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A Proposed Classification System for High-Level and Other Radioactive Wastes

D. C. Kocher
A. G. Croff

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Nuclear and Chemical Waste Programs

A PROPOSED CLASSIFICATION SYSTEM FOR HIGH-LEVEL AND OTHER RADIOACTIVE WASTES

D. C. Kocher[1] and A. G. Croff[2]

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NOTICE: This document contains information of a preliminary nature. It is subject to revision or correction and therefore does not represent a final report.

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LISTING OF ACRONYMS

AEC	[U.S.] Atomic Energy Commission
CFR	Code of Federal Regulations
CH	Contact-handled
DOE	[U.S.] Department of Energy
DOT	[U.S.] Department of Transportation
EPA	[U.S.] Environmental Protection Agency
FEIS	Final Environmental Impact Statement
GCD	Greater confinement disposal
HLW	High-level waste
ICRP	International Commission on Radiological Protection
LLRWPAA	Low-Level Radioactive Waste Policy Amendments Act
LLW	Low-level waste
NRC	[U.S.] Nuclear Regulatory Commission
NWPA	Nuclear Waste Policy Act
RH	Remote-handled
TRU	Transuranic
WIPP	Waste Isolation Pilot Plant

A PROPOSED CLASSIFICATION SYSTEM FOR HIGH-LEVEL AND OTHER RADIOACTIVE WASTES

D. C. Kocher and A. G. Croff

ABSTRACT

This report presents a proposal for quantitative and generally applicable risk-based definitions of high-level and other radioactive wastes. On the basis of historical descriptions and definitions of high-level waste (HLW), in which HLW has been defined in terms of its source as waste from reprocessing of spent nuclear fuel, we propose a more general definition based on the concept that HLW has two distinct attributes: HLW is (1) highly radioactive and (2) requires permanent isolation. This concept leads to a two-dimensional waste classification system in which one axis, related to "requires permanent isolation," is associated with long-term risks from waste disposal and the other axis, related to "highly radioactive," is associated with shorter-term risks due to high levels of decay heat and external radiation. We define wastes that require permanent isolation as wastes with concentrations of radionuclides exceeding the Class-C limits that are generally acceptable for near-surface land disposal, as specified in the U.S. Nuclear Regulatory Commission's rulemaking 10 CFR Part 61 and its supporting documentation. HLW then is waste requiring permanent isolation that also is highly radioactive, and we define "highly radioactive" as a decay heat (power density) in the waste greater than 50 W/m^3 or an external radiation dose rate at a distance of 1 m from the waste greater than 100 rem/h (1 Sv/h), whichever is the more restrictive. This proposal also results in a definition of Transuranic (TRU) Waste and Equivalent as waste that requires permanent isolation but is not highly radioactive and a definition of low-level waste (LLW) as waste that does not require permanent isolation without regard to whether or not it is highly radioactive.

Since, at the present time, HLW or TRU Waste and Equivalent generally are associated with disposal in deep geologic repositories, whereas "permanent isolation" as used in this report also encompasses less confining technologies for disposal of relatively dilute wastes in these classes, the definitions of HLW and TRU Waste and Equivalent also include explicit provisions for the acceptability of greater confinement disposal (GCD) on a site-, waste-, and technology-specific basis if applicable standards for protection of public health and safety are met. As a means of encouraging development of GCD options for some wastes that are not

generally acceptable for near-surface land disposal, this report presents an example analysis of concentration limits of radionuclides that would be acceptable for intermediate-depth burial.

EXECUTIVE SUMMARY

The Nuclear Waste Policy Act (NWPA) of 1982 provides the following definition of high-level radioactive waste (HLW):

> "(A) the highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations; and
>
> (B) other highly radioactive material that the [U.S. Nuclear Regulatory] Commission, consistent with existing law, determines by rule requires permanent isolation."

The primary purpose of this report is to develop a generally applicable and quantitative definition of HLW that addresses the description in Clause (B) above and also encompasses the description in Clause (A). The development of a generally applicable definition of HLW also results in definitions of two other waste classes: Transuranic (TRU) Waste and Equivalent and low-level waste (LLW).

HLW traditionally has been defined in terms of its source as waste from chemical reprocessing of spent nuclear fuel, and a source-based definition is given in Clause (A) above. However, wastes from fuel reprocessing were recognized as having certain characteristics, related to short-term risks from waste operations and to long-term risks from waste disposal, that provided the basis for the traditional definitions of HLW:

- high concentrations of shorter-lived fission products, principally ^{90}Sr and ^{137}Cs, resulting in high heat generation rates and external radiation doses;

- high concentrations of long-lived radionuclides, principally alpha-emitting TRU radionuclides, that would result in high internal radiation doses per unit activity of inhaled or ingested material.

These characteristics are used in this report to develop a generally applicable risk-based definition of HLW and the other waste classes.

On the basis of the definition in Clause (B) of the NWPA and the historical precedents for defining wastes from fuel reprocessing, we propose the following conceptual definition of HLW:

> HLW is waste that is -
> (1) highly radioactive and
> (2) requires permanent isolation.

Thus, we regard HLW as having two distinct attributes that must be present simultaneously. This conceptual approach results in a two-dimensional waste classification system in which one axis is related to the concept of "highly radioactive" and is associated with shorter-term risks, and the other axis is related to the concept of "requires permanent isolation" and is associated with long-term risks from waste disposal.

The conceptual definition of HLW also leads to the following conceptual definitions of TRU Waste and Equivalent and LLW:

- TRU Waste and Equivalent is waste that requires permanent isolation but is not highly radioactive;

- LLW is waste that does not require permanent isolation, without regard to whether or not it is highly radioactive.

TRU Waste and Equivalent may include radionuclides other than long-lived, alpha-emitting TRU radionuclides; and the definition of LLW is consistent with the NRC's rulemaking 10 CFR Part 61,[1,2] which considers only risks associated with near-surface land disposal of radioactive wastes.

A quantitative and generally applicable risk-based definition of "highly radioactive" is developed by associating this concept with high levels of decay heat (power density) or external radiation dose in a manner consistent with the first characteristic of source-based HLW described above. On the basis of analyses of levels of power density and external radiation dose that limit system design or operation in controlling short-term risks in a variety of waste management activities, including disposal, we propose the following generally applicable definition:

> "Highly radioactive" means -
> (1) a power density greater than 50 W/m^3 or
> (2) an external dose-equivalent rate at a distance of 1 m from the waste greater than 100 rem/h (1 Sv/h).

Thus, only one of these criteria must be met for a waste to be highly radioactive.

A determination of whether a waste is highly radioactive can be based on direct measurements of power density and external dose rate without knowledge of radionuclide concentrations in the waste. However, we also have used these levels of power density and external dose rate to derive, on the basis of simple models and calculations, radionuclide concentrations that define a Highly Radioactive boundary. These boundary concentrations are given in Table ES-1 and can be used to determine whether a waste is highly radioactive when the radionuclide concentrations

Table ES-1. Selected radionuclide concentrations corresponding to Highly Radioactive boundary in waste classification system[a]

Nuclide[b]	Boundary concentration (Ci/m^3)	Nuclide[b]	Boundary concentration (Ci/m^3)
C-14	2E5	U-232 + d	2E2
Ni-63	5E5	Pu-238	2E3
Sr-90 + d	7E3[c]	Pu-239	2E3
Cs-137 + d	5E3[c]	Pu-240	2E3
Sm-151	4E5	Pu-241	2E6
Pb-210 + d	1E3	Am-241	2E3
Ra-226 + d	3E2	Am-243 + d	1E3
Ac-227 + d	2E2	Cm-243	1E3
Th-229 + d	3E2	Cm-244	1E3
Pa-231	2E3	Cm-245	2E3

[a]Boundary concentration for any radionuclide is based on a power density of 50 W/m^3 or an external dose-equivalent rate at a distance of 1 m from the waste of 100 rem/h (1 Sv/h), whichever is more restrictive; for all radionuclides in this table except Cs-137, the boundary concentration is based on power density. Highly Radioactive boundary for wastes containing mixtures of radionuclides is determined from boundary concentrations for each radionuclide using sum-of-fractions rule, or may be determined from direct measurements of power density and external dose rate.

[b]Notation "+ d" means short-lived daughter products are assumed to be in secular equilibrium with parent radionuclide.

[c]Value corresponds to Class-C limit for near-surface land disposal, as specified by the NRC in 10 CFR Part 61 (ref. 1).

in the waste are known. It is important to note that the concentrations defining the Highly Radioactive boundary for ^{90}Sr and ^{137}Cs correspond to the Class-C limits for near-surface land disposal of these radionuclides, as specified by the NRC in 10 CFR Part 61.[1]

A quantitative and generally applicable risk-based definition of "requires permanent isolation" is developed by associating this concept with high concentrations of long-lived radionuclides in a manner consistent with the second characteristic of source-based HLW described above. We propose the following generally applicable definition:

> "Requires permanent isolation" means concentrations of radionuclides that exceed the Class-C limits that are generally acceptable for near-surface land disposal, as specified by the NRC in 10 CFR Part 61 and its supporting documentation and methodology.[1-4]

Thus, a radionuclide is "long-lived," by definition, if it can occur in concentrations greater than its Class-C limit. Furthermore, knowledge of the concentrations of the most important long-lived radionuclides in the waste is needed in determining if the waste requires permanent isolation. The concentrations of radionuclides that define the Permanent Isolation boundary according to this definition are given in Table ES-2.

