **Figures B-15 and B-16**, respectively. Estimated thyroid doses from gaseous effluent are presented in **Figure B-17**. The estimated potential doses to maximally exposed individuals is 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

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3 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.

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.

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.

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. **Figure B-18** 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) must also be included. The basis for the fixed cost for each of the PWR cases are presented in **Figure B-19**.

1. Liquid Radwaste Treatment Systems

Flow sheets were used to identify the kind and quantity of all components for each option. **Figure B-20** is a schematic flow sheet for Pressurized Water Reactor 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-4**. 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 have been replaced by subsystems from PWR Case 3. This results 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).

Note, in **Figure B-20**, that for each equipment item there is an identification number and the number of units in the system. **Figure B-21** 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. **<u>Figure B-22</u>** presents the detailed cost summary, identifying the equipment, labor, material, and total direct cost for L-2. **<u>Figure B-23</u>** 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, **<u>Figure B-24</u>** is a supplemental cost sheet used to estimate the installed cost for tanks of various size. Supplemental sheets detailing radwaste treatment subsystems and their cost were similarly developed. **<u>Figures B-25 and B-26</u>** 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, **<u>Figure B-27</u>** indicates the estimated number of drums of solid wastes annually from the systems L-1 through L-4.

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). **<u>Figure B-28</u>** presents 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.

<u>Discussion of PWR Liquid Radwaste Systems</u>

Data from the final environmental impact statement (FES) concerning PWR liquid radwaste systems and data for two additional alternate PWR liquid radwaste systems derived from information in the FES are presented in Figure B-29. 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 that 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 that 5 millirem at all site regimes considered.

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 FES. These subsystems shown in Figure B-28. All are defined in detail in the FES 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 Figure B-28A but at somewhat lower costs. These three additional liquid radwaste systems are described in Figure B-28B.

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 population doses from PWR stations with PWR Case a liquid radwaste systems and calculated to be 62 person-rem at a river site for the normalized annual release of 10 curies.

2. 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.

3. PWR Case C uses treatment equipment similar to a PWR Case A system, but the subsystems provided to treat the dirty waste has been replace 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 population doses were calculated in the same manner as described above for the PWR Case A liquid radwaste systems. Figure B-30 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 population 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 refer, 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 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 Figure B-30.

From Figures B-29 and B-30, 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 Paragraph a.1 of Section II of 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 Paragraph A.1 of Appendix I. This system has a calculated annual cost of $541,000, and the costs per person-rem of population 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 if 4.6 millirem. Annual doses to individuals near sites with more than two reactors were not specifically considered in the FES. While it is not expected that doses will be linearly related to the number of reactors at a site, 1\ 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 provide reasonable assurance of meeting design objective values. The calculated annual cost of a PWR Case 4 liquid radwaste system if $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 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.

2. 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 criteria is selected. For example, **Figure B-31** 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. **Figure B-32** summarizes 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 EDE had been used, rather than dose equivalent, there would be much less premium placed on radioiodine removal.

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 Figure B-33. The number of reactors which 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. Table N gives a brief description of each of the subsystems for each of the PWR gaseous release Cases considered in the FES, 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 Figure B-31A, are shown in Figure B-31B. 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 FES cost analysis indicated that the primary as holdup system used the PWR Case 6 had equivalent holdup performance and was slightly less costly; however, because such a system is 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.

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:

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. [An asterisk (*) after a PWR Case number indicated a radwaste system with 100-meter stack for all effluent.] 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.

2. 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.

3. 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) 1\ 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.

4. 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.

5. 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.

6. 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 population 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 $1000 per person-rem. For a cost parameter of $1500 per person-rem, the lowest total annual costs occur with the use of the 45-day holdup system. Figure B-33 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 2000 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 Figure B-32. The Cases are arranged in order of increasing annual cost and decreasing iodine release quantities. The lowest total annual cost 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 $1000 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 at distances of 500 meters or greater. PWR stations with Case E systems appear capable of meeting this guidance for a distance of 2000 meters, and Case F systems appear capable of meeting this guidance for a distance of 2000 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 Figures B-32 and B-33 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 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 (2400 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 <u>assumed</u> 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 applications, 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.[4] 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 US. A value of $1,000 per person rem was used in the cited AEC rule making 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. Presently , as noted elsewhere, the NRC recommends $2000 per person-rem while DOE recommends a range from $1000 to $6000 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 must be quantified rather arbitrarily. Optimization is the identification of the optional system, selected from several, that provides an acceptable dose to the maximally exposed individual and results in the minimum total annual cost.

Evaluation

The basic information important to the analysis is summarized in tabular form in **Figures B-29 and -32** 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 table presents 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 34 and 35** 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.

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[4] 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.

The total annual costs, including a range of monetary values assumed for a unit of collective, were evaluated for selected Cases. The results are presented in **Figures B-30 and B-33** for liquid and gaseous treatment systems, respectively. As may be seen in these figures, the results are not a sensitive to the assumed monetary value per unit of collective dose. This appears to be the case, generally, 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 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 combine 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-1

FIGURES FOR APENDIX B ONLY IN HARD COPY VERSION.

Figure B-2 MAJOR PARAMETERS EVALUATED FOR SOURCE TERM ESTIMATES FROM LWR STATIONS

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.

C. REMEDIATION OF THE WELDON SPRING CHEMICAL PLANT AND SELECTION OF TREATMENT METHOD FOR THE CONTAMINATED (QUARRY) WASTE WATER.

In the following example of an ALARA application an attempt has been made to summarized the effort to remediate the Weldon Spring facility. The implementation of the ALARA requirements (of Order DOE 5400.5, in this case) 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 of interest for several reasons:

1. It is an application where a large site complex is being remediated;
2. 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.
3. The bulk of the waste is associated with other media, principally the raffinate pit sludge, structural debris, and waste from the quarry.
4. 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.)
5. The site contains a variety of structures and several contaminants; and
6. It 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.
7. The project was conducted consistent and in compliance with DOE requirements but is being planned and implemented under CERCLA regulations.
8. The potential risks from residual contamination relate to both chemicals and radionuclides and as a result risks as well as dose were considered in comparison of alternatives.

The derived limits selected for Weldon Spring as a result of the ALARA process application are also presented in less detail, for comparative purposes, in **Section E** which discusses ALARA derived cleanup standards at several remote DOE sites.

Background

In 1941, the US Army acquired about 17,000 acres of land 48-km west of St Louis, Mo. to construct the Weldon Spring Ordinance Works for the manufacture of explosives. The location of the Weldon Spring site is shown in **Figure C-1**. 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 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 (that are 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 3.2 km east of the site with a combined population of about 850. St. Charles, about 24 km NE, has a population of about 50,000. There are about 10,700 persons living within 5 km of the site and less than 3,000,000 persons within 80 km.

The Weldon Spring site, a former uranium and thorium processing facility, is being cleaned in compliance with the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and the National Environmental Policy Act (NEPA).

<u>Contaminants</u>

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 a 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.)

1. Remediation

<u>Objectives</u>

The overall objectives of the remedial action at the Weldon Spring site was to: 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; implement the actions in a manner that will ensure compliance with applicable environmental requirements; and release, to the extent practicable, at least a portion of the property for unrestricted use. Initially, four determinations were needed:

(1) the selection of residual or "cleanup" levels for soil and other solid debris;
(2) the selection of methods for collecting and disposing of the solid material contaminated above the cleanup level;
(3) the selection of methods for removing, treating, and disposing of contaminated water impounded at the quarry and chemical plant areas; and
(4) choosing between discharging the quarry water to the Missouri River via the Femme Osage Creek or via a pipe that would by-pass the creek.

Doses and Risks

EPA (EPA/520/1-89-005) selected a risk coefficient of 600 cancer induction effects per 1 million person-rem (6×10^{-7} per person-mrem[5]) and a risk factor of 260 per 1 million person-rem for genetic effects. The EPA risk factor was used for deriving soil clean-up levels. All doses from intakes of radionuclides are 50-year committed dose equivalent and all doses are 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 are 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--that was incorporated in Order DOE 5400.5--was adopted. Cleanup criteria for soil (including sludge) was developed independently.

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[5] 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, difference 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 DOE RESRAD computer code for assessing the impacts of residual radioactive material in soil also includes a option to compute individual risk as well as dose. RESRAD calculations are consistent with the EPA methodology.

In order to implement the Uranium Mill Tailings Radiation Control Act (UMTRCA) and the National Oil and Hazardous Substances Pollution Contingency Plan (NCP), EPA has promulgated 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. Order DOE 5400.5 requires use of the ALARA process to consider reducing potential doses below the applicable standards. Ra-226 and its daughters is the contaminant of primary importance because it contributes 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 (chemicals that are generated by man that do not occur in nature) and, thus, truly constituting 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 10^{-4} (incremental lifetime risk for exposure from a given site) and the bottom of the range, referred to as the "point of departure," is 1×10^{-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 1989). 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 (EPA) program was used to evaluate population 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 (10^{-6} to 10^{-4}) was used to select clean-up levels for the contaminated soil. Interim cleanup levels from the NRC decommissioning guidance and Order DOE 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 below (see Section 2, Potential Exposures). The potential risk 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.

