Designation: E 2216 – 02

Standard Guide for
Evaluating Disposal Options for Concrete from Nuclear Facility Decommissioning[1]

This standard is issued under the fixed designation E 2216; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

INTRODUCTION

Numerous nuclear facilities containing large amounts of concrete are scheduled for decontamination and decommissioning over the next several decades. Much of this concrete is either not contaminated or only lightly contaminated on or near the surface. However, since concrete is slightly porous, it has the potential to be contaminated volumetrically. Volumetric contamination is more difficult to measure than surface contamination, and currently there are no release guidelines for volumetrically contaminated concrete. As a result, large volumes of concrete are often disposed of as radioactive waste at a large cost.

Under certain conditions, the depth or amount of contamination may be limited such that a case can be made for concrete release for other purposes outside of regulatory control. These cases are likely to be ones where the radioactive contamination is shallow and is limited to a depth that can be removed by scabbling (removal of the concrete surface), or where the depth can be estimated based on the history and condition of the concrete. In addition to surface contaminated concrete, some facilities contain activated concrete where the depths of contamination vary. This type of concrete should be handled on a case-by-case basis. Accurate measurements of the radiation source are difficult for activated concrete, because the activated portions of the embedded metal or concrete are partially shielded by the concrete that lies between the source and the measuring device. Care must be taken to measure radiation levels of activated concrete accurately, so actual radiation levels are documented and used when applying release criteria.

This standard guide applies to nonrubbelized concrete that is still in place with a defined geometry and known history where the depth of contamination can be measured or estimated based on its history. It is not practical to measure radiation levels of concrete rubble. The process outlined here starts with characterizing the concrete in place, then evaluating the dose to the public and cost of various disposal options.

1. Scope

1.1 This standard guide defines the process for developing a strategy for dispositioning concrete from nuclear facility decommissioning. It outlines a 10-step method to evaluate disposal options for radioactively contaminated concrete. One of the steps is to complete a detailed analysis of the cost and dose to nonradiation workers (the public); the methodology and supporting data to perform this analysis are detailed in the appendices. The resulting data can be used to balance dose and cost and select the best disposal option. These data, which establish a technical basis to apply to release the concrete, can be used in several ways: (*1*) to show that the release meets existing release criteria, (*2*) to establish a basis to request release of the concrete on a case-by-case basis, (*3*) to develop a basis for establishing release criteria where none exists.

1.2 This standard guide is based on the “Protocol for Development of Authorized Release Limits for Concrete at U.S. Department of Energy Sites,” (Arnish, J. et.al., 2000) from which the analysis methodology and supporting data are taken.

1.3 Guide E 1760 provides a general process for release of materials containing residual amounts of radioactivity. In addition, Guide E 1278 provides a general process for analyzing radioactive pathways. This standard guide is intended for

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[1] This guide is under the jurisdiction of ASTM Committee E10 on Nuclear Technology and Applications and is the direct responsibility of Subcommittee E10.03 on Radiological Protection for Decontamination and Decommissioning of Nuclear Facilities and Components.

Current edition approved June 10, 2002. Published October 2002.

use in conjunction with Guides E 1760 and E 1278, and provides a more detailed approach for the release of concrete.

2. Referenced Documents

2.1 *ASTM Standards:*

E 1278 Guide for Radioactive Pathway Methodology for Release of Sites Following Decommissioning[2]

E 1760 Guide for Unrestricted Disposition of Bulk Materials Containing Residual Amounts of Radioactivity[2]

E 1893 Guide for Selection and Use of Portable Radiological Survey Instruments for Performing In Situ Radiological Assessments in Support of Decommissioning[2]

2.2 *ANSI Standards:*[3]

ANSI/USAS N13.12 Surface and Volume Radioactivity Standards for Clearance

ANSI/USAS N13.2 Guide for Administrative Practices in Radiation Monitoring

2.3 *IAEA Standards:*[4]

Safety Series No. 111-P-1.1 Application of Exemption Principles to the Recycle and Reuse of Materials from Nuclear Facilities

IAEA-TECDOC-855 Clearance Levels for Radionuclides in Solid Materials, (Interim Report for Comment)

2.4 *ISO Standards:*[5]

ISO-4037 X and Gamma Reference Radiations for Calibrating Dosimeters and Dose-rate Meters and for Determining their Response as a Function of Photon Energy

ISO-6980 Reference Beta Radiations for Calibrating Dosimeters and Dose-rate Meters and for Determining Their Response as a Function of Beta Radiation Energy

ISO-8769 Reference Sources for the Calibration of Surface Contamination Monitors—Beta Emitters (Maximum Beta Energy Greater than 0.15 MeV) and Alpha Emitters

ISO-7503-1 Evaluation of Surface Contamination—Part 1: Beta Emitters (Maximum Beta Energy Greater than 0.15 MeV) and Alpha Emitters

ISO-7503-2 Evaluation of Surface Contamination—Part 2: Tritium Surface Contamination

ISO-7503-3 Evaluation of Surface Contamination—Part 3: Isomeric Transition and Electron Capture Emitters, Low Energy Beta Emitters (E_{Bmax}<0.15 MeV)

2.5 *DOE Standards:*[6]

DOE G 4441.1–7 Portable Monitoring Instrument Calibration Guide for Use With Title 10, Code of Federal Regulations, Part 835, Occupational Radiation Program, 6–17–1999.

Order 5400.5 Radiation Protection of the Public and the Environment, as amended

2.6 *U.S. Government Documents:*[7]

NUREG-1640 Radiological Assessments for Clearance of Equipment and Materials From Nuclear Facilities

NUREG/CR-5512 Residual Radioactive Contamination From Decommissioning

10 CFR 20 Standards for Protection Against Radiation

2.7 *NRC Standards:*[8]

Regulatory Guide 1.86 Termination of Operating Licenses for Nuclear Reactors

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *activated concrete*—concrete that has components (such as metal filings or pieces) that have become radioactive through exposure to high radiation fields; the concrete itself is radioactive.

3.1.2 *as low as reasonably achievable (ALARA)*—is a process used for radiation protection to manage and control exposures (both individual and collective to the work force and to the general public) and releases of radioactive material to the environment so that the levels are as low as is reasonable taking into account social, technical, economic, practical, and public policy consideration. **ANSI/HPS N13.12**

3.1.3 *release*—occurs when property is transferred out of regulatory control by sale, lease, gift, or other disposition, provided that the property does not remain under radiological control by a regulatory agency. The release does not apply to real property (such as real estate), radioactive wastes, soils, liquid discharges, or gaseous or radon emissions.