The proposed waste classification system described above for defining HLW, TRU Waste and Equivalent, and LLW is depicted in Fig. ES-1 and is summarized as follows:

- HLW is waste in which (1) the power density exceeds 50 W/m^3 or the external dose rate at a distance of 1 m from the waste exceeds 100 rem/h (1 Sv/h), i.e., radionuclide concentrations exceed the values in Table ES-1; and (2) radionuclide concentrations exceed the Class-C limits that are generally acceptable for near-surface land disposal, i.e., the values in Table ES-2.

- TRU Waste and Equivalent is waste in which (1) the power density is less than 50 W/m^3 and the external dose rate at a distance of 1 m from the waste is less than 100 rem/h (1 Sv/h), i.e., radionuclide concentrations are less than the values in Table ES-1; and (2) radionuclide concentrations exceed the Class-C limits that are generally acceptable for near-surface land disposal, i.e., the values in Table ES-2.

- LLW is waste in which radionuclide concentrations are less than the Class-C limits that are generally acceptable for near-surface land disposal, i.e., the values in Table ES-2, regardless of the levels of power density or external dose rate.

Table ES-2. Selected radionuclide concentrations corresponding to Permanent Isolation boundary in waste classification system[a]

Nuclide	Boundary concentration (Ci/m^3)	Nuclide	Boundary concentration (Ci/m^3)
C-14	8	Th-232	1E-2[c]
C-14[b]	8E1	Pa-231	3E-2[c,e]
Ni-59[b]	2E2	U-232	5E-2[c]
Ni-63	7E2	U-233	4E-1[c]
Ni-63[b]	7E3	U-234	5E-1[c]
Sr-90	7E3	U-235	4E-1
Nb-94[b]	2E-1	U-236	6E-1[c]
Tc-99	3	U-238	5E-1
Ag-108m	3E-2[c]	Np-237	4E-2
Sn-126	1E-2[c]	Pu-238	7
I-129	8E-2	Pu-239	1E-1
Cs-135	8E2	Pu-240	1E-1
Cs-137	5E3	Pu-241	5[f]
Pb-210	2E2[c]	Pu-242	1E-1
Ra-226	3E-2[d]	Am-241	1E-1
Ac-227	1[c]	Am-243	7E-2
Th-229	5E-2[c]	Cm-243	8E1[g]
Th-230	6E-2[c]	Cm-244	4E1[h]

[a]Boundary concentration is defined as Class-C limit that is generally acceptable for near-surface land disposal, as specified by the NRC in 10 CFR Part 61 and supporting documentation (refs. 1-4). Permanent Isolation boundary for wastes containing mixtures of radionuclides is determined from boundary concentration for each radionuclide using sum-of-fractions rule.

[b]Radionuclide in activated metals only.

[c]Value is not included in the NRC's 10 CFR Part 61 and supporting documentation (refs. 1-4) and is provisional.

[d]Value assumes Pb-210 is in secular equilibrium with Ra-226.

[e]Value assumes Ac-227 is in secular equilibrium with Pa-231.

[f]Value is 30 times boundary concentration for Am-241.

[g]Value is 850 times boundary concentration for Pu-239.

[h]Value is 360 times boundary concentration for Pu-240.

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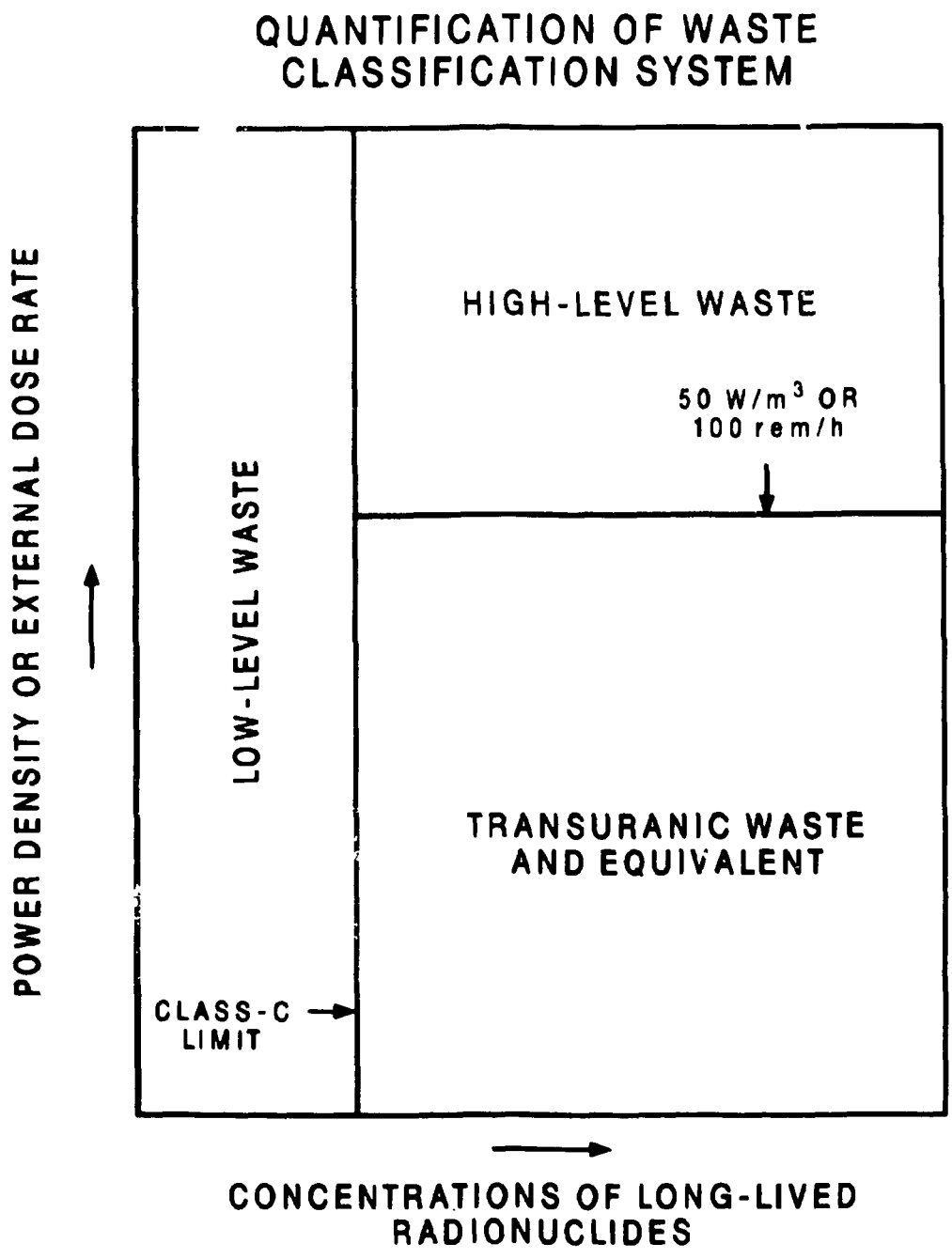

Fig. ES-1. Depiction of proposed waste classification system. Radionuclide concentrations corresponding to boundaries defining High-Level Waste, Transuranic Waste and Equivalent, and Low-Level Waste are given in Tables ES-1 and ES-2.

In applying the boundary concentrations in Tables ES-1 and ES-2 to wastes that contain mixtures of radionuclides, the sum-of-fractions rule is used; i.e., the quantity to be calculated is the ratio of each radionuclide concentration to its corresponding boundary concentration, summed over all radionuclides, and the Highly Radioactive or Permanent Isolation boundary is exceeded if the appropriate sum of fractions exceeds unity.

The proposed waste classification system is intended to be applied to expected radionuclide compositions and waste forms at the time of final disposal. However, the definitions of the three waste classes do not contain explicit reference to requirements for particular technologies for waste disposal. At the present time, LLW generally is associated with near-surface land disposal[1,2] and HLW and TRU Waste and Equivalent are associated with deep geologic repositories or equivalent,[5-8] primarily because these are the only disposal technologies currently recognized in law and for which regulatory standards and technical criteria have been developed. The association of HLW with disposal in deep geologic repositories also is particularly evident in the NWPA.

It is not our intention, however, to require deep geologic repositories or equivalent for disposal of all wastes defined as HLW or TRU Waste and Equivalent according to the proposed classification system (i.e., wastes with radionuclide concentrations greater than the Class-C limits that are generally acceptable for near-surface land disposal). Some of these wastes may be suitable for greater confinement disposal (GCD), which we define as any technology that is more confining than near-surface land disposal for Class-C waste[1,2] but is less confining than deep geologic repositories or equivalent. The role of GCD in the waste classification system is specified as follows:

- Wastes classified as HLW or TRU Waste and Equivalent may be acceptable for greater confinement disposal on a site-, waste-, and technology-specific basis provided applicable standards for protection of public health and safety will be met.

A variety of GCD technologies for wastes that are not generally acceptable for near-surface land disposal are in current use or in various stages of planning.[9] As a means of encouraging further development of GCD alternatives and appropriate regulatory standards and technical criteria of general applicability, an appendix of this report presents an example analysis for determining maximum concentrations of radionuclides that would be acceptable for GCD. The analysis assumes intermediate-depth burial as the disposal technology. The concentration limits for GCD then are based on the assumption of a solid-waste drilling scenario for an inadvertent intruder at the disposal facility[10] and a limit on annual

committed effective dose equivalent[11] for an intruder of 0.5 rem (5 mSv). The assumed dose limit for an inadvertent intruder is consistent with the limit that is implicit in the waste classification system for near-surface land disposal in the NRC's 10 CFR Part 61.[1,2]

The example calculations of concentration limits of radionuclides that would be acceptable for GCD using intermediate-depth burial indicate that it is reasonable to consider GCD as an alternative to deep geologic repositories for disposal of some wastes that are classified as HLW or TRU Waste and Equivalent. However, we emphasize that it is premature to use these calculations as the basis for defining a generally applicable set of concentration limits for GCD (i.e., minimum concentrations of radionuclides that would require deep geologic repositories or equivalent), primarily because doses to inadvertent intruders likely will be highly site- and technology-specific and appropriate regulatory standards and technical criteria for GCD have not been developed. Thus, at present, the acceptability of GCD for HLW or TRU Waste and Equivalent should be evaluated only on a case-by-case basis.