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 1×10^{-6} to 9×10^{-2}, with a median of 2×10^{-4}--largely due 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 3×10^{-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 1×10^{-4} cannot be met for Ra and Rn, and the issue is to select cleanup levels based on other considerations. The lowest level that Ra-226 in soil could reasonably be measured in the field is 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 is 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 1 ft of soil is presented in **Figure C-4**. 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 then 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 (EPA) 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--within the 100 mrem-annual dose limit for members of the general public, but slightly above the 30 mrem 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 in a year without taking credit for clean cover material. This value was applied to Ra and Th, 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 in a year without considering clean cover or less than 2 mrem 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 1 person-rem over 200 years.

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.

Tables C-3 and 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: a recreational visitor; a ranger; and a resident. Note that the risks (and, assuming the risk coefficient of 6×10^{-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 "Potential Exposures," below.

Selection of Treatment

Having selected the soil cleanup levels, the decision must 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 7 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 (EPA):

1. Overall protection of human health and the environment;
2. Compliance with ARARs;
3. Long term effectiveness and performance;
4. Reduction of contaminant toxicity, mobility, or volume through treatment;
5. Short-term effectiveness;
6. Implementability;
7. Cost;
8. State acceptance; and
9. Community acceptance.

The final alternatives that were 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 Evirocare facility (Utah); and

Alternative No.5 removal, vitrification, and disposal at the Hanford (Washington) facility.

The "no-action" alternative assumes:

1. the bulk waste excavated from the quarry would be in short-term storage;
2. the water treatment plants at the quarry and the chemical plant area would be operational;
3. the building and other structures would be dismantled and the resulting material would be in short term storage; and
4. 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 are 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 cost of the other alternatives are presented in **Table C-6**.

<u>Potential Exposures</u>:

The hypothetical receptors (exposure location, mode, time, frequency, and duration) were identified to characterize potential individual doses. These are presented in **Table C-5**. 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 are 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. Owing to the small fraction of total wildlife area occupied by the Chemical Plant (about 0.015), and only about 20% of the site surface soil is sufficiently contaminated to require remediation, that is, >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.

The potential doses to hypothetical receptors at various locations and from various pathways are presented in **Tables C-7 and C-8**, respectively. Recall that the each type of receptor is assumed to be subjected to typical exposure conditions. Individual, but not collective, doses were also 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. And 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.

These collective doses could be much too high if they are based on the dose estimates for the maximally exposed individuals 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 6×10^{-7} x risk = dose) to the onsite resident would be 8×10^{-6} (13 mrem) and a maximum of 6×10^{-3} (1×10^{4} mrem). The minimum dose could be zero. The estimated risk for a recreational visitor is 7×10^{-6} (12 mrem), and for a ranger the maximum risk is 2×10^{-4} (300 mrem) and the median is 2×10^{-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 Analysis:

Based on the results of the analyses, final alternative number 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 9 criteria stated in the NCP (see above), 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 International Commission on Radiological Protection (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 in a year from all sources. DOE has established a dose constraint for DOE only sources of 30 mrem 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, 10^{-4} serious health effects per person, was used with the EPA risk coefficient of 6×10^{-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 in a year would be in the target range and would be below the DOE dose constraint. Further, the collective doses are sufficiently low that their inclusion in a cost benefit analysis is unnecessary. Notice that the total cost (including collective doses evaluated at $2,000 per person rem) for all options are essentially the same as the cost without the collective dose consideration when data are presented within 2 significant figures.

3. The Quarry

The quarry at Weldon Spring is located in the southern part of the site about 1.6 km from the Missouri River and about 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 groundwater.

Contaminants:

The average concentration of uranium in the quarry pond is about 2,300 pCi/L, that exceeds the DOE criteria for triggering Best Available Technology considerations of 550 pCi/L for discharge to uncontrolled areas derived per discharge requirements of Order DOE 5400.5. The sources of mixed-waste contamination of the quarry water are stated in "Background," above.

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.
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 groundwater 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.
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-10 presents a summary of the costs and doses for the three alternative system designs for treating the quarry water. Order DOE 5400.5, among other things, 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 1/3 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/groundwater treatment, if necessary. [Note: The documentation does not make it clear why the ion-exchange is necessary given to 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 B-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.

d. Analysis

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 a 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 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 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. However, the summary is based on incomplete information and the referenced PMC report might speak to this. WS indicated that a "full evaluation" was performed. The WS is characterized as having a few limited area with high concentrations and the bulk of the site soil with very low concentrations. For this reason, the cost of remediating the soil at the WS site is largely independent of the cleanup standard selected.

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 maximally exposed individual and collective dose to the population of about 1.8 mrem and 35 person-rem respectively, after 10 years of operation. Order DOE 5400.5, among other things, 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 derived concentration guide (DCG) value (550 pCi/L) without being treated by the best available technology. However, discharging at 500 pCi/L, the dose to the maximally exposed individual from ingestion of water and local fish would be about 0.0014 mrem in a year (a very small fraction of the 100 mrem/y dose limit or the 30 mrem in a year dose constraint for DOE only sources). With alternative A, the concentration will be reduced to less than 550 pCi/L, say 500 pCi/L, (the system would have a design safety factor of about 3), consequently, discharge of effluent from the basic water treatment system could be permitted by DOE 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 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 was used. However, this alternative would likely not have been acceptable to EPA or the State of MO.

Treatment alternative B for the quarry water was selected on the 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. [WS observed that the option also provides a contingency/backup system in the event that the other unit operations do not perform as anticipated.] 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 maximally exposed individual and annual collective dose to the exposed population from ingesting water containing 0.0007 pCi/L of uranium from the Missouri River would be about 0.000077 mrem/y 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 0.0002 mrem/y. The collective dose from fish consumption would be about 0.000044 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 0.0009). 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 enroute to the ultimate discharge point. However, in the unlikely event that a hiker or hunter were 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. Therefore, the cost of construction of the 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, that is, issues based on political/perception rationale. 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.