3.1.4 *surface contamination*—radioactive contamination residing on or near the surface of an item. This contamination can be adequately quantified in terms of activity per unit area. **ANSI/HPS N13.12**

3.1.5 *volumetric contamination*—radioactive contamination residing in or throughout the volume of an item. Volumetric contamination can result from neutron activation or from the penetration of radioactive contamination into cracks or interior surfaces within the interior matrix of an item. **ANSI/HPS N13.12**

4. Significance and Use

4.1 This standard guide applies to concrete that is still in place with a defined geometry and known, documented history.

4.2 It is not intended for use on concrete that has already been rubbelized where it is difficult to measure the radiation levels and not easy to remove surface contamination to reduce radiation levels after concrete has been rubbelized.

4.3 This standard guide applies to surface or volumetrically contaminated concrete, where the depth of contamination can be measured or estimated based on the history of the concrete.

4.4 This standard guide does not apply to the reinforcement bar (rebar) found in concrete. Although most concrete contains

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[2] *Annual Book of ASTM Standards*, Vol 12.02.

[3] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036.

[4] Available from International Atomic Energy Agency, Wagramerstrasse, PO Box 100 A-1400, Vienna, Austria.

[5] Available from International Organization for Standardization (ISO), 1 rue de Varembé, Case postale 56, CH-1211, Geneva 20, Switzerland.

[6] Available from United States Department of Energy, National Technical Information Service, US Dept. of Commerce, Springfield, VA 22161.

[7] Available from the Superintendent of Documents, US Government Printing Office, Washington, DC 20402.

[8] Available from Nuclear Regulatory Commission, Public Document Room, 1717H St. NW, Washington, DC 20555.

rebar, it is generally removed before the concrete is dispositioned. In addition, rebar may be activated, and is covered under procedures for reuse of scrap metal.

4.5 General unit-dose and unit-cost data to support the calculations is provided in the appendices of this standard guide. However, if site-specific data is available, it should be used instead of the general information provided here.

4.6 This standard guide helps determine estimated doses to the public during disposal of concrete and to future residents of disposal areas. It does not include dose to radiation workers already involved in a radiation control program. It is assumed that the dose to radiation workers is already tracked and kept within acceptable levels through a radiation control program. The cost and dose to radiation workers could be added in to find an overall cost and dose for each option.

5. Elements of the Release Process

5.1 This standard guide describes the steps of an overall release process for radioactively contaminated concrete from decommissioning nuclear facilities. As one of the steps, it provides a method and supporting data to estimate the dose and cost impacts for various disposal options. This data can be used to select the best disposal option, which should be one that meets regulatory guidelines while reducing dose and cost. Release of any surface or volumetrically contaminated material must meet all criteria of the governing regulatory agencies.

5.2 S.Y. Chen, et al, (1999), described a 10-step release process in the publication, "Authorized Release of DOE's Non-Real Property: Process and Approach." These 10 steps are the basis for the, "Protocol for Development of Authorized Release Limits for Concrete at U.S. Department of Energy Sites" (Arnish, J., et al, 2000) and also for this standard guide.

5.2.1 Characterize property and prepare a description;

5.2.2 Determine whether applicable authorized or supplemental guidelines already exist;

5.2.3 Define authorized or supplemental guidelines needed;

5.2.4 Develop authorized or supplemental guidelines;

5.2.5 Compile and submit application for approval from the regulatory agencies;

5.2.6 Document approved guidelines in the public record;

5.2.7 Implement approved guidelines;

5.2.8 Conduct surveys/measurements;

5.2.9 Verify that applicable authorized or supplemental guidelines have been met; and

5.2.10 Release property.

5.3 *Characterize Property and Prepare a Description*:

5.3.1 Document the concrete's physical and radiological characteristics, including history. The concrete's history and condition can be used to estimate the depth of penetration of radioactive contamination, or this can be measured. Radiological surveys must be done to determine the isotopes and level of radioactive contamination on the surface of the concrete.

5.4 *Determine Whether Authorized Release Guidelines Already Exist*:

5.4.1 If surface or volumetric activity release guidelines exist, and the concrete is below those levels, the concrete can be released through approved regulatory methods. Documents including ANSI/HPS N13.12-1999, U.S. NRC Regulatory Guide 1.86, and others may provide applicable release guidelines. In any case, this standard guide can be used to complete an analysis of the dose and cost for various disposal options and select the best one. All required regulatory approvals must still be obtained before releasing the concrete.

5.4.2 If no existing guidelines apply, this standard guide can be used to estimate the ramifications of each disposal option, select the best disposal option, and then apply for approval to release the material based on these data. Such releases could be done on a case-by-case basis, or to set a new authorized release limit.

5.5 *Define What Authorized or Supplemental Guidelines are Needed*:

5.5.1 If authorized release guidelines do not exist, define what type of guidelines need to be developed:

5.5.1.1 Surface or volumetric contamination;

5.5.1.2 One-time or routine release;

5.5.1.3 Restricted or unrestricted release.

5.6 *Define Authorized or Supplemental Guidelines*:

5.6.1 Estimate the dose and cost for the various disposal options. Each disposal option consists of a set of actions such as decontamination and disposal. The dose and cost of a disposal option depend upon the actions that make up that option. Five actions are defined in the appendices: decontamination, demolition/crushing, packaging/transportation, reuse, and disposal/entombment. The appendices provide the methodology and supporting data to estimate the dose and cost of each action. To evaluate a disposal option, use the applicable sections in the appendices to calculate the dose and cost for each action in the disposal option. Then sum the dose and cost from all of the applicable actions to find the total dose and cost for that disposal option.

5.6.2 The dose estimate is based on the isotopes present, the estimated or measured depth of penetration, and the disposal option. The cost is based on factors associated with the disposal option, such as decontamination, transportation, and disposal. The cost analysis information here does not include cost avoidance through such things as schedule acceleration and reduced surveillance. Formulas and tables of unit-dose and unit-cost data for estimating the dose and cost are in the appendices. However, if site-specific information (such as cost and decontamination factors) is available, it should be used instead of the general information provided here.

5.6.3 After completing a detailed analysis of the estimated dose and cost for each option, compare the results and choose the best option. The best option is likely to be the one that meets regulatory guidelines while reducing dose and cost. The data can be used to support release of the concrete if release guidelines already exist. If release guidelines do not exist, the data can be used to establish a basis to request release of the concrete either on a case-by-case basis or to set new release guidelines.

5.7 *Compile and Submit an Application for Approval to Release Material*:

5.7.1 Present the results of the analysis for the chosen alternative to the governing regulatory agencies to request permission to release the concrete. Document any limitations or restrictions on the use of the concrete (such as decontamination to a certain level), and any comments or recommendations by federal, state, or regulatory agencies in the application. In addition, attach the survey procedures and results to the application.