Finally, this report presents a brief analysis of the impacts of the proposed waste classification system on selected commercial and defense wastes. The waste definitions would have minimal impacts on present plans for management and disposal of commercial spent fuel and reprocessing wastes, because these materials would be classified as HLW. Some defense reprocessing wastes at the Savannah River Plant that are to be encapsulated in borosilicate glass also would be classified as HLW. While more detailed analyses are needed for the wide variety of other defense wastes, the proposed classification system could have an impact on management and disposal of these wastes in two respects.

First, much of the defense waste that currently is called HLW, because of its source as waste from fuel reprocessing, apparently would be classified as TRU Waste and Equivalent or LLW, because of the relatively low concentrations of ^{90}Sr, ^{137}Cs, and long-lived TRU radionuclides. However, any reclassification of these wastes need not have adverse impacts on plans for disposal, because the proposed waste definitions are not associated with requirements for specific disposal technologies or disposal in specific facilities. Thus, these wastes could be disposed of as if they were HLW (e.g., in deep geologic repositories) or by means of any other technology that would meet applicable standards for protection of public health and safety.

Second, the proposed definition of TRU Waste and Equivalent differs from current waste acceptance criteria for defense TRU waste at the Waste Isolation Pilot Plant (WIPP)[12] in two aspects: (1) the use of a limit on power density of 50 W/m^3 for TRU Waste and Equivalent, instead of an implied limit of 300 W/m^3 for remote-handled TRU waste at the WIPP, and

(2) the use of minimum radionuclide-specific concentrations in Ci/m^3 for TRU Waste and Equivalent, instead of a single minimum concentration of 100 nCi/g for all long-lived, alpha-emitting TRU radionuclides at the WIPP. The differing limits on power density should not severely impact plans for waste disposal at the WIPP, because only a small volume of waste that meets current acceptance criteria for the facility has a power density between 50 and 300 W/m^3. On the other hand, the use of radionuclide-specific concentration limits in Ci/m^3 for defining TRU Waste and Equivalent could significantly impact the volume of contact-handled waste that would be acceptable for disposal at the WIPP, primarily because our definition includes long-lived, non-TRU radionuclides in this waste class. However, for most defense wastes that contain mainly TRU radionuclides, the radionuclide-specific concentration limits in Ci/m^3 are essentially equivalent to the single limit of 100 nCi/g for all long-lived, alpha-emitting TRU radionuclides. The principal exception occurs with wastes containing significant concentrations of ^{238}Pu, because the proposed limit in Ci/m^3 for this radionuclide is considerably higher than 100 nCi/g. We also emphasize that the proposed definition of TRU Waste and Equivalent is not intended to preclude the WIPP facility from maintaining its current minimum concentration of 100 nCi/g for all long-lived, alpha-emitting TRU radionuclides as a waste acceptance criterion; and, as discussed above, our proposed classification system supports this value for determining wastes that require permanent isolation.

1. INTRODUCTION

1.1 Objective and Scope of Waste Classification Study

The Nuclear Waste Policy Act (NWPA) of 1982 (Public Law 97-425) provides a general but qualitative definition of high-level radioactive waste (HLW) which has two aspects: (1) a description of HLW as waste from reprocessing of spent nuclear fuel, which reflects the historical emphasis on defining HLW on the basis of its source, and (2) a provision that other highly radioactive material requiring permanent isolation may be classified as HLW. The NWPA assigns responsibility for developing a generally applicable definition of HLW based on the second description to the U.S. Nuclear Regulatory Commission (NRC), and the NRC has indicated that a rulemaking on such a definition that also would quantify the source-based definition of HLW is forthcoming.[13]

The principal objective of this report is to develop a quantitative and generally applicable definition of HLW to address the second aspect of the NWPA definition described above. Such a definition also should encompass and quantify the traditional source-based definition of HLW.

The development of a quantitative and generally applicable definition of HLW proceeds as follows. First, we review historical descriptions and definitions of HLW including current definitions in regulations and guidances of the NRC, U.S. Department of Energy (DOE), and U.S. Environmental Protection Agency (EPA) and in the NWPA. Although HLW usually has been defined as waste from fuel reprocessing, descriptions of HLW often have indicated that these wastes have certain characteristics that could provide a basis for a generally applicable definition. We also review current definitions of transuranic (TRU) waste and low-level waste (LLW), because in developing a quantitative definition of HLW we will consider and define other classes of radioactive waste. This report does not consider the classification of wastes that might be considered hazardous because of their chemical toxicities.

1.2 Constraints for Development of Waste Definitions

Several important constraints were adopted for the present study, and these are summarized briefly as follows.

[1] The definitions of HLW and the other waste classes should be based principally on direct or indirect considerations of risks associated with waste management and disposal, and the definitions should have a sound technical foundation.

[2] The waste classification system should contain a minimal number of new waste classes that are not currently recognized in law.

[3] The definitions of waste classes should be generally applicable, i.e., applicable to any radioactive waste regardless of its source or isotopic composition.

[4] Consistent with the first constraint given above, the definitions of waste classes should not result in unnecessary or unreasonable adverse impacts on waste management and disposal systems, either existing or planned, for commercial and defense wastes.

[5] The waste classification system should provide support for the development of options for greater confinement disposal (GCD) as alternatives to deep geologic repositories for some types of wastes that are not generally acceptable for near-surface land disposal.

[6] The definitions of HLW and the other waste classes should, to the fullest extent possible, be compatible with existing law and regulations and with historical definitions and descriptions of different types of radioactive wastes.

1.3 Outline of the Report

The remainder of this report is organized as follows. Section 2 reviews historical definitions and descriptions of HLW and the current definitions of TRU waste and LLW. Section 3 describes the conceptual approach we have used in defining HLW and the other waste classes in terms of two distinct attributes - namely, the attributes "highly radioactive" and "requires permanent isolation" - and discusses the interpretation of these terms. This section also discusses (1) the role of time in defining waste classes and (2) the relationship between the definitions of waste classes, the selection of appropriate disposal technologies, and the development of waste acceptance criteria for specific facilities. Section 4 describes, in summary form, the proposed quantification of the definitions of HLW and the other waste classes in terms of the attributes "highly radioactive" and "requires permanent isolation," and describes application of the definitions to surface-contaminated wastes. Section 5 briefly summarizes impacts of the proposed waste classification system on waste management and disposal plans for selected commercial and defense wastes. The impacts analysis particularly focuses on defense wastes that currently are classified as HLW because of their source as waste from fuel

reprocessing and on TRU wastes that currently are intended for disposal at the Waste Isolation Pilot Plant.[8] Section 6 then presents a summary of the proposed waste classification system, including discussions of major issues that must be addressed in developing any classification system.

Several appendices in this report present details of the technical analyses used to develop and support the proposed definitions of HLW and the other waste classes. The appendices discuss (1) quantification of the attributes "highly radioactive" and "requires permanent isolation" used in defining HLW and the other waste classes, (2) an example analysis for quantifying maximum concentrations of radionuclides that could be acceptable for GCD, (3) the relationship between concentration limits for specific TRU radionuclides in Ci/m^3, as used in the proposed definition for the waste class called TRU Waste and Equivalent, and the more traditional use of a single limit in nCi/g for all long-lived, alpha-emitting TRU radionuclides, (4) data supporting the analysis of impacts of the proposed waste classification system on selected commercial and defense wastes, and (5) a description of the current status of technologies for GCD and associated health-risk assessments.

2. HISTORY OF DEFINITIONS OF HIGH-LEVEL WASTE AND OTHER WASTE CLASSES

As background for the development of quantitative and generally applicable definitions of HLW and other waste classes, this section briefly reviews historical definitions and descriptions of HLW and current definitions of TRU waste and LLW. An important constraint for this study is that the definitions of waste classes should, to the fullest extent possible, be consistent with existing law and regulations and with historical definitions and descriptions.

2.1 High-Level Waste

2.1.1 *Historical Definitions and Descriptions*

The historical development of definitions of HLW has been reviewed by Jacobs *et al.*,[14] and the following discussion is based largely on that review. Some of this discussion also is based on the Supplementary Information in the NRC's advance notice of proposed rulemaking on a definition of HLW.[13]

In the earliest descriptions of HLW, the term "high level" often was associated with two attributes of the waste: (1) high levels of external radiation that would necessitate extensive shielding to protect workers during waste handling and (2) high levels of heat from radioactive decay that would necessitate engineering systems for heat removal, e.g., to prevent self-boiling or self-dispersal of the waste. High levels of external radiation and decay heat resulted principally from high concentrations of shorter-lived fission products. The early descriptions of HLW thus were related only to the need to control short-term risks from waste handling and storage, but the descriptions did not consider attributes of the waste related to control of long-term risks from final disposal.

In addition to the descriptions of HLW in terms of high levels of external radiation or decay heat, the concept was developed that HLW is waste of a certain origin, i.e., from chemical reprocessing of spent nuclear fuel, because this was the only known source of waste with these properties. Thus, HLW came to be regarded as waste from fuel reprocessing in which most of the shorter-lived fission products have not decayed and significant radionuclide separations or waste dilutions have not occurred.