Figure C-1

Location of Weldon Spring Site

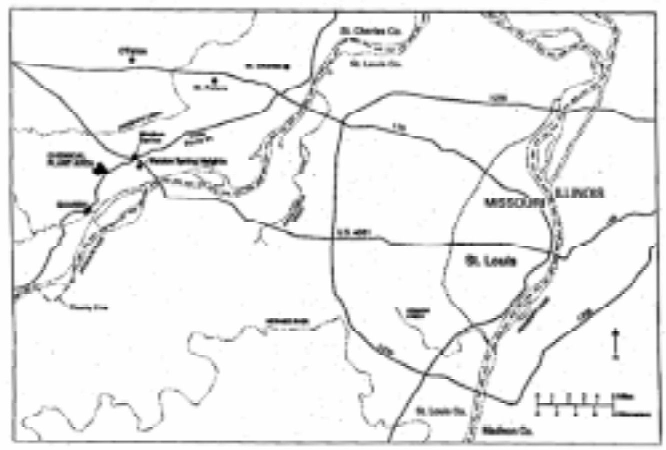

Figure C-2
Surface Features near the Weldon Spring Site

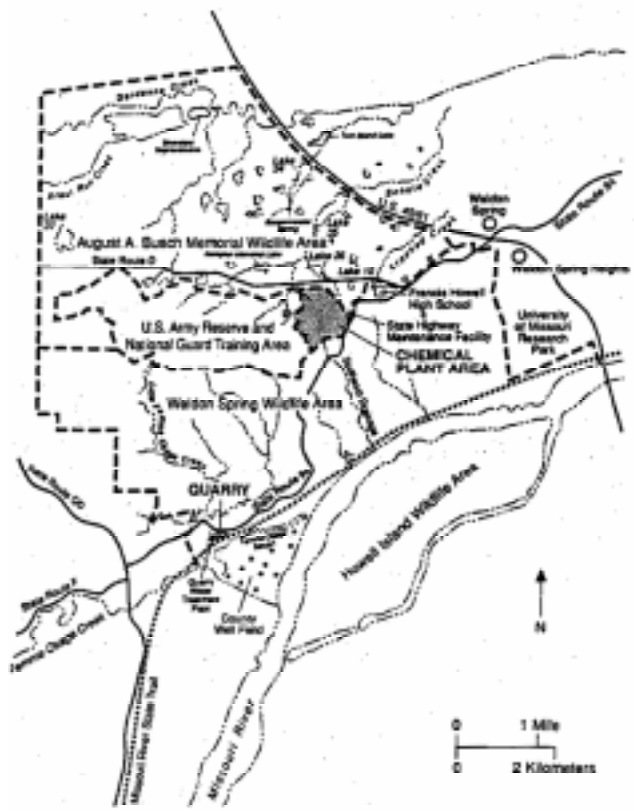

Figure C-3 Contaminated Media and Source Areas at Weldon Spring Site

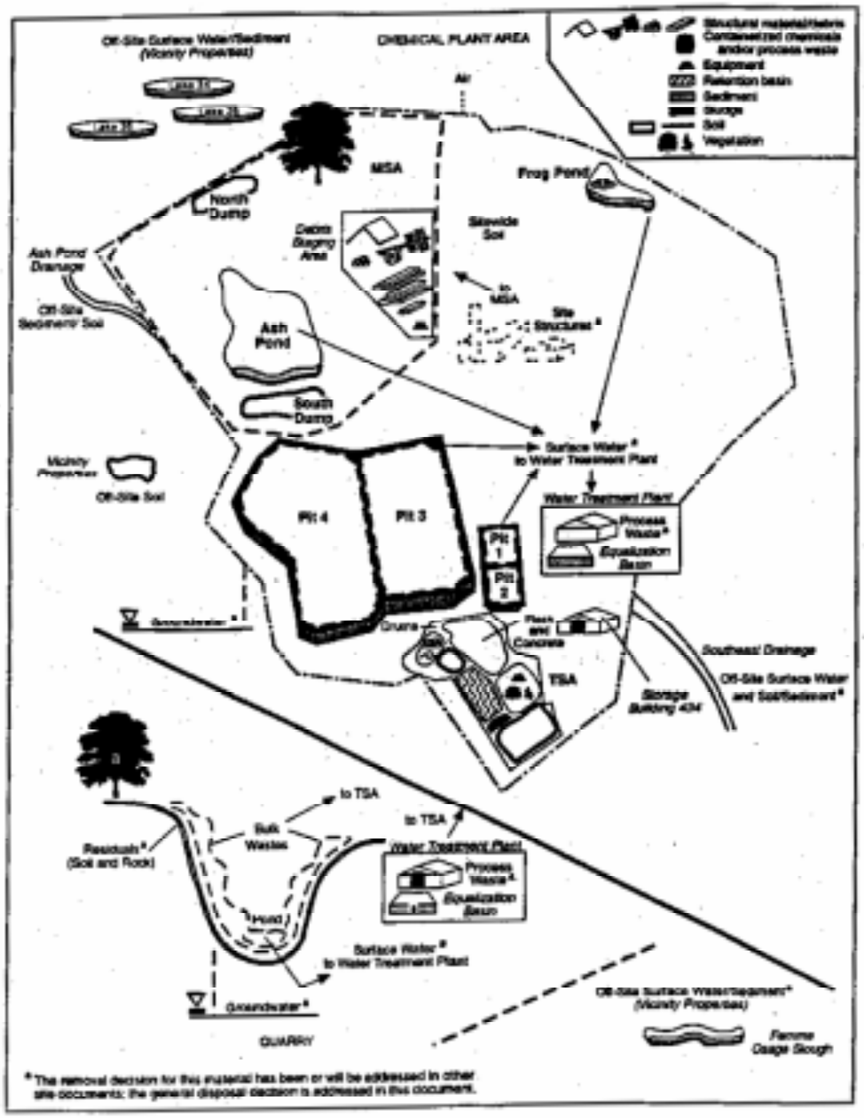

Figure C-4 Uranium-238 in Surface Soil (0.0 to 1.0 feet)

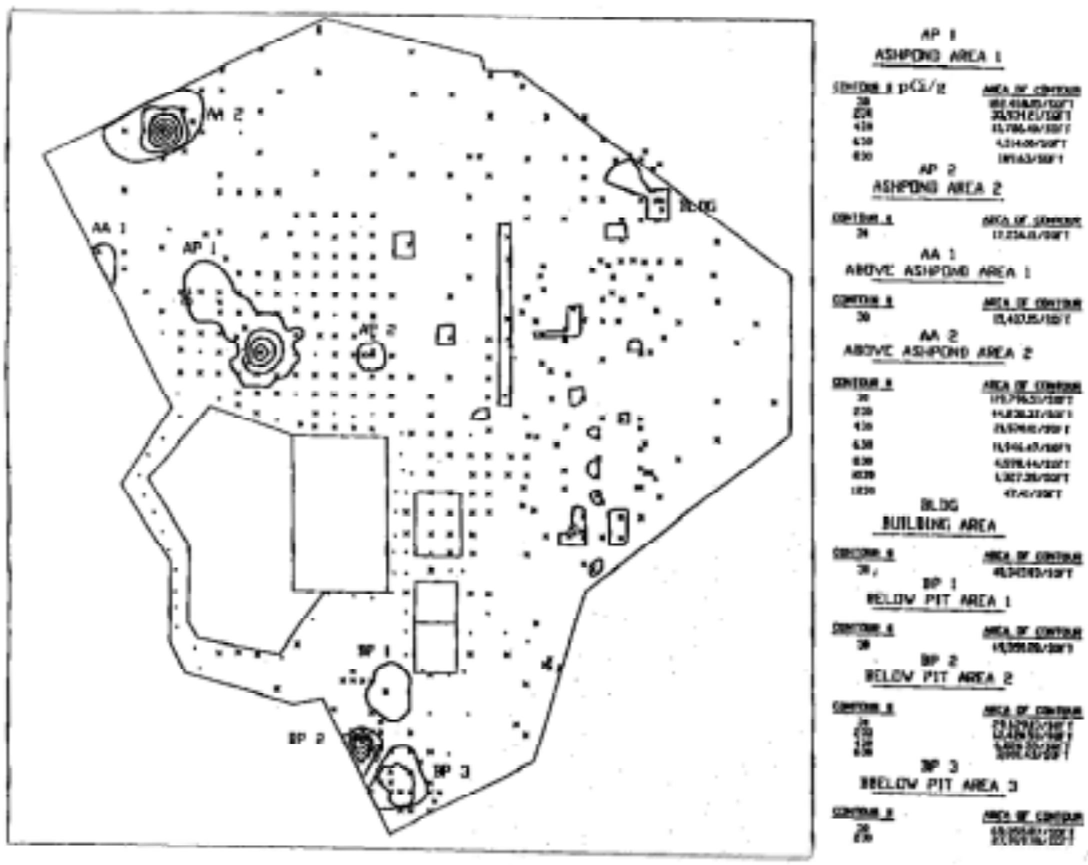

Figure C-5 Uranium-238 Subsurface (1.0 to 2.0 feet)

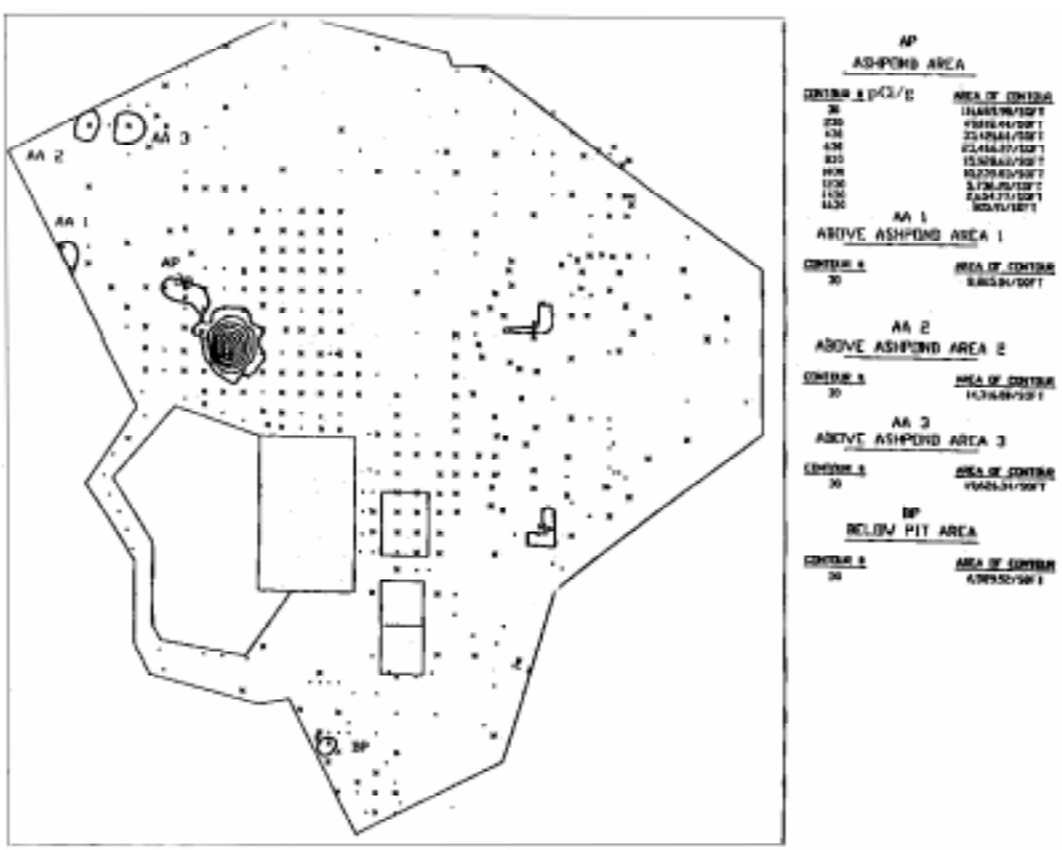

TABLE C-1 SOIL CONCENTRATIONS OF RADIONUCLIDES ASSOCIATED WITH TARGET LEVELS FOR RISK FOR SELECTED HYPOTHETICAL RECEPTORS

Receptor/ Radionuclide	Soil conc. (pCi/g) for risk[b] of 1 x 10^{-4}	Soil conc. (pCi/g) for risk[b] of 1 x 10^{-5}	Soil conc. (pCi/g) for risk[b] of 1 x 10^{-6}
Recreational Visitor			
Ra-226			
Ra-228	23	2.3	0.23
Th-230	46	4.6	0.46
Th-232	2,100	210	21
U-238	430	43	4.3
	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 WS area is about 1.2 pCi Ra-226/g soil, and the risk to a resident of 1 x 10^{-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.]