5.8 *Document the Approved Guidelines in the Public Record*:

5.8.1 Document the planned release of concrete in the public record to provide the public with information about radiation levels and expected dose.

5.9 *Implement the Approved Guidelines*:

5.9.1 Once the governing regulatory agencies approve the release, the approved guidelines can be implemented. This should be done in compliance with all required regulations and site specific procedures and requirements.

5.10 *Conduct Surveys/Measurements*:

5.10.1 Conduct radiological surveys to show that the concrete meets applicable release guidelines. Previously conducted surveys can be used if the documentation is sufficient to meet regulatory requirements. Documentation should show that surveys were done according to site-specific procedures and should include survey results. Guidelines such as Guide E 1893 may provide useful information about conducting surveys.

5.11 *Verify that Applicable Authorized or Supplemental Guidelines Have Been Met*:

5.11.1 Compare the survey results with the release guidelines to verify that the release guidelines have been met and document the results.

5.12 *Release Material*:

5.12.1 Before releasing the concrete, verify that all of the applicable regulations and procedures have been met. When compliance with all requirements has been verified and documented, the concrete may be released under direction of the governing regulatory agencies.

6. Quality Assurance

6.1 This standard guide addresses release of concrete that was previously radioactively contaminated, so quality assurance principles and methods should be applied both in the initial surveys and data collection, and in estimating the dose and cost of disposal options. Care should be taken to ensure that all work is done according to appropriate quality assurance methods and procedures. These quality assurance procedures should be established before initiating the calculations contained in the appendices. Quality assurance procedures are especially important when using site-specific data for the calculations in Appendix X1.

7. Use of the Appendices

7.1 Appendix X1 through Appendix X5 provide details about how to complete step 5.6 to estimate the dose and cost for various disposal options. The methodology and formulas are presented in Appendix X1, while Appendix X2 through Appendix X5 provide unit-dose factors, unit-cost factors, and other data that can be used in the formulas. After using the methodology and data in the appendices to complete step 5.6, the resulting estimates of dose and cost can be used to select the best disposal option and proceed through the remaining steps of the process.

APPENDIXES

(Nonmandatory Information)

X1. METHODOLOGY TO ESTIMATE DOSE AND COST FOR DISPOSAL OPTIONS FOR CONCRETE FROM D&D OF NUCLEAR FACILITIES

INTRODUCTION

Adapted from the Argonne report, “Protocol for Development of Authorized Release Limits for Concrete of U.S. Department of Energy Sites,” Arnish, J., et al, ANL/EAD/TM-92 Argonne National Laboratory, IL, July 2000.

X1.1 These sections describe the methodology used to estimate the costs and nonradiation worker doses for the disposal options. Seven general options are described here. Other options may be feasible, and can usually be analyzed as subsets of these general options. The options may include:

X1.1.1 Decontaminate, dispose of all low-level radioactive waste (LLW), crush and reuse as roadbed material.

X1.1.2 Crush without decontamination and reuse as roadbed material.

X1.1.3 Decontaminate, dispose of all LLW, demolish, and dispose of the decontaminated material as construction debris, or reuse as backfill.

X1.1.4 Demolish, without decontamination and either dispose as construction debris, or reuse it as backfill.

X1.1.5 Demolish without decontamination and dispose of all materials as LLW.

X1.1.6 Decontaminate the structure and reuse.

X1.1.7 Demolish with or without decontamination and entomb the demolished material.

X1.2 For each of the options, one or more of the following individual actions may apply:

X1.2.1 Decontamination;

X1.2.2 Demolition/crushing;

X1.2.3 Packaging/transportation;

X1.2.4 Reuse; and

X1.2.5 Disposal/entombment.

X1.2.6 The dose and cost calculation methods for each action are discussed in the individual sections of this appendix. To find the total nonradiation worker dose for each disposal option, the dose and cost for all applicable actions need to be summed. Table X1.1 provides a list of the options and the applicable sections of this appendix for estimating the costs and associated radiological doses.

X1.2.7 The costs or radiological doses (when applicable) can be estimated by using unit-cost or unit-dose factors. The unit-cost factors were obtained from such sources as Ayers et al. (1999), Chen et al. (1996), Dickerson et al. (1995), and others. The unit-cost factors for the applicable sections are provided in the individual sections and in Appendix X2 through Appendix X5. Unit-dose factors are used to estimate the radiological doses to members of the public from the reuse or disposal of concrete materials. These factors were generated with a suite of computer codes such as RESRAD (Yu et al. 1993), RESRAD-BUILD (Yu et al. 1994), RESRAD-RECYCLE (Cheng et al. 1999), TSD-DOSE (Pfingston et al. 1998), and RISKIND (Yuan et al. 1995). The unit-dose factors are presented in Appendix X2 through Appendix X5 and discussed in the specific sections below. These calculations assume that source distribution throughout the mass is uniform, and that no hot spots exist. If significant variations of source throughout the mass or in the surface distribution exist, these should be taken into account with more detailed analysis and calculations. Radiological doses are estimated only for nonradiation workers (that is, workers not already part of a radiation protection program). Although doses for radiation workers are not included here, they should be added when comparing the comprehensive cost and dose for each option. For the cost components, if site-specific or process-specific costs are available, then those values should be used instead of the unit-cost factors presented in this document.

X1.3 *Decontamination*—For contaminated concrete materials, decontamination can remove the amount of contamination on the material. In general, contaminants are less likely to migrate into the concrete when the surface is painted or coated. In dry areas, contaminant migration into unpainted concrete will probably be limited to the top ¼ in. If the concrete has been exposed to contaminated liquids for long periods, or is cracked, the contaminants may migrate farther into the concrete matrix. The process rates and costs for decontamination can vary greatly because of the large number of factors that affect technology efficiency and effectiveness. A common technique for removing fixed contamination from concrete walls and floors is the use of hand-held or automated scabbling units. These units mechanically remove a thin layer (⅛ to ¼ in.) from the surface of the concrete. Another commonly used technique for removing loose contamination is spraying the surface with a nontoxic cleaner and wiping, although strippable coatings have also been used with success. The use of water and abrasive blasting is limited because of problems with handling the waste that is generated. For each decontamination method considered, the decontamination efficiency, volume of waste generated, and cost need to be calculated. The decontamination efficiency will be used to estimate the dose from reuse or disposal. The volume of waste generated will be used to estimate the transportation and disposal costs. It is assumed that the decontamination worker is already part of an ALARA program, so this dose is not included here. To support completion of the formulas in the decontamination module, Appendix X2 has unit operational cost, production rates, and waste generation information for some decontamination methods. The waste from decontamination activities will be disposed of in a LLW radioactive disposal site.