The U.S. Atomic Energy Commission (AEC) was the first Federal agency to exercise jurisdiction over the possession, use, and disposal of commercial nuclear materials. The AEC also referred to HLW as material

from chemical reprocessing operations that emits radiation sufficiently strong to reduce the time a person could spend safely near the source, but the AEC further recognized the need to protect the public from potential long-term radiological hazards following waste disposal. The AEC thus broadened the description of HLW to include material "which by virtue of its radionuclear concentration, half life, and biological significance requires perpetual isolation from the biosphere."[15] This description reflected a change in emphasis in describing HLW from shorter-term operational concerns resulting from the presence of high concentrations of fission products to concerns over long-term risks from final disposal. The potential risks from disposal resulted from the presence of high concentrations of longer-lived radionuclides, principally alpha-emitting TRU radionuclides, that produce high levels of internal radiation dose per unit activity of inhaled or ingested material. The hazard potential from disposal of HLW was indicated by the fact that concentrations of some long-lived radionuclides were many orders of magnitude greater than maximum permissible concentrations in drinking water that have been established to ensure the protection of public health and safety.[16]

The first regulatory definition of HLW was developed in 1970 by the AEC in 10 CFR Part 50, Appendix F.[17] The regulation stated that:

> "....high-level liquid radioactive wastes means those aqueous wastes resulting from the operation of the first cycle solvent extraction system, or equivalent, and the concentrated wastes from subsequent extraction cycles, or equivalent, in a facility for reprocessing irradiated reactor fuels."

The emphasis on wastes from the first cycle solvent extraction system arises from the fact that these liquids contain more than 99% of the nonvolatile fission products removed during reprocessing. The AEC also specified that high-level liquid waste should be solidified within 5 years after generation and the solidified products, which also are referred to as HLW, sent to a Federal repository. While the definition developed by the AEC is qualitative and focuses on HLW as waste from fuel reprocessing, a recognition that HLW has certain general properties regardless of its source is implied by the reference in the definition to other concentrated wastes from subsequent extraction cycles, or equivalent.

The first statutory use of the term "high-level radioactive waste" appears in the Marine Protection, Research, and Sanctuaries Act of 1972 (Public Law 92-532). This Act adopted the definition of HLW from 10 CFR Part 50, Appendix F, described above but broadened the definition to include unreprocessed spent fuel as well as reprocessing wastes. The NRC essentially adopted the position in 10 CFR Part 50, Appendix F, and in the Marine Sanctuaries Act when it declared spent nuclear fuel to be a form of

HLW and when it found TRU-contaminated wastes not to be HLW.[18,19]

Another statutory description of HLW appears in the West Valley Demonstration Project Act of 1980 (Public Law 96-368), which authorizes the DOE to carry out demonstrations of solidification techniques which can be used to prepare HLW for disposal. This Act includes the following definition:

> "The term 'high level radioactive waste' means the high level radioactive waste which was produced by the reprocessing at the [West Valley] Center of spent nuclear fuel. Such term includes both liquid wastes which are produced directly in reprocessing, dry solid material derived from such liquid waste and such other material as the [Nuclear Regulatory] Commission designates as high level radioactive waste for purposes of protecting the public health and safety."

The NRC has not yet designated any "other material" as HLW under the West Valley Act. Rather, the NRC has interpreted this term in a manner consistent with the definition in 10 CFR Part 50, Appendix F; i.e., HLW is the liquid wastes in storage at West Valley and the dry solid materials derived from solidification of the liquid wastes.

2.1.2 *Current Regulatory Definitions of the NRC, EPA, and DOE*

U.S. Nuclear Regulatory Commission. The NRC's 10 CFR Part 60 contains technical criteria for disposal of HLW in geologic repositories.[7] The definition of HLW in these standards is similar to the definitions in 10 CFR Part 50, Appendix F, and the Marine Sanctuaries Act discussed in Section 2.1.1 above:

> "'High-level radioactive waste' or 'HLW' means: (1) irradiated reactor fuel, (2) liquid wastes resulting from the operation of the first cycle solvent extraction system, or equivalent, and the concentrated wastes from subsequent extraction cycles, or equivalent, in a facility for reprocessing irradiated reactor fuel, and (3) solids into which such liquid wastes have been converted."

Again, this definition is only qualitative and will be modified by rulemaking[13] in response to the definition in the NWPA (see Section 2.1.3 below).

U.S. Environmental Protection Agency. The EPA's 40 CFR Part 191 contains generally applicable environmental standards for management and disposal of spent fuel, HLW, and TRU waste.[5] These standards apply not only to commercial wastes, the disposal of which would be licensed by the

NRC according to the technical criteria in 10 CFR Part 60,[7] but also to the DOE's defense wastes. Spent nuclear fuel is defined by the EPA as "fuel that has been withdrawn from a nuclear reactor following irradiation, the constituent elements of which have not been separated by reprocessing," and HLW is defined as in the NWPA (see Section 2.1.3 below). The definition of TRU waste is considered in Section 2.2.

The standards for disposal of spent fuel, HLW, and TRU waste in 40 CFR Part 191 apply to any method, except disposal directly into the oceans or ocean sediments. Although the EPA's health-risk assessments in support of the standards assume disposal in deep geologic repositories,[6] the EPA permits alternative disposal technologies (i.e., GCD) that meet the requirements in the standards or in any alternative standards that the EPA may promulgate. Thus, the EPA does not impose or assume a unique correspondence between classes of radioactive waste and particular disposal technologies.

U.S. Department of Energy. The definition of HLW currently used by the DOE is contained in Order 5820.2[20] and is similar to those used by the NRC and EPA. HLW is defined as:

> "The highly radioactive waste material that results from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid waste derived from the liquid, that contains a combination of TRU waste and fission products in concentrations as to require permanent isolation."

In essence, this definition gives three criteria for identifying HLW: (1) the source of the waste is reprocessing of spent nuclear fuel; (2) the constituents of the waste are TRU waste and fission products; and (3) the waste is sufficiently hazardous to require permanent isolation. The importance of the third criterion is particularly evident from the following statement in Chapter I of the DOE Order:

> "This Chapter establishes policies and guidelines for managing the Department's high-level waste (HLW) and any other materials which, because of their hazardous nature (health risk, longevity of hazard, and thermal activity), are determined by Heads of Field Organizations to require similar handling."

However, no guidelines are given in the Order regarding concentrations of TRU waste and fission products that would be sufficient for reprocessing wastes to be classified as HLW.

The DOE Order specifies that new and readily retrievable existing HLW shall be disposed of in deep geologic repositories in accordance with the NWPA, but existing HLW that is not readily retrievable will be stabilized in place if the EPA's standards for disposal in 40 CFR Part 191[5] are met.

Thus, as with the EPA's standards, the DOE Order does not associate HLW with wastes that require a particular disposal technology, and the use of GCD for wastes that require a degree of isolation greater than near-surface land disposal but possibly less than a deep geologic repository is permitted explicitly.

2.1.3 *Nuclear Waste Policy Act of 1982*

In the NWPA, HLW is defined as:

> "(A) the highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations; and
>
> (B) other highly radioactive material that the [Nuclear Regulatory] Commission, consistent with existing law, determines by rule requires permanent isolation."

The definition in Clause (A) is similar to that in 10 CFR Part 50, Appendix F, described in Section 2.1.1 above (i.e., HLW is waste from reprocessing of spent nuclear fuel), but inclusion of the phrases "highly radioactive material" and "contains fission products in sufficient concentrations" not contained in previous definitions is noteworthy. However, the NWPA provides no guidance on quantifying these phrases or the phrases "other highly radioactive material" and "requires permanent isolation" in Clause (B). However, the definition in Clause (B) clearly points to the development of a generally applicable definition of HLW, i.e., one that is not based on the source of the waste.

The definition of HLW in the NWPA does not apply to the DOE's defense wastes unless commercial and defense wastes are commingled. However, the NWPA definition presumably will be applied to defense wastes by means of its adoption in the EPA's 40 CFR Part 191,[5] which specifically applies to any facility operated by the DOE as well as to commercial facilities.

The NWPA addresses disposal of HLW only in deep geologic repositories. Again, however, the EPA's 40 CFR Part 191 permits disposal of HLW using alternative technologies,[5,6] and this provision presumably will be applicable to disposal of defense wastes.

2.1.4 *Summary*

HLW traditionally has been defined on the basis of its source as waste from reprocessing of spent nuclear fuel. However, existing definitions generally have recognized that wastes from fuel reprocessing have certain characteristics related to short-term risks from waste operations and to long-term risks from waste disposal. These characteristics include:

- high concentrations of shorter-lived fission products, resulting in high rates of heat generation and external radiation;

- high concentrations of long-lived radionuclides, principally alpha-emitting TRU radionuclides, that would result in high internal radiation doses per unit activity of inhaled or ingested material.

These characteristics refer in a general way to HLW being "highly radioactive" and "requiring permanent isolation," irrespective of the source of the waste. The definitions in the NWPA and DOE Order 5820.2 point clearly to a generally applicable definition of HLW, i.e., a definition based on intrinsic characteristics of the waste and not on its source.

HLW often has been associated with disposal in deep geologic repositories, because the wastes require a high degree of isolation from the biosphere in order to provide long-term protection of public health and safety. However, current regulations of the EPA and DOE recognize the potential acceptability of alternative disposal technologies for HLW if applicable health-protection standards are met. Thus, these regulations have established that wastes called HLW need not be associated with a particular disposal technology.