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

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 RECEPTORS[a] 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	5×10^{-5}	8×10^{-4}	2×10^{-2}
ALARA goal	5.0	4×10^{-5}	6×10^{-4}	8×10^{-3}
Background	1.2	9×10^{-6}	2×10^{-4}	2×10^{-3}
Ra-228				
Cleanup target	6.2	2×10^{-5}	2×10^{-4}	1×10^{-3}
ALARA goal	5.0	1×10^{-5}	2×10^{-4}	8×10^{-4}
Background	1.2	3×10^{-6}	5×10^{-5}	2×10^{-4}
Th-230				
Cleanup target	6.2	3×10^{-7}	4×10^{-4}	8×10^{-6}
ALARA goal	5.0	2×10^{-7}	3×10^{-4}	6×10^{-6}
Background	1.2	6×10^{-8}	8×10^{-5}	2×10^{-6}
Th-232				
Cleanup target	6.2	2×10^{-6}	2×10^{-4}	4×10^{-5}
ALARA goal	5.0	1×10^{-6}	2×10^{-4}	3×10^{-5}
Background	1.2	3×10^{-7}	4×10^{-5}	7×10^{-6}
U-238				
Cleanup target	120	2×10^{-5}	2×10^{-4}	5×10^{-4}
ALARA goal	30	4×10^{-6}	5×10^{-5}	1×10^{-4}
Background	1.2	2×10^{-7}	3×10^{-6}	8×10^{-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.*

TABLE C-4 ESTIMATED LIFETIME DOSES* FOR INDIVIDUAL HYPOTHETICAL RECEPTORS[a] 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	8×10^{1}	1.3×10^{3}	3×10^{4}
ALARA goal	5.0	7×10^{1}	1×10^{3}	1.3×10^{4}
Background	1.2	1.5×10^{1}	3×10^{2}	3×10^{3}
Ra-228				
Cleanup target	6.2	3×10^{1}	3×10^{2}	1.7×10^{3}
ALARA goal	5.0	1.7×10^{1}	3×10^{2}	1.3×10^{3}
Background	1.2	5×10^{0}	8×10^{1}	3×10^{2}
Th-230				
Cleanup target	6.2	5×10^{-1}	7×10^{2}	1.3×10^{1}
ALARA goal	5.0	3×10^{-1}	5×10^{2}	1×10^{1}
Background	1.2	1×10^{0}	1.3×10^{2}	3×10^{0}
Th-232				
Cleanup target	6.2	3×10^{0}	3×10^{2}	7×10^{1}
ALARA goal	5.0	1.7×10^{0}	3×10^{2}	5×10^{1}
Background	1.2	5×10^{-1}	7×10^{1}	1.2×10^{1}
U-238				
Cleanup target	120	3×10^{1}	3×10^{2}	8×10^{2}
ALARA goal	30	7×10^{0}	8×10^{1}	1.7×10^{2}
Background	1.2	3×10^{-1}	5×10^{0}	1.3×10^{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 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]*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.*

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.

TABLE C-6 BASELINE CALCULATED DOSES (EDE) TO INDIVIDUAL RECEPTORS FROM VARIOUS EXPOSURE PATHWAYS*.

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 4600
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	1700

**Lifetime dose associated with scenario.*

[a]*Exposure time, frequency, and duration differ among receptor scenarios.*

[b]*Visitor evaluated for uncontrolled access.*

[c]*Ingestion of sludge and soil is incidental.*

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 1000)[a] 80	(0 to 10000) 330	50
Inhalation	83	(830 to 17000) 830	(1 to 130000) 33	17000
Ingestion of soil	10	-- 150	(1 to 5000) 17	670+1200[b]
Total dose	100	(1000 to 17000) 1160	(2 to 130000) 380	17000

[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	4×10^{-3} to 0.2	6×10^{-3} to 0.3	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.d ose (x $1M)	--	157.2	182.3	351.3	304.3
dCost/dDose ($/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 (1 WLM = 1 rem).*

[b] *Number of workers: 200 offices; 80 for 6a; 110 for 7a; 160 for 7b and 7c.*

[c] *Number of receptors: 0 to 3 miles = 10,700 persons; 0 to 50 miles = 3×10^{6} persons.*

[d] *Total cost includes $1,000/person-rem for workers and for public collective dose.*

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)	2300	b	35	base case
No. A Chemical/filter / adsorp.	550[a]	1.27	8.25	1270K ------ = 47K 26.75
No. B above + ion exchange	100	1.44	1.5	170K ----- = 64K 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.*

REFERENCES

Engineering Evaluation/Cost Analysis for the Proposed Management of Contaminated Water in the Weldon Spring Quarry RI/FS-EIS-0185D DOE/OR/21548-039, Jan. 1989.

Baseline Assessment for the Chemical Plant Area of the Weldon Spring Site RI/FS-EIS-0185D Baseline Assessment: DOE/OR/21548-091, Nov. 1992.

Feasibility Study for Remedial Action at the Chemical Plant Area of the Weldon Spring Site (and Appendixes) DOE/EIS-0185D, Feasibility Study: RI/FS-EIS-0185D DOE/OR/21548-148, Vol. I-II: Main Text, Nov. 1992.

Remedial Investigation for the Chemical Plant Area of the Weldon Spring Site DOE/EIS-0185D, DOE/OR/21548-074, Vol. I: Remedial Investigation, Nov. 1992.

Addendum to the Remedial Investigation for the Chemical Plant Area of the Weldon Spring Site DOE/EIS-0185D, DOE/OR/21548-272, Vol. II: Addendum, Nov. 1992.

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Off-Site Population Radiological Dose and Risk Assessment for Potential Airborne Emissions from the Weldon Spring Site ANL/EAIS/TM-78, Nov. 1992.

Potential Radium-226 and Thorium Remedial Action Standards for the Weldon Spring Site DOE/OR/21548-247, Rev. A, Dec. 1991.

D. NEVADA TEST SITE

This is a good example of optimization. The following is an attempt to summarize the draft report "Cost/Risk Benefit Analysis of Alternative Cleanup Requirements for Plutonium-Contaminated Soils On and Near the Nevada Test Site." It demonstrates the value of the output of the ALARA process with respect to decision-making. The appendix of the draft report contains the numerous assumptions, data, models, and other information used in the study.

Background

In 1993, EPA published an issues paper on radiological site cleanup restoration. EPA considered a two-tiered cleanup criteria for remediating the plutonium contaminated ares in the NTS and adjacent areas: (1) cleanup areas to be released without control until the projected dose from residual Pu is 15 mrem/yr above background to the reasonably maximally exposed individual(s) (RME) for 1000 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/yr above background to the RME. In 1994, DOE undertook a cost-benefit analysis to better understand the issues and examine the consequences of a variety of cleanup standards. A draft report "Cost/Risk Benefit Analysis of Alternative Cleanup Requirements for Plutonium-Contaminated Soils On and Near the Nevada Test Site" was issued December 1994 by DOE for review and comment. A very brief summary of the findings in the draft is presented. Note: this case study is based on the draft report which has been issued as a final report subsequent to the analysis below. The next revision of this report will update the discussion to be consistent with the final DOE Nevada report.

Contamination

The location of the NTS and nearby areas (totaling about 6,000 square miles) are shown in **Figure D-1**. (Note: **Figures** and **Tables** for this section are located at the end of the section.) 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 is 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. Factors used in projections and the results are presented in **Tables D-3 and D-4**. 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 **Tables D-5 and 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 US Bureau of the Census [1991] finding that the mean residential time is 10 years, with 5 and 95 percentiles of 0.4 and 36 years. For farm/rural locations, the mean 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 guidance, 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 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. Re-vegetation is 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 remediation can have a devastating impact that may be irreversible.

Impact of the EPA Cleanup Criteria

Population risks

The main components of the integration model used to estimate costs, risks, and benefits are illustrated in **Figure D-4**. 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 defines the RME as the exposure dose at the 95% percentile. The applicable exposure distribution is illustrated in **Figure D-6**. 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/yr (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-7 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. The risks averted due to various cleanup levels were integrated over more than 100,000 years. There is almost three-orders of magnitude spread between the $\pm$ 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 must be excavated and the location of the disposal site. Total expected and $\pm$ 90% confidence bounds of the cost are presented in **Figure D-8** as a function of Pu concentration in soil (also note that 169 pCi/g is associated with 15 mrem/y).

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-9 presents an "influence diagram" that indicates how the various decisions and factors considered in the remediation activity are inter-related. **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 must be placed on a fatality (cancer) in order to justify the various cleanup criterion. 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-10**, that 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/yr level with no discounting to almost $40 Trillion for 10 mrem/yr 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/yr cleanup level, $390M for a 15 mrem/yr level, and $970M for a 5 mrem/yr level. Considering the effects of uncertainties, the study concluded that if the cleanup level were to be set at 75 mrem/yr, 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

FIGURES FOR APPENDIX D PRESENTLY ONLY IN HARD COPY.

E. COMPARISON OF DERIVED STANDARDS AT DOE FACILITIES.

The following comparisons were made 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 to demonstrate various semi-quantitative evaluation processes employed to satisfy ALARA process requirements when selecting Authorized Limits. The benefits or limitations to the approaches are also discussed. The comparisons also demonstrate that some knowledge of projected collective dose is important to the decision-making process to aid in and explain decisions.

1. Colonie, NY

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 (State and NRC) licensed 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 direct the Department to remediate the plant and residential properties around the plant. Vicinity properties have been remediated. Remedial activities for the Colonie site area are currently underway and include the development of an engineering evaluation and cost assessment and supporting environmental documentation to support the selection of the preferred remedial alternatives. This discussion deals primarily with the vicinity properties that were remediated in the late 1980's.