X1.3.1 *Decontamination Efficiency*—Decontamination efficiency (D_{EF}), a measure of the amount of contamination left after decontamination, must be estimated so that the dose from either reuse or disposal after decontamination can be estimated. The decontamination efficiency is defined here to be the inverse of the decontamination factor (DF) (that is, $D_{EF} = 1/DF$). The D_{EF} value of 0 is interpreted as meaning all radioactive material has been removed from the surface of the concrete material; the D_{EF} value of 1 means no decontamination was performed. Generally, decontamination is limited to surface-contaminated concrete materials; hence, for most activated volumetrically contaminated concrete, the decontamination efficiency should be set equal to 1.

X1.3.1.1 If field measurements are available, the decontamination efficiency is derived in the following manner:

$$D_{EF} = \frac{A_{Final}}{A_{Initial}} \tag{X1.1}$$

where:

TABLE X1.1 Concrete Disposal Options and the Corresponding Cost and Dose Assessment Sections

Options	Appendix Sections
Decontaminate the concrete material, dispose of all LLW, and crush and reuse the decontaminated material	Decontamination, Demolition/Crushing, Packaging/Transportation, Reuse, and Disposal
Crush and reuse the concrete without decontamination	Demolition/Crushing, Packaging/Transportation, and Reuse
Decontaminate the concrete, dispose of all LLW, demolish the structure, and dispose of the decontaminated material as construction debris (nonradiological landfill) or reuse as backfill	Decontamination, Demolition/Crushing, Packaging/Transportation, Reuse, and Disposal
Demolish the structure and dispose of the concrete material as construction debris or reuse as backfill (nonradiological landfill—no decontamination)	Demolition/Crushing, Packaging/Transportation, Reuse, and Disposal
Demolish the structure and dispose of all materials as LLW	Demolition/Crushing, Packaging/Transportation, and Disposal
Decontaminate the building and reuse as office space	Decontamination, Packaging/Transportation, Reuse, and Disposal
Demolish the building and entomb on-site	Demolition/Crushing, and Disposal/Entombment

A_{Final} = total activity, dpm/100 cm^2, after decontamination, and
$A_{Initial}$ = total activity, dpm/100 cm^2, prior to decontamination.

X1.3.1.2 If no field measurements are available, the decontamination efficiency can be estimated for contamination distributed uniformly throughout a given thickness of the concrete material as:

$$D_{EF} = \left[1 - \left(\frac{RR}{T_C}\right) \times P\right] \qquad (X1.2)$$

where:
D_{EF} = decontamination efficiency applied to all isotopes,
RR = removal rate, thickness/pass,
P = number of passes or treatments, and
T_C = thickness of the contamination.

X1.3.1.3 Appendix X2 lists some decontamination technologies for both loose and fixed contamination and provides estimated parameter values for the removal rate.

X1.3.2 *Waste Generation*—The total amount of waste generated during decontamination is used as input when estimating the cost associated with the transportation of the decontamination wastes to a LLW disposal facility. For decontamination technologies that provide a waste generation rate in units of cubic feet of waste generated per square foot of material treated (ft^3/ft^2), the total amount of waste generated is estimated as:

$$WasteGen = Area \times WGR + Other \qquad (X1.3)$$

where:
$WasteGen$ = total amount of waste generated, ft^3,
$Area$ = area of the concrete material being decontaminated, ft^2,
WGR = waste generation rate, ft^3/ft^2, and
$Other$ = other wastes generated during the decontamination process (personal protective equipment [PPE], chemicals, etc.).

X1.3.2.1 For fixed contamination, decontamination is performed by physically removing layers of concrete. Hence the total amount of waste generated is estimated as:

$$WasteGen = Area \times RR \times P + Other \qquad (X1.4)$$

where:
RR = removal rate (thickness/pass), and
P = number of passes or treatments.

X1.3.2.2 If a concrete structure is decontaminated with abrasive blasting, the total amount of waste generated is a combination of both factors and is therefore estimated as:

$$WasteGen = Area \times [(RR \times P) + WGR] + Other \qquad (X1.5)$$

Appendix X2 provides the waste generation rates for some decontamination technologies.

X1.3.3 *Decontamination Costs*—Three components must be considered in estimating the cost for the decontamination technologies: (*1*) amortization cost for the equipment, (*2*) process costs, and (*3*) labor costs. The amortization cost for the equipment takes into account the cost of purchasing the decontamination equipment, the equipment life, and the interest rate. The process cost is the cost of operating the equipment, which may include supplies required to run the equipment or may include costs for routine maintenance. The labor costs are the costs associated with workers using the decontamination equipment. Although other costs may also be associated with decontamination, only these costs are considered here because they would contribute the most to the total cost associated with decontamination activities. The hourly amortization cost (EC), over the life of the equipment is given as:

$$EC = \left[\frac{PI\,(1+I)^N}{\{(1+I)^N - 1\}}\right] \times \frac{1}{8760} \qquad (X1.6)$$

where:
P = purchase cost of the equipment,
I = interest rate,
N = equipment life, yr, and
1/8760 = conversion from per year to per h.

X1.3.3.1 The total cost for decontamination operations is estimated as:

$$Decon\$ = EC \times UT \times A \times P \times \left(PC + \frac{1}{PR} \times HC\right) \qquad (X1.7)$$

where:
$Decon\$$ = total cost for decontamination, \$,
EC = amortization cost for the decontamination equipment, \$/h,
UT = equipment use time for decontamination operations, h,
A = area, ft^2,
P = number of passes or treatments,
PC = process cost, \$/ft^2/pass or treatment,
PR = production rate, ft^2/h/pass or treatment, and
HC = hourly cost for a decontamination worker, \$/h.

The values for the capital cost, production rates, and hourly costs for some decontamination technologies are provided in Appendix X2.

X1.4 *Demolition/Crushing*—For all options except building reuse, the concrete material would undergo some demolition and possibly further processing, including crushing. The methods used to demolish concrete structures include controlled blasting and use of wrecking balls, backhoe-mounted rams, rock splitters, paving breakers, and others. The size and type of concrete material to be demolished would determine the actual method selected. As they are for decontamination, the demolition workers are assumed to be part of a radiation protection program; hence, the radiological doses associated with demolition are already kept ALARA and are not included here. The unit-cost factor for demolition has been estimated at $\$1/ft^2$($\$10.76/m^2$) of building area (Ayers et al. 1999). The cost for demolition is estimated as:

$$Demol\$ = A \times DemolCF \qquad (X1.8)$$

where:
$Demol\$$ = cost for demolition, \$,
A = building area, ft^2, and
$DemolCF$ = demolition unit cost factor, \$/ft^2.