2.2 Transuranic Waste

TRU waste traditionally has referred to materials that contain sufficient concentrations of long-lived, alpha-emitting TRU radionuclides but lower levels of beta/gamma-emitting radionuclides (i.e., lower levels of decay heat and external radiation) than spent fuel or HLW from fuel reprocessing. TRU waste arises principally from fuel reprocessing and fabrication of plutonium weapons and plutonium-bearing reactor fuel.[21] A separate waste class was developed for these materials in recognition of the high potential hazard from inhalation and ingestion of TRU radionuclides and, thus, the need for long-term isolation from the

biosphere in limiting risks to the public from waste disposal.

2.2.1 *Current Regulatory Definitions of the EPA, DOE, and NRC*

Current definitions of TRU waste are given in the EPA's 40 CFR Part 191[5] and DOE Order 5820.2.[20] In addition, the NRC's 10 CFR Part 61[1,2] discusses disposal requirements for long-lived TRU radionuclides.

U.S. Environmental Protection Agency. In the EPA's 40 CFR Part 191, TRU waste is defined as:[5]

> "....waste containing more than 100 nanocuries of alpha-emitting transuranic isotopes, with half-lives greater than twenty years, per gram of waste, except for: (1) high-level radioactive waste; (2) wastes that the Department [of Energy] has determined, with the concurrence of the Administrator, do not need the degree of isolation required by this Part; or (3) wastes that the [Nuclear Regulatory] Commission has approved for disposal on a case-by-case basis in accordance with 10 CFR [Part] 61."

Thus, the principal characteristic of TRU waste is a minimum concentration of 100 nCi/g for alpha-emitting TRU radionuclides with half-lives greater than 20 years. The exception that HLW is not TRU waste recognizes implicitly that the former contains high concentrations of fission products not present in the latter, but the definition provides no guidelines regarding minimum concentrations of fission products that would distinguish HLW from TRU waste. The other two exceptions refer to wastes that can be disposed of safely by methods more confining than near-surface land disposal[1,2] but less confining than a deep geologic repository. As discussed in Section 2.1.2 above, the EPA's standards emphasize disposal of TRU waste in deep geologic repositories, but alternative disposal technologies are permitted if appropriate health-protection requirements are met.

U.S. Department of Energy. In DOE Order 5820.2, TRU waste is defined as:[20]

> "Without regard to source or form, radioactive waste that at the end of institutional control periods is contaminated with alpha-emitting transuranium radionuclides with half-lives greater than 20 years and concentrations greater than 100 nCi/g. Regarding the Waste Isolation Pilot Plant, high-level waste and spent nuclear fuel as defined by this Order are specifically excluded by this definition."

The definition of TRU waste thus is the same as in the EPA's 40 CFR Part 191,[5] and the definition also is explicit in excluding HLW and spent fuel.

Again, however, the definition does not indicate how HLW is distinguished from TRU waste that contains similar concentrations of TRU radionuclides but differing concentrations of fission products. Acceptance criteria for disposal of defense TRU waste at the Waste Isolation Pilot Plant (WIPP) are discussed in Section 2.2.2 below.

U.S. Nuclear Regulatory Commission. The NRC's 10 CFR Part 61 does not explicitly define TRU waste, but the standards set a concentration limit of 100 nCi/g for the general acceptability of near-surface land disposal for alpha-emitting TRU radionuclides with half-lives greater than 5 years.[1] Higher concentration limits for near-surface land disposal were set for ^{241}Pu and ^{242}Cm, which are short-lived but decay to longer-lived, alpha-emitting daughter products.

The NRC's concentration limit of 100 nCi/g for near-surface land disposal of TRU radionuclides is consistent with the definition of TRU waste in the EPA's 40 CFR Part 191[5] and in DOE Order 5820.2,[20] but the lower limit on half-life is 5 years instead of 20. The source of this seeming inconsistency is the different disposal technologies to which the various regulations generally apply. The NRC's standards apply to near-surface land disposal, and the value of 5 years is appropriate in this case because, for an assumed period of institutional controls over a facility of 100 years,[1] radionuclides with half-lives less than 5 years will decay to innocuous levels within the control period and, thus, will not present a potential health risk to the public. However, the EPA's standards and the DOE Order apply to wastes that generally are intended for disposal in deep geologic repositories or, alternatively, using other technologies that provide greater long-term isolation from the biosphere than near-surface land disposal; and a lower limit for the half-life of 20 years is regarded by the EPA and DOE as appropriate for defining TRU radionuclides that could present a potential long-term health risk using the more confining disposal technologies.

Finally, neither the NWPA nor the Low-Level Radioactive Waste Policy Amendments Act (LLRWPAA) of 1985 (H.R. 1083) explicitly refer to TRU waste. Thus, TRU waste has been defined only by the EPA and DOE; and, again, the existing definitions do not provide clear guidance for distinguishing between HLW and TRU waste.

2.2.2 *Waste Acceptance Criteria for the WIPP Facility*

TRU waste is generated principally in defense activities, and the DOE is developing the WIPP facility[8] for disposal of these wastes. TRU wastes that cannot be certified for disposal at the WIPP shall be evaluated for alternative disposal.[20]

In certifying TRU waste for disposal at the WIPP, two types of waste are considered: contact-handled (CH) and remote-handled (RH) waste. This section briefly discusses acceptance criteria for CH and RH TRU waste that could be used in developing generally applicable definitions of waste classes. Again, as defined in DOE Order 5820.2,[20] both types of TRU waste contain greater than 100 nCi/g of alpha-emitting TRU radionuclides with half-lives greater than 20 years.

Acceptance criteria for CH TRU waste at the WIPP include the following.[12]

- Waste packages shall have a surface dose-equivalent rate no greater than 0.2 rem/h, and neutron contributions greater than 20 mrem/h shall be reported separately.

- Waste packages or package assemblies shall have a removable surface contamination no greater than 50 pCi per 100 cm^2 for alpha-emitting isotopes and 450 pCi per 100 cm^2 for beta/gamma-emitting isotopes.

- Average thermal power densities which exceed 3.5 W/m^3 for individual waste packages shall be recorded.

- The fissile or fissionable isotope content for waste packages shall be no greater than the following values, expressed in ^{239}Pu fissile gram-equivalents: 200 g per 55-gallon drum; 100 g per 30-gallon drum; 500 g per Department of Transportation 6M container; and 5 g/ft^3 in boxes, up to 350 g maximum.

- Waste packages shall not contain more than 1000 Ci of ^{239}Pu-equivalent activity.

The limits on ^{239}Pu fissile gram-equivalents are based on the need to prevent nuclear criticality in the waste. The limits on ^{239}Pu-equivalent activity are derived from maximum permissible concentrations of TRU radionuclides in water, which are based on the requirement that radiation doses to the public will not exceed applicable standards for long-term performance of the repository.[12]

Acceptance criteria for RH TRU waste at the WIPP include the following.[12]

- Waste packages shall have a surface dose-equivalent rate no greater than 100 rem/h. Neutron contributions are limited to 270 mrem/h, and contributions greater than 20 mrem/h shall be reported. On an exception basis, canisters with a dose-equivalent rate in excess of

100 rem/h but less than 1000 rem/h may be approved.

- Waste packages shall have a removable surface contamination no greater than 50 pCi per 100 cm^2 for alpha-emitting isotopes and 450 pCi per 100 cm^2 for beta/gamma-emitting isotopes.

- The thermal power in any waste package shall not exceed 300 W.

- The fissile or fissionable isotope content of the waste shall not exceed 1.9 g/L, averaged over any 5 L with a maximum 50% void space. If such a distribution cannot be ensured, then the canister is limited to 240 g total in ^{239}Pu fissile gram-equivalents. The canister may be loaded with Department of Transportation 17C or 17H drums, which will provide internal partitioning and increase the limits to 100 g each for 30-gallon drums and 200 g each for 55-gallon drums.

- Waste packages shall not contain more than 1000 Ci of ^{239}Pu-equivalent activity.

In addition, RH TRU waste must be packaged in standard containers of nominal volume 1 m^3. Thus, the limit on thermal power per waste package can be converted to an equivalent limit on power density of 300 W/m^3.

Comparison of the acceptance criteria for the two types of TRU waste shows that CH and RH waste differ primarily in the limits on thermal power and external dose-equivalent rate at the surface of a waste package. Again, these are the two common measures of the attribute "highly radioactive" that has been associated with HLW from fuel reprocessing.

2.3 Low-Level Waste

Current definitions of LLW differ from those for HLW and TRU waste in the sense that LLW is defined by exclusion. DOE Order 5820.2[20] defines LLW as "Radioactive waste not classified as high-level waste, TRU waste, spent nuclear fuel, or byproduct material as defined by this Order." In the LLRWPAA, LLW is material that "(A) is not high-level radioactive waste, spent nuclear fuel, or byproduct material...; and (B) the Nuclear Regulatory Commission, consistent with existing law and in accordance with paragraph (A), classifies as low-level radioactive waste." The absence of any reference to TRU waste in the LLRWPAA definition is noteworthy, because the definition in Clause (A) implies that TRU waste could be included in LLW. Thus, to the extent that unambiguous definitions of HLW

and TRU waste are lacking, an unambiguous definition also is lacking for LLW.

The NRC's 10 CFR Part 61 gives limits on concentrations of radionuclides that are generally acceptable for near-surface land disposal.[1,2] Although these standards do not explicitly define LLW, materials with concentrations below the limits for near-surface land disposal generally are regarded as LLW. However, since a definition of LLW is not given by the NRC, wastes with concentrations greater than the limits that are generally acceptable for near-surface land disposal also could be classified as LLW.