Basis for Standard:

The cleanup standard or authorized limit being used for cleanups at Colonie, NY, is 35 pCi/g for depleted uranium (U-238). This standard was derived in the early to mid-1980's using a process similar but different from that contained in DOE 5400.5 (1990). DOE conducted dose assessments that assume 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 in a year. Based on a cost evaluation and through meetings with NY State and EPA officials, it was determined that 35 pCi/g was 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, hence 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 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 spotty 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 in a year (an average of the doses to the maximally exposed individual from each of the properties evaluated). The maximum dose for any single property was 3.3 mrem in a year. This dose is less than 15% of the dose used to select the authorized limits for uranium at this site[6].

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, assuming 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 over-estimating dose, and assuming that the residential scenario 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 1000 year period evaluated, the contribution is insignificant.

Table E-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 E**-1 presents pre- and post-remedial action doses by property). It is interesting to note that pre-remedial action doses for these properties ranged from about 1 mrem per year to less than 15 mrem per year. In other words, although the

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[6] 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.

generic dose assessment used to develop the standard assumed that the potential dose on the contaminated properties could be as high as 25 mrem 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[7].

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 suggests that most individuals spend on average 7 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 4 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 and are presented with Table E-1. 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 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 was 0.02 (this is effectively no cancers). The estimated cost per health effect averted for the project is about $10,000,000.

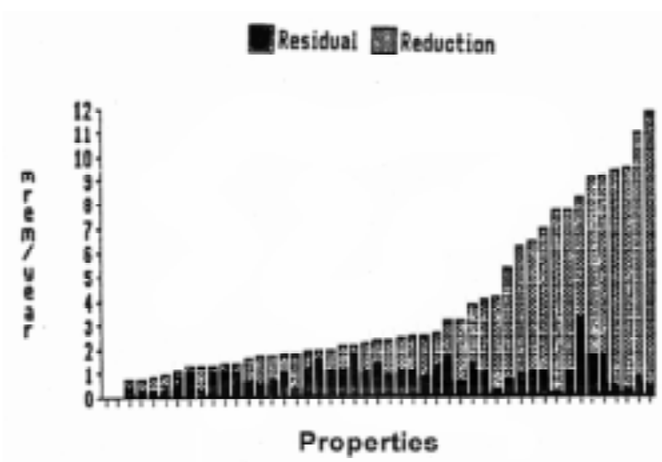
Authorized Limits used for this remedial action were established at a concentration that provides assurance that doses would be less than 30 mrem in a year. However, in this situation, it was developed using the worse plausible use scenario as the expected use scenario. Data from this site also demonstrate the importance of employing dose estimates that are as realistic as possible in developing Authorized Limits. The results of modelling pre- and post-remedial action doses shows that the conservative scenario and qualitative analysis used to derive the 25 mrem/year-based authorized limits significantly over estimated actual doses. Even before remedial action all of the properties cleanup under this project were well below the 25 mrem in a year dose constraint given actual use of the properties.

[7] Conservative assumptions routinely result in over-estimates of dose. Generic modelling conducted (in the early 1980's) 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.

TABLE E-1 Colonie Ny 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

Figure E-1 Estimated Doses (Total Pre-cleanup, Residual and Reduction) by Property



2. Elza Gate Site, TN

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 limits were 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, will likely 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 1970's. The property is now an industrial park that includes about 20 acres. The primary radionuclides of concern were Ra-226, Th-230 and Uranium. The 5 pCi/g surface and 15 pCi/g subsurface criteria was used for Ra-226 and Th-230 based on a qualitative ALARA assessment because levels were not unlike 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 was 35 pCi/g for U-238 and 5 pCi/g surface and 15 pci/g subsurface for the combined activities of radium and thorium isotopes. The uranium standard was developed independent of the radium[8] standard. A dose assessment was completed for several scenarios and a uranium concentration that would meet a dose limit of 100 mrem in a year were calculated for each. The results are presented in **Table E-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.

An 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 E-2**). The analysis indicated that costs began to increase dramatically between

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[8] 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.

concentrations of 30 and 40 pCi/g U-238. Given that the estimated individual dose in this concentration range for the likely-use of the site was about 4 mrem in a year which, as recommended by DOE guidance, is well below the DOE constraint of 30 mrem in a year, and the worst-case future use scenario dose was about 15 mrem in a year, (well below the 100 mrem 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).

<u>Results</u>:

Pre- and post-remedial action concentrations (in pCi/g) are presented in **Table E-3**. Post-remedial action doses were estimated for use of the site using the Net Average residual concentrations of the above radionuclides and estimating U-234 and U-235 (and decay products) as a standard ratio to U-238. For the likely-use of the site (industrial use) the maximum individual dose was estimated to be 1.5 mrem in a year (less than 40% of the modeled dose[9]). Potential doses for recreational use of the property was estimated at less than 1 mrem in a year and the worst-case use dose for the resident farmer scenario (using an ansate pond for drinking water and irrigation[10]) was estimated to be about 12 mrem in a year. Individual risk under the likely use of the property (industrial) is estimated to be about $7.5x10^{-7}$ annually and $2x10^{-5}$ (2 in 100,000) for lifetime risk assuming a worker spends 25 years at the site. Use under the residential-farmer scenario (worst case) would suggest potential lifetime risks on the order of $2x10^{-4}$ (2 in 10,000).

Assuming a 20 acre industrial site could maintain a work force of 150 persons, the collective dose and estimated number of associate cancers for 1, 25, 50, and 200 years for continued use of the site under pre- and post remedial action conditions were estimated and presented in **Table E-4**.

Based on current use of the site (industrial/commercial) and assuming pre-remedial action radiological conditions, dose to the reasonable maximum exposed individual at the site was estimated to be about 78 mrem 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

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[9] 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.

[10] Extremely unlikely assumption due to slope and proximity to river.

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 2200 for 200 years of operation and $18,000 for the 25-year period. This equates to about $4,200,000 per potential cancer averted 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 E-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 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-rams 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.

TABLE E-2 Dose for Several Scenarios and Uranium Concentrations for 100 Mrem in a Year

þ Industrial use (current & likely use) (if U-238 used as an indicator for measurement)	- 1800 pCi/g (Uranium) - 880 pCi/g (U-238)
þ Recreational use (U-238 as indicator)	- 4000 pCi/g (Uranium) - 2000 pCi/g (U-238)
þ Residential use[11] (worst-case use) (U-238 as indicator)	- 470 pCi/g (Uranium) - 230 pCi/g (U-238)

[11] 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.

TABLE E-3 Elza Gate Site Pre- and Post-Remedial Action Concentrations

Pre-remedial Action Concentrations			
Radionuclide	Measured Average	Average Background	Average Net
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 Average	Average Background	Average Net
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.

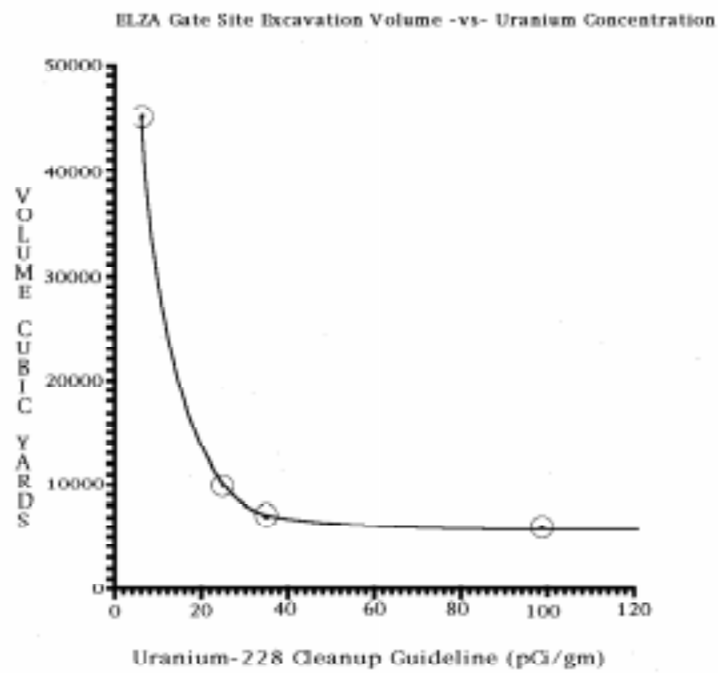
TABLE E-4 Elza Gate Site, Tn Pre- and Post Remedial Action Conditions for Industrial Scenario

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

Figure E-2 ELZA Gate Site Waste Volume vs. Cleanup Level



3. Maywood, NJ

This case-study represents a reasonable 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 quantitative analysis which used conservative but reasonable scenarios for exposure under all conditions, the results of a second analysis which use reasonable assumptions for the no action option and worst-case exposure assumptions for cleanup alternatives, is discussed. This comparison demonstrates the importance of using best estimate scenarios for 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 for 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 is 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 is being remediated by DOE and it is on the CERCLA national priority list (NPL).