X1.4.1 For the options that involve further processing of the concrete material by crushing, the cost for crushing is estimated as:

$$Crush\$ = M \times CF \qquad (X1.9)$$

where:

$Crush\$$ = cost for crushing the concrete material, \$,

M = mass of the material, metric ton (MT), and

CF = unit cost factor for crushing the material.

Ayers et al. (1999) provide a lognormal distribution for the cost associated with concrete crushing. On the basis of the parameters of the lognormal distribution, the 50th percentile value for the unit-cost factor for crushing and screening the concrete material was estimated at \$23/MT.

X1.4.2 The process of crushing concrete into aggregate for reuse generates unusable fines that must be sent to a disposal facility. The mass of fines generated has been estimated to be approximately 30 % of the mass of the pre-crushed concrete (Ayers et al. 1999). Hence, the amount of fines (M_{Fines}) is estimated as:

$$M_{Fines} = F \times M \tag{X1.10}$$

where:

F = fraction of mass converted to fines, and

M = mass of the pre-crushed concrete.

X1.5 *Packaging/Transportation*—This section provides the means for estimating the costs and risks associated with packaging and transporting the concrete materials and any waste generated from decontamination, demolition, and crushing activities. To complete this section, the distance, number of shipments, and associated costs should be documented. Unit-cost data for packaging, transport, and disposal is in the appendix. The methodology for estimating the dose to a truck driver transporting these materials is applied to the options involving transport of the concrete material to a nonradiological landfill. This dose is proportional to the number of shipments, amount and type of isotopes, and distance. For such options, the assumption is made that the truck driver is not a radiation worker and, hence, is not part of a radiation protection program, so the dose is included here. However, a truck driver transporting LLW to a radioactive disposal site is not included, as it is assumed that this person is already part of an ALARA program. In all cases, dose to people living along the transportation corridor should be included.

X1.5.1 *Packaging/Transportation Costs*—Two components are involved in estimating the costs of transportation activities: packaging costs and the costs associated with transportation. The packaging costs are estimated by evaluating the expenses associated with packaging the concrete into 55-gal drums, B25-type containers, or soft-sided containers.

X1.5.1.1 For 55-gal drums, the number of containers can be estimated on the basis of the mass of the material by using the equation below:

$$Containers = \frac{M}{\rho} \times \frac{1}{Vol_{container}} \tag{X1.11}$$

where:

M = mass of the material,

ρ = bulk density, and

$Vol_{container}$ = volume of the shipping container.

X1.5.1.2 If the volume of the material (rather than the mass of the material) is provided, then the number of containers required can be estimated by using this equation:

$$Containers = \frac{V}{Vol_{container}} \tag{X1.12}$$

where:

V = volume of the material, and

$Vol_{container}$ = volume of the cargo container (provided in Appendix X3).

X1.5.1.3 The B25 and soft-sided containers have weight restrictions that must be met. These restrictions are approximately 8000 lb per container for B25 containers and 24 000 lb for soft-sided containers. Therefore, if the amount of material placed into the cargo container is limited by weight, the number of containers can be estimated from:

$$Containers = \frac{M}{K} \tag{X1.13}$$

where:

M = mass, lb, and

K = weight restriction, lb.

X1.5.1.4 If the volume of the material is known, then the number of containers can be estimated as:

$$Containers = \frac{V \times \rho}{K} \tag{X1.14}$$

where:

V = volume, ft^3, and

ρ = bulk density, lb/ft^3.

For most applications, the bulk density for segmented concrete is approximately 112 lb/ft^3(1.8 g/cm^3).

X1.5.1.5 The total costs for packaging either the concrete or waste materials can be estimated by using the following equation:

$$Packaging\$ = \sum_{MaterialType} [(ULC + CC) \times Containers] \tag{X1.15}$$

where:

$Packaging\$$ = packaging cost, \$,

ULC = unit loading costs, \$/container,

CC = container cost, \$/container, and

$Containers$ = number of containers (estimated by using the previous equations).

The unit loading and container costs are provided in Appendix X3.

X1.5.1.6 The transportation costs are estimated by applying the methodology from Chen et al. (1996). The total transportation cost is proportional to the total number of shipments, which can be estimated from the number of containers that need to be shipped. For B25-type containers, the assumption is that 5 containers are shipped per truck and 10 per railcar, while 2 soft-sided containers can be shipped per truck and 6 per railcar. For 55-gal drums, up to 36 drums can be shipped per truck, while up to 120 may be shipped per railcar. The number of drums per truck or railcar is based on a bulk density of 180 lb/ft^3, a gross vehicle weight restriction of 80 000 lb for trucks, and a 60-ton payload capacity per railcar (Chen et al. 1996). The per-shipment costs are estimated by using the following equation:

$$Trans\$ = (UCF \times D + SCF) \times Shipments \tag{X1.16}$$

where:

$Trans\$$ = transportation cost, \$,
UCF = unit-cost factor, \$/shipment-mi,
D = distance to the disposal site, mi,
SCF = per-shipment cost factor, \$/shipment, and
$Shipments$ = number of shipments.

The unit-cost factors and the per-shipment cost factors are provided in Appendix X3.

X1.5.2 *Transportation Dose—Driver Scenario*—For the options that involve transportation of the demolished concrete materials to a nonradiological landfill, the dose to the driver of the truck transporting that material is evaluated. Since the material is assumed to be released from radiological control, it is assumed that the truck driver is not a radiation worker and therefore is not part of a radiation protection program. Evaluation of the driver dose takes into consideration the dose associated with the operation of the vehicle, as well as routine stops for rest or fuel. Truck stops are assumed to occur at a rate of 0.011 h/km (Neuhauser et al. 1992), and an average speed of 50 km/h is maintained while moving. The only applicable exposure pathway considered is external radiation. The radiation dose to the driver is estimated as:

$$D_{Driver} = \sum_{i=1}^{n} A_i \times UDF_i \times D_{EF} \times M \times D \times 1000 \qquad \text{(X1.17)}$$

where:

D_{Driver} = driver dose, mrem,
A_i = initial activity concentration of the ith isotope, pCi/g,
UDF_i = unit-dose factor for the ith isotope for the driver scenario, mrem/pCi/km,
DEF = decontamination efficiency (concrete material only) (unitless),
M = mass, kg,
D = distance to the disposal facility, km, and
1000 = a conversion factor, from kg to g.

For either concrete materials that have not undergone decontamination or for wastes generated during decontamination activities, the decontamination efficiency should be equal to 1. The unit-dose factors for the driver scenario were calculated with the TSD-DOSE computer model (Pfingston et al. 1998) and are provided in Appendix X3.