Wastes are classified in 10 CFR Part 61 only in relation to risks associated with waste disposal, but risks associated with waste operations have no bearing on the concentration limits in the standards. Thus, this approach differs fundamentally from the historical approach to defining HLW. Indeed, wastes acceptable for near-surface land disposal may have levels of decay heat or external radiation at the time of disposal that are much higher than those in spent fuel or HLW (e.g., ^{60}Co which emits intense, high-energy photons is generally acceptable for near-surface land disposal in any concentration). However, the radionuclides in these cases must have sufficiently short half-lives that the activity will decay to acceptable levels for ensuring protection of inadvertent intruders by the end of the 100-year period of active institutional controls over the disposal facility.[1,2]

LLW generally is associated with near-surface land disposal. However, DOE Order 5820.2 contains the explicit provision that LLW shall be disposed of by shallow-land burial or GCD.[20] Furthermore, although GCD is not mentioned explicitly in 10 CFR Part 61, the NRC permits alternative disposal methods on a case-by-case basis for wastes with radionuclide concentrations greater than those that are generally acceptable for near-surface land disposal.[1] Thus, as with HLW and TRU waste, the current definitions and descriptions of LLW do not associate these wastes with a particular disposal technology.

3. CONCEPTUAL DEFINITIONS OF HIGH-LEVEL WASTE AND OTHER WASTE CLASSES

This section presents the conceptual approach used in this report to obtain quantitative and generally applicable risk-based definitions of HLW and other waste classes. The other two waste classes defined in this study are called TRU Waste and Equivalent and LLW. This section also discusses other aspects of the proposed waste classification system including (1) the role of time in defining waste classes and (2) the relationship between the definitions of waste classes, the choice of a disposal technology, and the development of waste acceptance criteria for specific facilities.

3.1 Conceptual Definition of High-Level Waste

As discussed in Section 2.1, HLW (i.e., waste from fuel reprocessing) traditionally has been described in terms of two characteristics: (1) the presence of high concentrations of shorter-lived fission products, resulting in high rates of external radiation and heat generation that necessitate extensive shielding and systems for heat removal to limit short-term risks from waste handling and storage, and (2) the presence of high concentrations of long-lived radionuclides, principally alpha-emitting TRU radionuclides, that necessitate a high degree of isolation from the biosphere to limit long-term risks from waste disposal. As discussed in Section 3.1.2 below, high heat generation rates also must be considered in the design of repositories for disposal of HLW.

In this report, we assume that the two characteristics described above provide a suitable basis for developing a generally applicable definition of HLW. The view that HLW has these characteristics, regardless of the source of the waste, is supported by the definition in Clause (B) of the NWPA (see Section 2.1.3); i.e., HLW is "other highly radioactive material that...requires permanent isolation."

3.1.1 *Statement and Interpretation of Conceptual Definition*

On the basis of historical precedents for defining HLW and the definition in Clause (B) of the NWPA, we propose the following conceptual definition of HLW:

HLW is waste that is -

(1) highly radioactive and

(2) requires permanent isolation.

Thus, we regard HLW as having two distinct attributes that must be present simultaneously. This conceptual approach results in a two-dimensional waste classification system in which one axis is related to the concept of "highly radioactive" and the other axis to the concept of "requires permanent isolation." The conceptual definition of HLW also leads to conceptual definitions of the other two waste classes, which are given in Section 3.2.

The approach to implementing the generally applicable conceptual definition of HLW is to develop quantitative boundaries defining "highly radioactive" and "requires permanent isolation." The approaches to quantifying these attributes are described in Sections 3.1.3 and 3.1.4.

3.1.2 *Discussion of Conceptual Definition*

The word "and" contained in the proposed conceptual definition of HLW given above does not appear explicitly in Clause (B) of the NWPA definition. Thus, alternative interpretations of the NWPA definition, and its historical precedents, are possible.

One alternative interpretation of Clause (B) of the NWPA definition is that HLW requires permanent isolation because it is highly radioactive. In this interpretation, "highly radioactive" and "requires permanent isolation" are essentially synonymous and, thus, would not describe distinct attributes of the waste. The definitions of HLW and the other waste classes then would be based only on those characteristics of the waste related to requirements for limitation of long-term risks from waste disposal but not on considerations of shorter-term risks due to high levels of decay heat and external radiation. As discussed in Section 2.3, this approach would be consistent with that taken by the NRC in 10 CFR Part 61 in classifying wastes that are generally acceptable for near-surface land disposal.[1,2] More generally, since the primary interest in defining waste classes is in relation to requirements for disposal, this interpretation could provide an approach in which each waste class would be associated with a particular disposal technology.

It appears desirable, however, to retain the concept expressed in historical definitions of HLW that "highly radioactive" is an attribute distinct from "requires permanent isolation," even when disposal is the principal concern of waste management. First, high concentrations of shorter-lived radionuclides that produce high levels of decay heat or

external radiation, such as ^{90}Sr and ^{137}Cs, still can provide potentially significant hazards beyond the 500-year time period for prevention of exposures of inadvertent intruders that was assumed by the NRC in deriving the Class-C concentration limits for near-surface land disposal in 10 CFR Part 61.[1,2] Second, high levels of decay heat and external radiation are important in the design of disposal systems, so there is a need to distinguish between wastes that are highly radioactive and those that are not even when both types of waste require permanent isolation. For example, the NRC's technical criteria for disposal of HLW in geologic repositories in 10 CFR Part 60 include a requirement for substantially complete containment of radionuclides within waste packages for a time period of at least 300 years, because the NRC believes that there are large uncertainties in predicting radionuclide transport during the period of high heat generation in the waste.[7] However, such a requirement presumably would not be needed for wastes with similar concentrations of long-lived TRU radionuclides but relatively low heat generation rates from fission-product decay. Finally, the NRC has indicated that it would not find tenable the argument that a waste requires permanent isolation because it is highly radioactive, primarily because the need for permanent isolation correlates with the length of time the waste will remain hazardous, whereas long half-lives correlate with low rather than high levels of radioactivity.[13]

The existence of TRU waste as a class distinct from HLW has been recognized in practice and in regulations for many years, but this distinction would no longer be maintained if "highly radioactive" were essentially synonymous with "requires permanent isolation." As emphasized in Section 1.2, it is desirable to be consistent with existing law and historical precedents to a reasonable extent, and we find no compelling reason to abandon the historical distinction between TRU waste and HLW.

3.1.3 *Approach to Defining "Highly Radioactive"*

From the discussion in Section 2.1 on historical precedents for defining HLW, it is evident that the attribute "highly radioactive" has been associated with shorter-term risks resulting principally from high levels of heat and external radiation produced by the decay of shorter-lived fission-product radionuclides. Therefore, we assume that "highly radioactive" is a general attribute of waste that is related to the potential for significant shorter-term risks and is associated with high heat generation rates (power densities) or external dose rates. Power density and external dose rate generally are proportional to the concentrations of all radionuclides in the waste, but high levels of these

quantities generally are associated only with high concentrations of shorter-lived radionuclides.

The approach to quantifying "highly radioactive" is to estimate levels of power density or external dose rate that could have an adverse impact on shorter-term risks if appropriate control measures were not applied. Important control measures include containment and heat removal to prevent self-dispersal and self-boiling of the wastes and shielding to prevent unacceptable radiation exposures. Any waste with a power density or external dose rate above the levels so estimated would be highly radioactive.

As described in Section 2.1.1, early descriptions of HLW in terms of high levels of decay heat and external radiation focused on control of short-term risks from waste handling and storage. However, since waste disposal is now the primary concern, we focus on defining "highly radioactive" on the basis of levels of decay heat and external radiation that could have an impact on short-term risks from disposal. The quantification of "highly radioactive" is discussed in Section 4.2.

3.1.4 *Approach to Defining "Requires Permanent Isolation"*

As discussed in Section 2.1, the concept that HLW "requires permanent isolation" clearly is concerned with the limitation of long-term risks from disposal of high concentrations of long-lived radionuclides, principally alpha-emitting TRU radionuclides. However, this concept also has been used more generally, so the meaning of "permanent isolation" in the present waste classification system requires explanation.

The concept of "permanent isolation" or "permanent disposal" has been applied to the disposal of all types of radioactive waste, as evidenced by the similarity of definitions of "disposal" or "isolation" applicable to HLW, TRU waste, or LLW given in the NWPA, the LLRWPAA, 40 CFR Part 191,[5] 10 CFR Part 60,[7] 10 CFR Part 61,[1] and DOE Order 5820.2.[20] For any waste, "permanent" means that there is no intent to recover the waste after disposal, regardless of where it is placed, and "isolation" refers to the requirement that amounts and concentrations of radionuclides in man's exposure environment will be kept within prescribed limits that provide long-term protection of public health and safety, regardless of the disposal technology used.

Since our primary focus is on defining HLW, the term "requires permanent isolation" as used in this report means disposal by any technology that is more confining than near-surface land disposal, as described by the NRC in 10 CFR Part 61.[1,2] The approach to quantifying "requires permanent isolation" thus involves determining maximum

concentrations of radionuclides that would be generally acceptable for near-surface land disposal. The quantification of "requires permanent isolation" is discussed in Section 4.3. The issue of selecting disposal technologies that are acceptable for waste that requires permanent isolation is discussed in Section 3.4 below.

3.2 Conceptual Definitions of Other Waste Classes

From the proposed conceptual definition of HLW as waste that simultaneously is highly radioactive and requires permanent isolation, conceptual definitions of the other waste classes assumed in this study, i.e., TRU Waste and Equivalent and LLW, then follow immediately:

[1] TRU Waste and Equivalent is waste that requires permanent isolation but is not highly radioactive;

[2] LLW is waste that does not require permanent isolation, without regard to whether or not it is highly radioactive.