Basis for Standards:

The cleanup criteria being used for the action is the DOE 5400.5 guidelines for radium and thorium, that is to reduce the concentrations to levels to 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. The attached **Table E-5** "Predicted post-remediation radiation dose" provides project costs, doses and collective doses integrated over 200 year 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 it progeny being 4 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. Decontamination of these properties to 30 pCi/g will reduce collective doses by 11,000 person-rem at a cost of $61,000,000. The incremental reduction to 15 pCi/g will avert an additional 440 person-rem and cost an additional $61,000,000. 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 $30,000,000 and $120,000,000[12] additional. The incremental cost per person-rem avoided under each alternative 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 E-5**.) This equates to about $9,000,000 per hypothetical fatal cancer avoided at the 30 pCi/g level and $230,000,000 per hypothetical cancer averted for the 30 to 15 pCi/g increment and between $180,000,000 and $270,000,000 for 15 to 5 pCi/g increment.

As in the other examples, risks associated with the remedial actions have not been taken into account in the results stated above. However, Table E-5 also lists projected worker doses. The **Table E-6** also presents the risks of fatal accidents for remedial workers due to the transport of the waste as well as the risk averted in the analysis above. The worker and transportation related risk are insignificant at the

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[12] 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.

30 pCi/g criteria, but they reduce the incremental risk averted from lowering the criteria from 30 pCi/g to 15 pCi/g by as much as 50%. 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.

The data above are based on the Department 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. The average individual dose for residential and industrial/commercial uses and residual and averted collective doses for the worst-case scenario are presented in **Table E-7**. 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 ($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 has the effect of artificially reducing 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.

In any case, the comparison of these two analyses (expected scenario analysis and worst-case analysis) demonstrate 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 a different cleanup criteria.

The Department believes that 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 95 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 E-7**, 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 1/3 or 1/4 to ensure compliance with a15 mrem/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 they were 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.

TABLE E-5 Predicted Costs, Radiation Doses, and Collective Doses for Various Criteria at Maywood, NJ

Alternative Remedial Action Criteria	Total Project Cost[13] ($M)	Residual Dose to Exposed Individual (mrem/yr)	Residual Collective Dose (person-rem) for 200 years[14]	Remediation Worker Collective Dose (person-rem)
No action	16	12-2800	12,000	--
30 pCi/g	77	3.6 (Res[15]) 8.2 (Com[16])	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

[13] 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.

[14] 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.

[15] Estimated for expected conditions following remediation at residual properties (current use).

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

TABLE E-6 Comparison of Risk Averted to Worker and Transportation Risk at Maywood, NJ

Remedial Action Criteria	Incremental Transportation Accident Risk[17] (fatalities)	Incremental Remediation Worker Accident Risk (fatalities)	Incremental Excess Fatal Cancers due to Remediation Worker Exposure[18]	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

[17] 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.

[18] 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).

TABLE E-7 Predicted Post-Cleanup Dose, Collective Dose, And Collective Dose Averted by Criteria at Maywood (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[19]) 66 (Com[20]) 189 (Future[21])	9,800 7,000[22]	2,200 person-rem 5,000 person-rem[22] (1.1 cancers) (2.5 cancers)[22]
5 pCi/g	40 (Res) 22 (Com) 61 (Future)	3,200 2,400[22]	8,200 person-rem 4,600 person-rem[22] (4.1 cancers) (2.3 cancers)[22]

[19] Estimate for worst-case conditions following remediation of residential properties.

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

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

[22] Assumes all properties are residual in the future.

4. Ventron, MA

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.

Standard Approved: 100 pCi/g total uranium (about 48 pCi/g U-238 and U-234, and 4 pCi/g U-235)

Site:

The former Metal Hydrides site in Beverly, MA, processed uranium compounds and scrap to produce uranium for the MED and AEC. Operations contaminated portions of the buildings and grounds on site plus some of the properties around the site. The site is presently used for industrial applications. It is about 3 acres in size.

Basis for Standard:

The authorized limit for cleanup of this site was developed consistent with DOE 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 in a year dose limit would not be exceeded if total uranium concentrations were less than 1800 pCi/g, 3100 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 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) were generally 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 was approved. This limit would ensure that doses under the expected use of the property would be less than 5.5 mrem in a year to the most exposed individual. Lifetime risk of a fatal cancer for a worker continuously exposed (for 25 years) to this dose would be about 7×10^{-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/year estimated for the maximally exposed individual. 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[23] the maximum dose would be less than 21 mrem in a year. This represents a $3x10^{-4}$ lifetime risk of cancer. Continuous exposure to such a dose (assuming the site could support 6 persons under the resident-farmer scenario) would produce a maximum collective dose of 0.1 person-rems/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, that 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 4 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/year (individual lifetime risk about 1.5 in 10,000) and for higher floors about 1.5 mrem/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. Integrated over a 200 year period would indicate less than 11 person-rem (hypothetical 0.06 fatal cancers in 200 years).

Summary:

The summary of collective doses from the various scenarios is presented in **Table E-8**. This analysis was prepared prior to completion of remedial action; however, preliminary engineering estimates at the proposed uranium criteria indicate the cost of the project will 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 is anticipated that residual levels of uranium at the site will be below those used in the dose assessments reported above and hence, the actual potential doses and associated risks will also be lower.

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. If additional remedial measures were implemented to reduce the potential maximum

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This is a good example of unrealistic and conservative exposure scenarios and assumptions used in many guidelines development efforts. The Ventron Site is a small 3 acre site in a heavily developed area that directly abuts Massachusetts Bay (actually the mouth of the Danvers River) on 2 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.

dose for the residential scenario from 21 to 15 mrem in a year, the uranium criteria of 100 pCi/g (48 pCi/g U-238) would be reduced to about 70 pCi/g (35 pCi/g U-238). This would increase the expected waste volume by about 1550 cubic yards **(Figure E-3)**. This would incur an additional cost of about $530,000 for waste disposal and transportation (assuming $220/cu.yd. for disposal and $120/cu.yd. for transportation). This would equate to a 10, 7 and 42 person-rem reduction and a cost per person-rem avoided of $53,000, $76,000, and $12,000 for the industrial, residential-farmer and condominium scenarios respectively (over the 200 year integration period). 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 uthorized 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 draw-back 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.

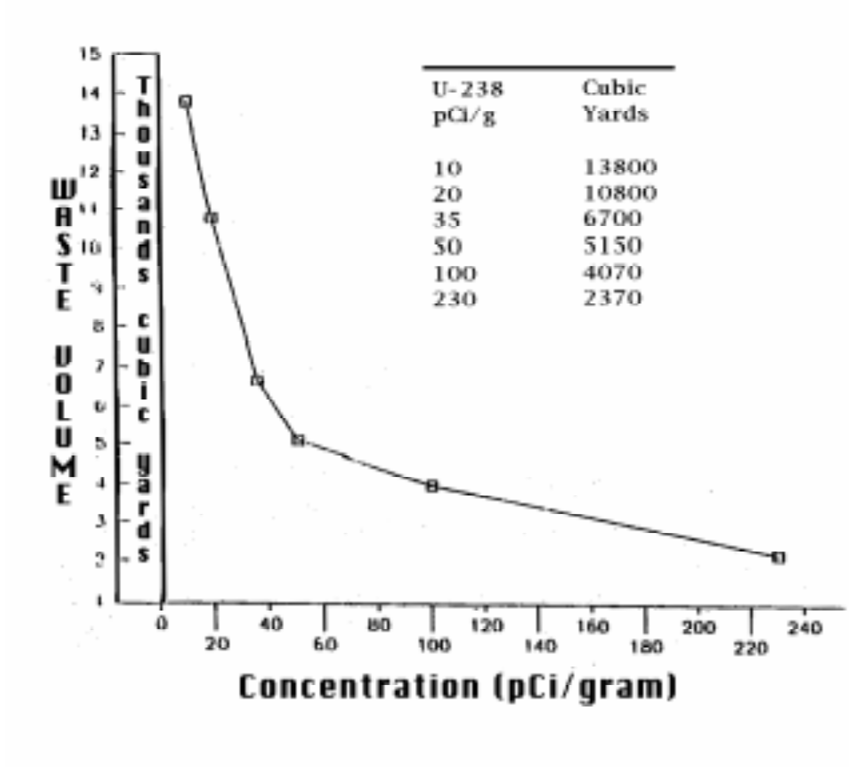
TABLE E-8 Ventron, MA, Exposure Scenario Collective Dose Analyses

Years	Residual Collective Dose person-rem	Residual Risk Total Potential Cancers

	Industrial Use Scenario	
25		
200	4	0.002
	33	0.02
	Residential Use Scenario	
25	3	0.002
200	25	0.01
	Condominium Complex	
25	18	0.009
200	144	0.07

Figure E-3

Alternative Concentration Limits vs. Estimated Waste Volume



5. Weldon Spring Site, MO.

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. (See Section C for a more detailed review of the decision-making process and ALARA evaluation for this site.)

Standard Approved: 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 US Army to construct an ordinance 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 U 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 is extremely non-homogeneous, with a few highly concentrated areas that extend to a depth of a few 10s 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, is highly contaminated but confined. Contaminated surface water runoff is contained in a quarry. The estimated volume of contaminated media is presented in **Table E-9**.

Basis for Standard:

The site is being cleaned in compliance with CERCLA and NEPA. The standard was derived in 1991, using a site-specific process similar to that required by Order DOE 5400.5. Contaminated debris from buildings and equipment constitute the bulk of the volume (and cost) to be disposed and the soil, regardless of the level selected, will comprise 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 must be removed to reduce the residual 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/y, that EPA has used for several source-specific regulations including management of U and Th by-product material, was also 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 E-10** shows the relationship of target U-238 concentrations in soil to cost and dose. An ALARA goal of 5 pCi/g was selected for 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/y, that 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/y) was selected, with an ALARA goal of 30 pCi/g. As can be seen from the data in Figure E-4 there is little incremental risk reduction associated with the significant cost increases beyond the proposed action level.