X1.5.3 *Transportation Dose to Persons along the Transportation Corridor*—Persons living along (off-link) or sharing (on-link) the transportation corridor could be exposed to low levels of radiation during the shipment of concrete or waste materials. The collective dose to the off-link and on-link receptors is estimated by using unit-risk factors generated with the computer programs RISKIND (Yuan et al. 1995) and TSD-DOSE (Pfingston et al. 1998). The unit-dose factors for the off-link receptors were estimated by assuming that 90 % of the travel occurred in a rural area (population density of 7 persons/km^2), 5 % in a suburban area (766 persons/km^2), and 5 % in an urban area (1,282 persons/km^2) (U.S. Department of Commerce [DOC] 1993). The average speed of the truck while moving was assumed to be 50 km/h. The unit-dose factors for the on-link receptors were estimated on the basis of two persons per vehicle and a traffic density of 930 vehicles per hour (Yuan et al. 1995). The only applicable exposure pathway considered is external radiation. On the basis of these assumptions, the collective dose to off- and on-link persons can be estimated by using the following equation:

$$D_{On-link,Off-link} = \sum_{i=1}^{n} A_i \times UDF_i \times D_{EF} \times D \times Shipments \qquad \text{(X1.18)}$$

where:

$D_{On\text{-}link,Off\text{-}link}$ = on- and off-link collective dose, person-rem,
A_i = initial activity for the ith isotope, pCi,
UDF_i = unit-dose factor for the ith isotope, person-rem/pCi/km,
D_{EF} = decontamination efficiency (concrete material only),
D = distance to the disposal site, km, and
$Shipments$ = number of shipments.

For either concrete that has not undergone decontamination or for wastes generated during decontamination activities, the decontamination efficiency should be equal to 1.

X1.6 *Reuse*—The reuse section considers the dose to construction workers from the reuse of the concrete materials if the structure is demolished or to the office worker if the building is reused. Depending on the option, the concrete may or may not be decontaminated before reuse.

X1.6.1 *Construction Worker Scenario*—The unit-dose factors for the construction worker scenario were estimated with the RESRAD-RECYCLE computer code (Cheng et al. 1999). Since the concrete material is free released, it is assumed that the exposed construction worker is not a radiation worker and is not included in a radiation protection program. The scenario was based on the assumption that a construction worker would take 0.067 h to construct 1 yd^2 of road surface (Ayers et al. 1999). The exposure pathways assumed for this scenario include external exposure, ingestion, and inhalation of airborne particulates. The inhalation and ingestion pathways are included because dust would be generated from the concrete materials during construction activities. For external exposure, the source was modeled as a 100-MT full cylinder with a 15-cm thickness, a radius of 940 cm, and a density of 2.4 g/cm^3. The average distance from the source was assumed to be 1 m. An inhalation rate of 1.2 m^3/h was used in the calculations. The dust loading concentration was assumed to be 0.001 g/m^3, and the respirable fraction was set at 0.1. An ingestion rate of 0.00625 g/h was used for the construction worker. It was estimated that the construction worker would be required to work a total of 22.3 h for a throughput of 100 MT of concrete.

X1.6.1.1 These calculations assume that source distribution throughout the mass is uniform, and that no hot spots exist. If significant variations of source throughout the mass or in the surface distribution exist, these should be taken into account with more detailed analysis and calculations.

X1.6.1.2 For the ALARA analysis, the dose to the construction worker was estimated in the following manner:

$$D_{Construction} = \sum_{i=1}^{n} A_i \times UDF_i \times M \times D_{EF} \times (1 - F) \qquad \text{(X1.19)}$$

where:

$D_{Construction}$ = dose to the construction worker, mrem,
A_i = initial activity concentration for the i^{th} isotope, pCi/g,
UDF_i = unit-dose factor for the i^{th} isotope for the construction worker scenario, (mrem)/((pCi/g) MT),
M = mass of the crushed concrete material in metric tons, MT,
D_{EF} = decontamination efficiency for the decontamination technique considered (unitless), and
F = fraction of the material converted to "fines" from the demolition and crushing process (unitless).

For conservatism, F could be set to 0, indicating that none of the concrete material is lost to fines. However, Ayers et al. (1999) assume that 30 % ($F = 0.3$) of the material is converted to fines. Appendix X4 provides the unit-dose factors for the construction worker scenario for the isotopes analyzed. For the options that do not consider decontamination prior to reuse, D_{EF} is set to 1.

X1.6.2 *Building Reuse Scenario*—The unit-dose factors for the building reuse scenario were calculated for a building occupant with the RESRAD-BUILD computer code (Yu et al. 1994). Because the building is released from radiological control, it is assumed the building occupant is not a radiation worker and is not part of a radiation protection program. The scenario was based on a building area of 200 m^2 and a building height of 2.5 m. The contamination was assumed to be present only on the floor because the building has been decontaminated and decommissioned with all other radiation removed. If radiation remains in other areas of the building, the calculations should be adjusted to account for other sources of radiation. Occupancy would occur immediately after the building was released. The occupant would spend 2000 h per year inside the building. The exposure pathways included in this scenario are direct external exposure from surface sources, inhalation of resuspended surface contamination, inadvertent ingestion of surface contamination, inhalation of indoor radon aerosol, external exposure from deposited particles, and external exposure during submersion in airborne radioactive dust. For direct external exposure, the midpoint of the occupant was assumed to be at a height of 1 m from the center of the source. All other parameters were set at RESRAD-BUILD default values.

X1.6.2.1 For the ALARA analysis, the dose to the building occupant in the building reuse scenario is estimated by the following equation:

$$D_{building\ reuse} = \sum_{i=1}^{n} A_i \times UDF_i \times D_{EF} \qquad \text{(X1.20)}$$

where:

$D_{building\ reuse}$ = dose to the building resident, mrem/yr,
A_i = the initial activity concentration for the i^{th} isotope, pCi/m^2,
UDF_i = unit-dose factor for the i^{th} isotope for the building reuse scenario (mrem/yr)/(pCi/m^2), and
D_{EF} = decontamination efficiency for the decontamination technique considered (unitless).

Appendix X4 provides the unit-dose factors for the building reuse scenario for the isotopes analyzed. For the options that do not consider decontamination prior to building reuse, the D_{EF} is set to 1.

X1.7 *Disposal/Entombment*—The disposal/entombment section evaluates the costs and radiological doses associated with either disposal or entombment of the concrete materials. For the options that include disposal at a nonradiological landfill, the doses to the landfill worker and a future resident at the former landfill site must be estimated. However, for the option that considers entombment, only the dose to a future resident at the former building site is considered.

X1.7.1 *Disposal Costs*—The disposal/entombment costs of the concrete materials can be estimated by using the following equation:

$$Disposal\$ = V \times UCF \qquad \text{(X1.21)}$$

where:

$Disposal\$$ = cost, \$,
V = volume of the concrete materials, ft^3, and
UCF = unit-cost factor for burial, \$/ft^3.