The definition of TRU Waste and Equivalent differs from the definitions of TRU waste discussed in Section 2.2 in that our definition applies to high concentrations of any long-lived radionuclides, not just to long-lived TRU radionuclides. While TRU radionuclides will be the most important constituents of many wastes classified as TRU Waste and Equivalent, this class also may contain wastes in which the principal constituents include, for example, ^{14}C, ^{99}Tc, ^{126}Sn, and ^{129}I.

The conceptual definitions of the three waste classes are depicted in Fig. 1. Again, the assumption that "highly radioactive" and "requires permanent isolation" are distinct attributes results in a two-dimensional waste classification system. The vertical line labeled PERMANENT ISOLATION BOUNDARY represents the limits on concentrations of long-lived radionuclides that are generally acceptable for near-surface land disposal, and this boundary separates LLW from HLW or TRU Waste and Equivalent. The horizontal line labeled HIGHLY RADIOACTIVE BOUNDARY is determined by levels of power density or external dose rate that could have an adverse impact on short-term risks, absent adequate control measures, and this boundary separates HLW from TRU Waste and Equivalent. The Highly Radioactive boundary does not extend to the left of the Permanent Isolation boundary because, as discussed in Section 2.3, levels of decay heat or external radiation are not taken into consideration in determining wastes that are generally acceptable for near-surface land disposal.

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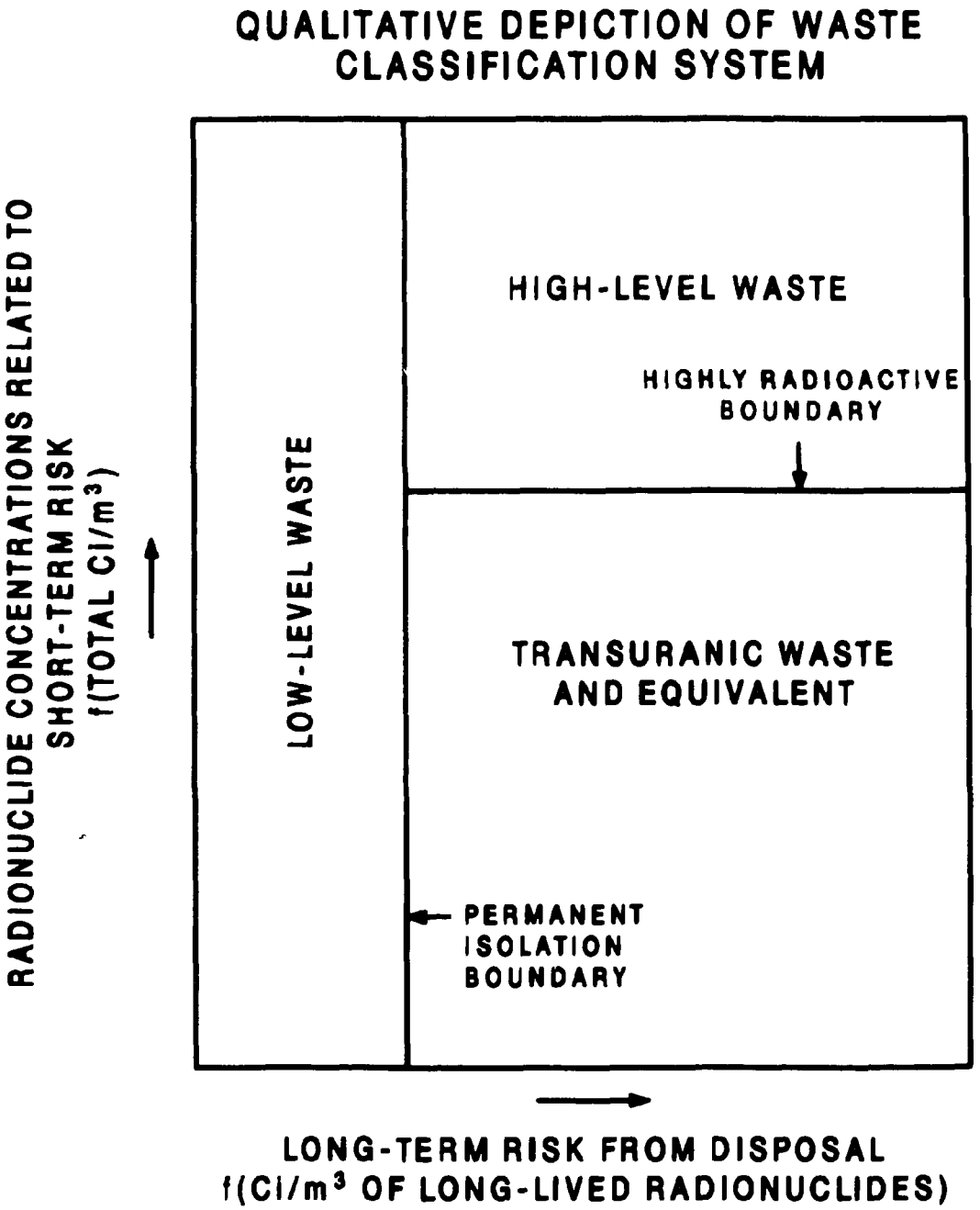

Fig. 1. Qualitative depiction of proposed waste classification system. The vertical axis related to short-term risk, which depends primarily on the concentrations of shorter-lived radionuclides, is associated with the attribute "highly radioactive" and is determined by the levels of power density or external dose rate. The horizontal axis related to long-term risk from disposal, which depends on the concentrations of long-lived radionuclides, is associated with the attribute "requires permanent isolation."

3.3 Role of Time in Waste Definitions

The definitions of HLW and the other waste classes developed in this report do not specify a particular time for classification of wastes. However, since disposal is the primary goal of waste management, we intend that the waste classification system should be applied to expected radionuclide compositions and waste forms at the time of final disposal. Issues related to short-term handling and storage of waste are different from those related to disposal. An example discussed in Section 2.3 is that waste classified as LLW could require more stringent control of short-term risks due to heat generation and external radiation than wastes classified as HLW. Furthermore, good waste management practices often will involve decontamination, concentration, solidification, partitioning, or other treatment of wastes that could change the waste classification from that at the time of generation, and defining waste classes at the time of disposal would encourage flexibility in developing such practices.

We do not intend, however, that waste disposal can be postponed indefinitely in order to achieve a change in waste classification by radioactive decay. On the contrary, expeditious disposal should be an important goal of waste management. Thus, we suggest that a limit of 100 years after waste generation be placed on the assumed time for final disposal. This limit corresponds to the assumed period for active institutional controls over near-surface land disposal facilities[1] and deep geologic repositories.[5]

3.4 Relationship Between Waste Definitions, Disposal Technologies, and Waste Acceptance Criteria

In Section 2, we emphasized that current and historical definitions of HLW, TRU waste, and LLW generally have not contained requirements that specific disposal systems be used with each type of waste. The one exception is that the NWPA implies that commercial spent fuel and reprocessing wastes (if commercial reprocessing is instituted) require deep geologic repositories. In this report, we retain the view that it is neither necessary nor desirable to associate the three waste classes defined herein with particular disposal systems.

A decoupling of the definitions of waste classes from requirements for particular disposal systems has two important implications. First, although near-surface land disposal (for LLW) and deep geologic repositories (for HLW and TRU waste) are the only disposal technologies currently recognized in law and for which regulatory standards and technical criteria have been developed, wastes classified as HLW or TRU

Waste and Equivalent would not necessarily require deep geologic repositories. Various GCD alternatives might be considered for relatively dilute wastes that are not generally acceptable for near-surface land disposal, provided standards for long-term protection of public health and safety, i.e., those in the EPA's 40 CFR Part 191,[5] are met. Second, waste disposal could involve technologies more confining than those that would be required to meet applicable standards for long-term protection of public health and safety; e.g., relatively dilute HLW or TRU Waste and Equivalent could be placed in deep geologic repositories even though less confining technologies would provide safe disposal. Thus, the waste classification system encourages flexibility in selecting disposal technologies that not only protect public health and safety but also do so in a cost-effective manner.

Finally, it must be emphasized that although LLW generally would be associated with near-surface land disposal and HLW and TRU Waste and Equivalent with deep geologic repositories or various forms of GCD, provided GCD becomes an accepted technology with an appropriate legal and regulatory framework, the waste classification system does not provide a substitute for site-specific analyses of the long-term performance of any disposal system, regardless of the type of waste to be emplaced therein. In all cases, including those where a particular type of waste requires a specific disposal technology by law, it always will be necessary to assess the long-term performance of the disposal system on a site-specific basis to ensure that applicable health-protection standards and technical criteria are met. This process may result in the development of waste acceptance criteria either for the particular technology and site or of a more general applicability. An example of waste acceptance criteria of general applicability is provided by the concentration limits for Class-C wastes that are generally acceptable for near-surface land disposal, as specified in the NRC's 10 CFR Part 61.[1,2] However, the waste classification system is not equivalent to waste acceptance criteria, but serves mainly to indicate the type of disposal technology that likely will be acceptable for a particular type of waste.

4. QUANTIFICATION OF DEFINITIONS OF HIGH-LEVEL WASTE AND OTHER WASTE CLASSES

In Section 3.1, HLW was defined conceptually as waste that is highly radioactive and requires permanent isolation. As discussed in Section 3.2, this definition also leads to conceptual definitions of TRU Waste and Equivalent and LLW, and the resulting waste classification system is depicted qualitatively in Fig. 1.