<u>Results</u>:

The primary cleanup effort to date has been directed toward remediating buildings and equipment--the major cost item. A water treatment facility is planned for decontaminating the water from the quarry prior to disposal in the river. The site is adjacent to a large recreation 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 6×10^{-3} with a median of 8×10^{-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 1×10^{-4}. This reflects the difficulty in achieving either the target risk range or annual dose limit of 25 mrem 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 E-9 VOLUME OF CONTAMINATED MEDIA AT WELDON SPRING, MO

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 E-10 RELATIONSHIP OF TARGET U-238 CONCENTRATIONS IN SOIL TO COST AND DOSE AT WELDON SPRING, MO

Conc. 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	0.38 @10,000y

F. EXAMPLES OF DECISION MAKING TECHNIQUES

Throughout this guidance and in most of the examples and case studies in the appendices, emphasis is on the cost/benefit assessments supporting the ALARA decision-making process. As noted, in the guidance, there are many important factors or attributes that may need to be considered in the decision. When these factors can be quantified through a monetary equivalent value they can be integrated into the cost/benefit evaluation whether it be quantitative or semi-quantitative. For example, the "Natural Resource Evaluation Handbook: Concepts and Techniques," draft January 1996, discusses methods that have or can be used for the valuation of natural resources. In other situations only qualitative comparisons may be possible. As noted in examples and case studies previously discussed in this guidance, simple cost effectiveness approaches coupled with qualitative comparisons of factors not addressed in the cost effectiveness assessment may be used to satisfy ALARA requirements. Another alternative is to employ multi-attribute utility analyses may be employed as one approach to quantify these otherwise unquantifiable factors (whether they be costs or benefits).

In most cases, multi-attribute utility type of analyses identifies then ranks the factors (or attributes) and assigns each a weighting factor that is indicative of its importance. Alternative controls or control options are than evaluated for each of the factors or attributes. The rank or desirability for each alternative is given by its score which is the sum of the values for all attributes times its weighting factor for each. (See DOE-STD-xxx, Draft March 1997, "Application of Best Available Technology for Radioactive Effluent Control," for additional discussion and examples of the multi-attribute utility analysis approach in environmental decision-making.) Cost-benefit analyses or cost effectiveness assessments may be used in conjunction with multi-attribute utility analyses when comparing factors that may be quantitatively evaluated with those that cannot.

There are many procedures by which the scores and weighting factors can be determined but in almost all cases, they require expert judgement. Therefore, it is recommended that such analyses be conducted with input from interested parties possibly through site advisory or in conjunction with state and local regulators. In some situations it may be advisable to establish peer review panels to validated the results. The level of public involvement in the process should be commensurate with the complexity, interest and sensitivity of the issue. However, in every case all materials support such decisions must be made available to the public and conducted in an open and transparent process.

Multi-attribute utility analyses are discuss in most modern management texts and there is a plethora of reference material available on its application and implementation. This guidance cannot address the topic adequately and the discussion below is intended for illustrative purposes only.

To illustrate the multi-attribute process the following hypothetical example is provided. For illustrative reasons, this example is overly simplistic. 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:

- o public protection
- o worker protection
- o environmental protection
- o cost
- o schedule
- o public acceptance
- o protection of cultural resources

Each of these is evaluated to define performance measures that are 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 will clearly 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 input from 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 these factors does not suggest that public acceptance is less importance, rather, such actions should be based on the best means of considering the factor in the analysis. In this example, public acceptance influenced the acceptability of alternatives under various factors and was felt best addressed in combination with the other factors.)

To obtain the weightings for each factor, they were compared to one another rating the more important factor with a 1 and that of lesser import with a zero. If both are of equal importance they are given a 0.5. They results of this rating is given in Table F-1. There are many techniques that can be used to develop weightings in this example it is presumed that ALARA team consensus was used to establish the individual comparative scores in Table F-1. The relative weighting is determined by the score for the factor divided by the sum of the scores.

Although the weightings 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 example below illustrates how the public protection factor might be rated.

Table F-1. Example weighting of factors (attributes)

Factor below rated against factor to the right (numbers keyed as below):	Factor 1.	Factor 2.	Factor 3.	Factor 4.	Factor 5.
1. Public Protection	N/A	0	0	0	0
2. Worker Protection	1	N/A	0.5	0	0
3. Environment and Cultural Resources	1	0.5	N/A	0.5	0.5
4. Costs	1	1	0.5	N/A	0.5
5. Schedule	1	1	0.5	0.5	N/A
Score ---	4	2.5	1.5	1	1
Relative Weighting ---	0.4	0.25	0.15	0.1	0.1

The new installation must at least ensure that public dose limits are achieved. That requires that doses to the maximum exposed individual be less that 30 mrem in a year for all DOE sources combined. Given that the maximum dose from all other DOE activities on the site is less than 1 mrem in a year, conceivably, this activity could contribute up to 29 mrem 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 where established:

> DOE dose constraint - unacceptable = alternative rejected
< dose constraint but more than 15 mrem in a year - not desirable = 0 pt
<15 mrem in a year to the MEI - acceptable = 0.5 pt
less than 1 mrem in a year - desirable = 1 pt

DOE air pathway limit is 10 mrem in a year. Therefore, for the air pathway alone, the following conditions were established (no undesirable but acceptable category was used):

> 10 mrem/year - unacceptable = alternative rejected
< 10 mrem/year - acceptable = 0.5 pt
< 1 mrem/year - desirable = 1 pt

For this example, no separate water related pathways were considered and it is presumed that no emissions other than radiological are of concern. Criteria for evaluating collective dose are also important in assessing the acceptability of an alternative; however, collective dose was assume in this case to be addressed with the cost factor were reduced collective dose is a negative cost using $2000 per person-rem as the monetary equivalent for the dose. Therefore, 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.

Assuming 5 alternatives were identified and were rated as shown in Table F-2, 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 but Alternative A would be selected unless other special considerations would indicated that Alternative B 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. The draft DOE standard "Application of Best Available Control Technology for Radioactive Effluent Control," March 1997, contains additional information that may be useful in using multi-attribute utility type approaches. Multi-attribute utility analyses are discussed further below.

Table A-2. Scoring Alternatives in Illustration.

Factor (weight)	Alternative A	Alternative B	Alternative C	Alternative D	Alternative E
Factor 1. (0.4)	Rejected	0.5	1	1	0
Factor 2. (0.25)	1	1	.75	1	1
Factor 3. (0.15)	0.5	0.5	1	1	0.5
Factor 4. (0.1)	1	1	0.5	Rejected	1

Factor 5. (0.1)	1	1	0.5	Rejected	1
Score	Rejected	0.725	0.837	Rejected	0.5

ICRP publication 55 ("Optimization and Decision-Making in Radiological Protection," 1989) also contains helpful examples. Some examples of this report are included below. This example, although it only considers occupational exposure, provides some insight into the use of cost effectiveness in conjunction with multi-attribute utility analysis.

In the ICRP example, a hypothetical small uranium mine employs 17 miners. The miners have been divided into three groups depending on their exposure level. The four highest exposed miners are Group I; four others with intermediate exposures are in Group II; and the remaining nine, which are the least exposed, are in Group III. Five options have been identified to decrease the exposures of the miners by increasing the ventilation rate in the mine. The increased flow-rates also affect the comfort level for the workers, owing to the temperature drop with increased flow. The annual cost and projected collective doses associated with the options are presented in Table F-3.

Cost-Effectiveness Analysis

Only two variables are normally considered using cost-effectiveness analysis. In the mine example, the variables are the annualized protection cost (X) and the annual collective dose (S) or "**detriment**." Of interest is the differences in each of the variables considering progressive options and the ratios of the two. These are shown in Table F-4. It is noted that this example only considers worker collective dose. In a more detailed example, public collective dose would also have to be addressed. It is likely that increases in ventilation employed to lower worker dose would increase public collective dose. (Some variations of the cost-effectiveness concept were illustrated in Section E where volume of waste was used as a surrogate for cost and soil concentration was used to represent dose.)

Table F-3. Data for the options considered in the uranium mine example.

Protection Option	**1**	**2**	**3**	**4**	**5**
Annual Protection Cost, $	10400	17200	18500	32200	35500
Annual collective dose, man-Sv	0.561	0.357	0.335	0.196	0.178
Annual average individual	II		34.5		22.3
dose to workers in group, mSv	III		28.9		17.1
I		40.8		28.4	

			Discomfort	no problems	slight
26.0			from		
21.0	17.5	15.8	ventilation		
16.3	12.6	11.3			
	8.4	7.8			
slight	severe	difficult			
		to work			

Table F-4. The cost-effectiveness ratios for the uranium mine example.

Option n	Annual cost difference $	Annual collective dose difference, man Sv	Cost-effectiveness ratio $(man Sv)$^{-1}$
1			
	6800	0.20	33000
2			
	1300	0.02	59000
3			
	14000	0.14	99000
4			
	3300	0.02	180000
5			

Neither the ratio nor the trend determined by cost-effectiveness analysis will identify the optimum option. The data could be supplemented by collective dose or protection cost constraints and by selecting an option which either minimized the collective dose for a fixed protection cost or minimized the protection cost for a limited collective dose. However, neither of these cost-effectiveness techniques will identify an **optimum** (least total cost option), because they do not involve a tradeoff between protection cost and collective dose. One technique to accomplish this is **cost-benefit analysis**.