Unit-cost factors for disposal at nonradiological landfills vary by site; therefore site-specific data should be used.

X1.7.2 *Landfill Worker*—For the options that involve the transportation of the demolished concrete material to a nonradiological landfill, the dose to the landfill worker is evaluated. Since the material is assumed to be released from radiological control, it is assumed that the landfill worker is not a radiation worker and is not part of a radiation protection program. The exposure pathways include external exposure and inhalation. The inhalation pathway was included in this scenario because dust from the concrete materials may be generated when the concrete material is being placed in the landfill. The unit-dose factors for the landfill worker scenario were generated with the TSD-DOSE computer code (Pfingston et al. 1998). The dose to the landfill worker can be estimated by the following equation:

$$D_{Landfill\ Worker} = \sum_{i=1}^{n} A_i \times UDF_i \times M \times D_{EF} \times 1000 \qquad \text{(X1.22)}$$

where:

$D_{Landfill\ Worker}$ = dose to the landfill worker, mrem,
A_i = initial activity concentration of the concrete material for the i^{th} isotope, pCi/g,
UDF_i = unit-dose factor for the i^{th} isotope for the landfill scenario, mrem/pCi,
M = mass of the material, kg,
D_{EF} = decontamination efficiency (unitless), and

1000 = conversion factor from kg to g.

For concrete material that has not been decontaminated, the decontamination efficiency is set to 1. Appendix X5 provides the unit-dose factors for the landfill worker scenario.

X1.7.3 *Future Resident (Homesteader)*—The dose to a future resident is calculated for the options that dispose of the concrete materials at a nonradiological disposal facility or by on-site entombment. The scenario involves a person that builds a house and homesteads either on top of the former landfill or at the former site of the structure some time after the landfill or facility has closed. All exposure pathways are active and include external radiation, inhalation, and ingestion (crops, meat, milk and soil). The dose to the future resident can be estimated with the following equation:

$$D_{Future\ Resident} = \sum_{i=1}^{n} A_i \times UDF_i \times M \times D_{EF} \qquad \text{(X1.23)}$$

where:

$D_{Future\ Resident}$ = dose to the future resident, mrem/yr,

A_i = initial activity concentration of the ith radionuclide in concrete, pCi/g,

UDF_i = unit-dose factor for the ith radionuclide for the future resident, (mrem/yr)/((pCi/g)MT),

M = mass of the concrete material, metric tons (MT), and

D_{EF} = decontamination efficiency.

The unit-dose factor, UDF_i, will be case-specific depending on the mass of material to be disposed of and the volume in which it will be disposed and dilution effects, if any, on the effective source and source density. The unit dose factor can be calculated for each isotope using computer codes such as RESRAD or DandD. For the options where the concrete material is not decontaminated before disposal, D_{EF} is equal to 1.

X2. DECONTAMINATION UNIT-COST FACTORS

INTRODUCTION

Adapted from the Argonne report, “Protocol for Development of Authorized Release Limits for Concrete of U.S. Department of Energy Sites,” Arnish, J., et al, ANL/EAD/TM-92 Argonne National Laboratory, IL, July 2000.

TABLE X2.1 Common Decontamination Technologies with Unit-Cost and Process Factors for Removal of “Loose” Contamination

Technology	Capital Cost ($1,000)	Production Rate (ft^2/h)	Estimated Cost ($/$ft^2$ cleaned)	Secondary Waste Generation
CO_2 pellet blasting	150 to 350	10-90	0.90 to 1.75	Low—filters from HEPA systems
Water/steam blasting	50	Variable	0.50 to 2	High—large volumes of water to clean/process
Hand scrubbing (with spray on chemicals)	Low	Variable (10 to 100)	82	Low
Strippable coatings	Low	Up to 100	1 to 1.40	Low
Abrasive blasting with soft grits	50 to 200	60-200	0.20 to 2.15	10 to 50 ft^3/ft^2

TABLE X2.2 Common Technologies for Removing “Fixed” and Subsurface Contamination from Concrete (Removal of ¹⁄₁₆- to ½-in. layers of concrete)

Technology	Capital Cost ($1,000)	Production Rate (ft^2/h/pass)	Process Cost ($/$ft^2$/pass)	Removal Rate (in./pass)	Waste Generation
Abrasive blasting with aggressive grits	50 to 300	50 to 400	5 to 10	¹⁄₁₆	0.03 ft^3 solids/ft^2 cleaned and concrete removed
Hand held scarification/scabbling	5	10 to 30	1.85 to 2.50	¹⁄₁₆ to ¼	Concrete removed
Automated floor scabbling	30 to 175	20 to 400	5 to 30	¹⁄₁₆ to ½	Concrete removed
Automated wall scabbling	100 to 300	60 to 200	10 to 30	¹⁄₁₆ to ¼	Concrete removed, if water used up to 6 gal/min recycled.
Shot blasting	30 to 150	420	50 to 400	¼	0.01 to 0.19 ft^3/ft^2

X3. TRANSPORTATION UNIT-COST AND DOSE FACTORS

INTRODUCTION

Adapted from the Argonne report, "Protocol for Development of Authorized Release Limits for Concrete of U.S. Department of Energy Sites," Arnish, J., et al, ANL/EAD/TM-92 Argonne National Laboratory, IL, July 2000.

TABLE X3.1 Volumes and Unit Costs for Selected Cargo Containers

Container Type	Container Volume (ft^3)	Container Cost ($)	Unit Loading Cost ($)
B-25 type box[A]	87	790	160
Soft-sided container	260	500	301
55-gal drum[A]	7.4	50	100

[A] Source: Chen et al. (1996).

TABLE X3.2 Unit Costs for Concrete Shipments as a Function of Cargo and Transportation Mode

Cargo Shipped	Transportation Mode	Fixed Cost per Shipment ($)	Variable Cost per Shipment-Mile ($)	Applicable Mileage
Concrete in B-25 type or soft-sided boxes[A]	Truck	335	1.43	0 to 9,999
	Rail	750	2.32	0 to 1,000
			1.91	1,000 to 2,000
			1.60	2,000 to 9,999
Waste in drums[A]	Truck	880	4.00 to 5.94	0 to 9,999
	Rail	750	2.32	0 to 1,000
			1.91	1,000 to 2,000
			1.60	2,000 to 9,999

[A] Source: Chen et al (1996).

TABLE X3.3 Unit-Dose Factors[A] from the Transportation for the Driver and Persons Living along (off-link) or Sharing (on-link) the Transportation Corridor

Radionuclide	Driver Dose (mrem/pCi/km)	Collective Dose (person-rem/pCi/km)
Ac-227+D[B]	4.1E-14	1.24E-17
Ag-108m	2E-13	6.22E-17
Ag-110m	3.5E-13	1.10E-16
Am-241	2.3E-16	3.41E-20
Ce-144+D	6.4E-15	1.96E-18
Co-57	9.6E-15	2.81E-18
Co-60	3.3E-13	1.04E-16
Cs-134	1.9E-13	6.01E-17
Cs-137+D	7.0E-14	2.21E-17
Eu-152	1.4E-13	4.41E-17
Eu-154	1.5E-13	4.81E-17
Eu-155	2.3E-15	5.61E-19
Fe-55	0.00E+00	0.00E+00
I-129	1.0E-20	1.16E-27
Mn-54	1.1E-13	3.21E-17
Ni-63	0.00E+00	0.00E+00
Np-237+D	2.2E-14	6.82E-18
Pu-238	1.7E-19	1.78E-23
Pu-239	5E-18	1.54E-21
Pu-240	1.7E-19	1.82E-23
Pu-241+D	3.5E-19	1.02E-22
Ra-226+D	2.3E-13	7.22E-17
Ru-106+D	2.7E-14	8.22E-18
Sb-125+D	5.1E-14	1.58E-17
Sr-90	0.00E+00	0.00E+00
Tc-99	1.8E-18	5.01E-22
Th-230	1.7E-17	4.41E-21
U-232	1.2E-17	3.01E-21
U-233	2.7E-17	8.22E-21
U-234	3.5E-18	7.62E-22
U-235+D	1.5E-14	4.61E-18
U-238+D	2.6E-15	7.82E-19
Zn-65	7.5E-14	2.41E-17

[A] The unit-dose factors for the driver and the collective dose factors for the persons living along the or sharing the transportation corridor are calculated using TSD-DOSE (Pfingston et al. 1998) and RISKIND (Yuan et al. 1995) computer codes.

[B] "+D" means progeny nuclides with half-lives less than 180 days are in secular equilibrium with the parent.

X4. REUSE UNIT-DOSE FACTORS

INTRODUCTION

Taken with modifications from the Argonne report, “Protocol for Development of Authorized Release Limits for Concrete of U.S. Department of Energy Sites,” Arnish, J., et al, ANL/EAD/TM-92 Argonne National Laboratory, IL, July 2000.

TABLE X4.1 Unit-Dose Factors[A] for the Construction Worker and Building Resident for Reuse

Radionuclide	Construction Worker (mrem)/((pCi/g)MT)	Building Resident (mrem/yr)/(pCi/m^2)
Ac-227+D[B,C]	2.44E-04	2.62E-02
Ag-108m	NA[D]	1.43E-05
Ag-110m	2.37E-04	1.42E-05
Am-241	1.85E-05	1.84E-03
Ce-144+D	4.51E-06	6.99E-07
Co-57	6.49E-06	5.57E-07
Co-60	3.26E-04	1.90E-05
Cs-134	1.78E-04	1.12E-05
Cs-137+D	7.47E-05	5.16E-06
Eu-152	1.48E-04	9.82E-06
Eu-154	1.60E-04	1.05E-05
Eu-155	NA	5.98E-07
Fe-55	9.38E-10	1.20E-08
I-129	NA	4.12E-06
Mn-54	7.75E-05	4.70E-06
Ni-63	1.11E-09	3.15E-08
Np-237+D	4.56E-05	2.25E-03
Pu-238	1.57E-05	1.61E-03
Pu-239	1.73E-05	1.79E-03
Pu-240	1.73E-05	1.79E-03
Pu-241+D	3.25E-07	3.18E-05
Ra-226+D	2.44E-04	6.67E-05
Ru-106+D	2.07E-05	2.19E-06
Sb-125+D	4.83E-05	3.25E-06
Sr-90	7.47E-07	6.85E-06
Tc-99	4.99E-09	5.02E-08
Th-230	9.63E-06	1.33E-03
U-232	1.97E-05	2.81E-03
U-233	4.13E-06	5.53E-04
U-234	4.01E-06	5.39E-04
U-235+D	1.99E-05	5.07E-04
U-238+D	6.44E-04	4.84E-04
Zn-65	5.01E-05	2.97E-06

[A] The unit-dose factors for the construction worker and the building resident are calculated using the RESRAD-RECYCLE (Cheng et al. 1999) and RESRAD-BUILD (Yu et al. 1994) computer codes.

[B] “+D” means progeny nuclides with half-lives less than 180 days are in secular equilibrium with the parent.

[C] These calculations assume that source distribution throughout the mass is uniform, and that no hot spots exist. If significant variations of source throughout the mass or in the surface distribution exist, these should be taken into account with more detailed analysis and calculations.

[D] NA = not applicable.

X5. DISPOSAL UNIT-DOSE FACTORS

INTRODUCTION

Taken with modifications from the Argonne report, “Protocol for Development of Authorized Release Limits for Concrete of U.S. Department of Energy Sites,” Arnish, J., et al, ANL/EAD/TM-92 Argonne National Laboratory, IL, July 2000.

TABLE X5.1 Unit-Dose Factors[A] for the Landfill Worker (nonradiological landfill disposal option)

Radionuclide	Landfill Worker (mrem/pCi)
Ac-227+D[B,C]	9.9E-11
Ag-108m	4E-12
Ag-110m	7.1E-12
Am-241	6.5E-12
Ce-144+D	1.3E-13
Co-57	1.7E-13
Co-60	6.7E-12
Cs-134	3.9E-12
Cs-137+D	1.4E-12
Eu-152	2.9E-12
Eu-154	3.1E-12
Eu-155	2.9E-14
Fe-55	3.9E-17
I-129	2.5E-15
Mn-54	2.1E-12
Ni-63	9.2E-17
Np-237+D	8.3E-12
Pu-238	5.7E-12
Pu-239	6.3E-12
Pu-240	6.3E-12
Pu-241+D	1.2E-13
Ra-226+D	4.7E-12
Ru-106+D	5.4E-13
Sb-125+D	1E-12
Sr-90	1.9E-14
Tc-99	1.5E-16
Th-230	4.8E-12
U-232	9.6E-12
U-233	2E-12
U-234	1.9E-12
U-235+D	2.1E-12
U-238+D	1.8E-12
Zn-65	1.5E-12

[A] The unit dose factors for the landfill worker are calculated using the TSD-DOSE (Pfingston et al. 1998) and RESRAD (Yu et al. 1993) computer codes.

[B] “+D” means progeny nuclides with half-lives less than 180 days are in secular equilibrium with the parent.

[C] These calculations assume that source distribution throughout the mass is uniform, and that no hot spots exist. If significant variations of source throughout the mass or in the surface distribution exist, these should be taken into account with more detailed analysis and calculations.

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