B. Cost-Benefit Analysis

One characteristic of cost-benefit analyses is that the factors are generally expressed in monetary terms. The simplest case of optimization for radiation protection purposes may be demonstrated for the mine example described above. In this case, a monetary value "alpha" (þ), is selected for a unit of annual collective dose, S. Then the monetary value of the collective dose (detriment), Y, is $þS. 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 which has the least total annual cost is the optimum selection. To illustrate this technique, a monetary value for collective dose of $20000 (person-Sv)$^{-1}$ will be assumed.[24] Table F-5 presents the data for a **simple cost-benefit analysis** of the uranium mine example, provided above.

Table F-5 The simple cost-benefit analysis for the uranium mine options.

Protection option n	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 þ = $20000 (person-Sv)$^{-1}$.
The optimum solution is underlined.

In Table F-5, 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 þ and the projected annual collective dose, S_n, for each option. The total annual cost for each option is the sum $X_n + Y_n$. As may be seen, in this example, the first option is the optimum. However, note in Table F-3, that the doses to one group of workers would be uncomfortably close to the 50 mSv dose limit for Option 1 and the preferred choice would be Option 2.

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:

$$Y_n = þS + þ\, ß_j\, S_j$$

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

Historically, values for alpha ranging from "a few pounds Sterling" to $1000 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 which has been justified, rationalized, or endorsed by any national or international authority, nor is there any consensus value. The NRC has selected $1000 (person-rem)$^{-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.

the range j. The distribution of average and collective doses of the workers among the three groups are presented in Table F-6.

Table F-6 Average individual doses to workers in the three groups and corresponding collective doses for the options

Protection option	Average annual individual dose I	II (mSv)	III	Annual collective dose I	II (man-Sv)	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:

$ß_1$ (<5 mSv) = 0
$ß_2$ (5 to 15 mSv) = \$40000 (person-Sv)$^{-1}$
$ß_3$ (15 to 50 mSv) = \$80000 (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, e.g., 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, there are no values for beta or the ranges of importance for doses which have been endorsed by national or international authorities. 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).

Because the average individual dose for workers in all three groups exceed 15 mSv for Option 1, the entire collective dose of 0.561 man-Sv is in the range 15 to 50 mSv, where the value of ß is $80000 per man-Sv. The product, $80000 x 0561 = $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 are also within range 15 to 50 mSv and are evaluated similarly. For Option 4, 0.070 man-Sv are in range 15 to 50 mSv and 0.126 man-Sv in range 5 to 15 mSv. Therefore, the cost Y(ß) for Option 4 is $80000 x 0.070 + $40000 x 0.121 = $5600 + $4840 = $10,440 and for Option 5, Y(ß) = $9,640. The partial detriment annual costs, Y(ß), are presented in Table F-7.

Table F-7. Annual collective doses in each individual dose range and partial Y(ß) detriment cost for the options considered.

Protection option n	Annual collective dose - total (S) man-Sv	Annual collective dose - Range 1 (S_1) man-Sv	Annual collective dose - Range 2 (S_2) man-Sv	Annual collective dose - Range 3 (S_3) man-Sv	Partial detriment annual cost, Y(ß), $
1	0.561	0	0	0.561	44900
2	0.357	0	0	0.357	28600
3	0.335	0	0	0.335	26800
4	0.196	0	0.126	0.070	10400
5	0.178	0	0.115	0.063	9600

Note: [a] $ß_1$ (<5 mSv) = 0
$ß_2$ (5 to 15 mSv) = $40000 (person-Sv)$^{-1}$
$ß_3$ (15 to 50 mSv) = $80000 (person-Sv)$^{-1}$

Applying the selected beta values, as well as the alpha factor in the previous example, the data in Table F-7 was 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 F-8.

Table F-8. Extended cost benefit analysis for the options considered for the uranium mine options.

Protection option n	Annual protection cost (X) $	Annual detriment cost Y(þ), $	Annual detriment cost[a] Y(ß), $	Total annual cost = X + Y(þ)+Y(ß), $
1	10400	11200	44900	66000
2	17200	7100	28600	53000
3	18500	6700	26800	52000
4	32200	3900	10400	<u>47000</u>
5	35500	3600	9600	49000

Note:[a] Assumes þ = \$20000 (person-Sv)$^{-1}$.

$ß_1$ (<5 mSv) = 0

$ß_2$ (5 to 15 mSv) = \$40000 (person-Sv)$^{-1}$

$ß_3$ (15 to 50 mSv) = \$80000 (person-Sv)$^{-1}$

The optimum solution is underlined.

In the example of extended cost-benefit analysis, above, the "comfort" factor was not included in the optimization determination. Note in Table F-3 that Option 4 (the optimum) involves severe discomfort for the workers owing to the substantially increased airflow. Taking this factor into consideration, the likely decision would be to select Option 3, since it involves only slight discomfort.

Multi-Attribute Utility Analysis

An alternative method of choosing among options is by **multi-attribute utility analysis**. This method requires that the n relevant factors important to radiological protection be identified. These factors are known as **attributes**. Each of these attributes must 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, it used to express the relative importance (or weight)assigned to each attribute. The scaling factors are generally normalized so that E k_j = 1. The multi-attribute **utility function** for option i, U_i, is given by:

$$U_i = \text{þ}_{j=1}^{n} k_j u_j$$

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

The results of the 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 F-5.

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 is used to relate the collective dose for each option to cost in a linear manner.

$$\frac{k(X)}{R(X)} = \frac{k(S)}{\text{þ}R(S)} \qquad \text{and} \qquad k(X) + k(S) = 1$$

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

From Table F-3, R(X) = \$35500 - \$10400 = \$25100
R(S) = 0.561 - 0.178 = 0.383 (person Sv)
þ = \$20000 (person Sv)$^{-1}$

$$k(X) = \frac{[1 - k(X)]\ R(X)}{þ\ R(S)}$$

$$k(X)\ þ\ R(S) = R(X) - k(X)\ R(X)$$

$$k(X)\ [þ\ R(S) + R(X)] = R(X)$$

$$k(X) = \frac{R(X)}{[þR(S) + R(X)]}$$

$$k(X) = \frac{25100}{[20000 \times 0.383 + 25100]} = \underline{0.766}$$

Then $k(X) + k(S) = 1$

$0.766 + K(S) = 1$

$k(S) = 1 - 0.766 = \underline{0.234}$

Because u = 1 for u_1 (the least annual protection cost among the options), and $u_5 = 0$ (the costliest of the options, the **partial utility** for each of the other options can be determined by the proportionality:

$$u_i(X) = \frac{[X_{max} - X_2]}{R(X)}$$

$u_2(X) = [35500 - 17200]/25100 = 18300/25100 = 0.729$

$u_3(X) = [35500 - 18500]/25100 = 0.677$

$u_4(X) = [35500 - 32200]/25100 = 0.131$

On the other hand, the lower annual collective dose is desirable and, therefore, has a partial utility of 1; and the highest collective dose is assigned the partial utility value of 0.

The complete data for the multi-attribute analysis is presented in Table F-9.

$$u_i(S) = \frac{[S_{max} - S_2]}{R(S)}$$

$u_2(S) = 0.533$

$u_3(S) = 0.590$

$u_4(S) = 0.953$

Table F-9. Partial utilities and utility analysis corresponding to the simple cost-benefit analysis for the options considered

Protection Option, n	Annual protection cost, X $	Annual collective dose, S man-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	510400	0.561	1	0	0.77	0	<u>0.77</u>
2	17200	0.357	0.729	0.533	0.56	0.12	0.68
3	18500	0.335	0.677	0.590	0.52	0.14	0.66
4	32300	0.196	0.131	0.953	0.10	0.22	0.32
5	35500	0.1781	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 and the 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 F-6. 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 ranges are determined from Table F-6 as 0, 0.126, and 0.498 person-Sv. The scaling constant for the n portion of the collective dose is defined by:

$$\frac{k(X)}{R(X)} = \frac{k(S_n)}{\beta_n R(S_n)}$$

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

$$k(X) + k(S) + \sum_{1}^{3} k(S_n) = 1$$

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, and $k(S_3)$=0.513. Calculating the partial utilities and applying the scaling constants provides the data summarized in Table F-10.

The remaining factor, comfort, can be expressed as a utility function. "No problem" receives a value of 1 and "difficult to work" is assigned 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.

Table F-10 Partial utilities and utility analysis corresponding to the extended cost benefit analysis for the options considered.

Pro-tection option	Partial utility u(X)	Partial utility $u(S)_1$	Partial utility $u(S_2)$	Partial utility $u(S_3)$	Scaled k(X)þ u(X)	Scaled $k(S_1)$þ $u(S_1)$	Scaled $k(S_2)$þ $u(S_2)$	Scaled $k(S_3)$þ $u(S_3)$	Utility U
1	1	0	1	0	0.323	0.065	0	0.388	0.388
2	0.729	0.533	1	0.410	0.235	0.065	0.210	0.563	0.563
3	0.677	0.590	1	0.454	0.219	0.065	0.233	0.575	0.575
4	0.131	0.953	0	0.986	0.042	0	0.506	0.642	<u>0.642</u>
5	0	1	0.087	1	0	0.006	0.514	0.618	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