This section presents, in summary form, the quantification of the Highly Radioactive and Permanent Isolation boundaries that define HLW and the other two waste classes. Since one of the constraints for this study is to define waste classes based on considerations of risk, we first discuss the interpretation of "risk" in relation to defining "highly radioactive" and "requires permanent isolation." Following presentation of the proposed quantification of the waste classification system, we discuss (1) the resulting boundary concentrations for the important fission products ^{90}Sr and ^{137}Cs, (2) the role of greater confinement disposal (GCD) in the waste classification system, (3) a proposal for classifying surface-contaminated wastes, and (4) the volume of a waste package to which the proposed definitions apply.

4.1 Interpretation of Risk in the Waste Classification System

As outlined in Section 1.2, an important constraint in developing quantitative and generally applicable definitions of HLW and the other waste classes is that the definitions should be based principally on direct or indirect considerations of risks associated with waste management and disposal, and that the definitions should have a sound technical foundation. As discussed in Section 3.1, the definitions of waste classes should focus primarily on risks from waste disposal. This section describes the interpretation of "risk" in relation to defining the attributes "highly radioactive" and "requires permanent isolation."

In any practice involving radiation or radioactive materials, including waste management and disposal, a primary concern is limitation of radiation exposures of individuals (either radiation workers or members of the public) to levels corresponding to risks that generally are acceptable to those individuals. The term "risk" in this context has two components:[22] (1) the probability of an initiating event or process that gives rise to a particular radiation dose (or any other potentially harmful consequence) and (2) the probability of a deleterious health effect (e.g., latent cancer fatalities or genetic defects) resulting from the particular dose (or any other type of insult). Consideration of these

two components of risk leads to somewhat different interpretations of risk limitation in relation to the proposed definitions of "highly radioactive" and "requires permanent isolation."

As described in Section 3.1.4, "requires permanent isolation" is associated with long-term risks from waste disposal. As summarized in Section 4.3 below, quantification of the Permanent Isolation boundary involves the assumption that the expected performance of a disposal system will result in exposures of some individuals with a probability of unity. In this case, limitation of risk to acceptable levels involves limitation of radiation exposures from expected events and processes, and limits on radiation dose normally are used as surrogates for limits on risk based on an assumed dose-response relation.[11] Thus, for expected long-term performance of a waste disposal system, limitation of risk involves a relatively straightforward procedure of estimating limits on quantities or concentrations of radionuclides for disposal such that expected doses to individuals will not exceed prescribed limits.

As described in Section 3.1.3, "highly radioactive" is associated with shorter-term risks due to high levels of decay heat and external radiation. Here, "risk" has a somewhat different interpretation than that described above for "requires permanent isolation," because risk limitation primarily involves prevention of accidental or unexpected events and processes that likely would lead to unacceptable exposures of individuals; i.e., the emphasis is on prevention of exposures rather than limitation of exposures that are expected to occur. In this case, a dose limit is not a suitable surrogate for a limit on risk. As summarized in Section 4.2 below, quantification of the Highly Radioactive boundary is based on the concept that, for some levels of decay heat or external radiation, engineered systems or other design considerations must be used to prevent accidental occurrences that could result in unacceptable exposures.

Although the goal of this study is to develop objective risk-based definitions of "highly radioactive" and "requires permanent isolation," it is apparent from the analyses summarized in Sections 4.2 and 4.3 below that a rigorous and objective quantification of these attributes based on considerations of risk is not achievable, because technical analyses alone do not provide a clear demarcation between wastes that are highly radioactive and those that are not or between wastes that require permanent isolation and those that do not. Rather, the technical analyses based on considerations of risk indicate a range of possible quantifications for these attributes, and subjective judgments then must be used to select the quantitative definitions that appear most reasonable. These judgments generally involve consideration of the consequences of the possible range of choices.

4.2 Quantification of Highly Radioactive Boundary

This section presents the proposed quantification of the Highly Radioactive boundary that separates HLW from TRU Waste and Equivalent (see Fig. 1 in Section 3.2). Again, "highly radioactive" is associated with shorter-term risks resulting from high levels of decay heat (power density) or external radiation that are due primarily to high concentrations of shorter-lived radionuclides, and the primary focus in quantifying "highly radioactive" is on limitation of short-term risks from waste disposal.

4.2.1 *Data to Support Level of Power Density That Defines "Highly Radioactive"*

Control of short-term risks resulting from high levels of power density in waste materials involves measures for heat removal, e.g., to prevent self-dispersal or self-boiling of the waste or boiling of liquid that might contact the waste. The determination of a level of power density that defines "highly radioactive" is based on the assumption that such accidental occurrences should be prevented in order to limit risk to acceptable levels. As discussed in Section 3.1.2, the NRC also regards heat generation rate as an important consideration in the design of disposal systems for HLW.[7]

In order to estimate a level of power density that defines the proposed Highly Radioactive boundary, we examined a variety of waste handling, transport, storage, and disposal systems and estimated the levels of power density that would limit system design or operation if effective control measures were not taken to prevent accidental occurrences. The results of these investigations are summarized below and are discussed in more detail in Section A.1 of Appendix A.

- A limit on power density of about 50 W/m^3 would be required to limit the temperature rise to less than 55 ^{o}C (100 ^{o}F) in a stack of waste containers with a nominal diameter of 5 m. Such a limit on temperature rise should be sufficient to prevent degradation of waste materials or boiling of any water that contacts the waste containers.

- Power densities in the range 10-50 W/m^3 require active cooling systems to prevent self-boiling of liquid wastes in large storage tanks.

- The power density in a transport container for contact-handled (CH) defense TRU waste is limited to 40 W/m^3.[23]

- For stacking of containers for CH TRU waste in the WIPP facility, with no credit taken for void spaces between containers, the power density is limited to 15 W/m^3; and for remote-handled (RH) TRU waste which will be emplaced with a prescribed areal density of waste packages, the nominal limit on power density for the standard waste package is 300 W/m^3.[12]

- A nominal power density of 100 W/m^3 requires special considerations in the design of deep geologic repositories in a variety of repository environments.[24]

4.2.2 *Choice of Power Density That Defines "Highly Radioactive"*

The analyses summarized above indicate that power densities in the range 15-300 W/m^3 require special control measures to mitigate potential short-term risks in a variety of waste systems. Of the systems analyzed, the most relevant one for estimating a level of power density that defines "highly radioactive" for purposes of waste disposal is the need to limit the temperature rise in a stack of waste containers. An analysis of this situation gave a limit of about 50 W/m^3 for a stack size that would be reasonable for disposal, e.g., in a shallow trench. Additional support for a power density of about 50 W/m^3 to define "highly radioactive" is obtained from the levels that would require active cooling measures to prevent self-boiling in large liquid waste tanks, but this situation makes a somewhat weaker case because liquid wastes are not in a form appropriate for final disposal.

The limit on power density for RH TRU waste at the WIPP facility[12] and the nominal limit on power density that would require special design considerations for deep geologic repositories in a variety of environments[24] also are relevant for waste disposal and provide support for a power density somewhat greater than 50 W/m^3 for defining "highly radioactive." However, these limits are based on analyses of the effects of decay heat on particular repository environments rather than on the waste itself, and the effects of heat on the waste are more relevant for obtaining generally applicable limits on power density that are related to mitigation of potential short-term risks. On the other hand, it is noteworthy that the limiting power densities for the two situations do not differ greatly.

Thus, we propose a power density of 50 W/m^3 as one aspect of a quantitative and generally applicable definition of "highly radioactive." In Section 4.5 below, we suggest further that this choice has desirable consequences with regard to the concentration of the important fission product ^{90}Sr that corresponds to the Highly Radioactive boundary.

4.2.3 *Level of External Dose Rate That Defines "Highly Radioactive"*

The second aspect of a quantitative and generally applicable definition of "highly radioactive" is the level of external radiation. While the analysis in Sections 4.2.1 and 4.2.2 suggests that there are reasonable technical arguments for selecting a level of power density that is "highly radioactive" based on considerations of risk, such is not the case for external radiation for the following reasons.

First, control of external radiation generally is of less concern for limitation of short-term risks from waste disposal than control of decay heat. High levels of beta and gamma radiation can affect the leaching behavior of waste forms, but studies on borosilicate glass and other materials indicate only minor changes in dissolution rates due to self-irradiation, and other effects of radiation on waste-form properties appear to have little impact on waste-package performance.[25] Radiolysis by alpha, beta, and gamma radiation can change the chemistry of water and, thus, affect the leachability of waste forms. However, the effects of radiolysis often are observed to be unimportant even for gamma dose rates in excess of 1 Mrad/h,[25] so radiolysis does not appear to provide a suitable basis for defining "highly radioactive."

Second, levels of external radiation during waste operations that would not require shielding or limits on exposure times in order to prevent unacceptable doses to workers (i.e., annual dose equivalents to whole body greater than 5 rem)[16] appear to be much too low to provide a suitable basis for defining wastes that are highly radioactive. Furthermore, for any situation that requires shielding for limitation of external dose, additional shielding always can be added to reduce doses to acceptable levels.

Thus, selection of a level of external radiation for defining wastes that are highly radioactive is rather arbitrary. We propose that an external dose-equivalent rate of 100 rem/h (1 Sv/h) at a distance of 1 m from the surface of a waste package be used to define this aspect of "highly radioactive." The dose rate includes contributions from neutrons as well as photons, and the definition applies to the waste package that is intended for use in final disposal.

Support for this aspect of the definition of "highly radioactive" is provided by the acceptance criterion for RH TRU waste at the WIPP facility of a limit on dose-equivalent rate at the surface of a waste package of 100 rem/h, which is based on the amount of shielding that can be accommodated routinely by waste handling systems at the facility.[12] Our definition differs from the WIPP acceptance criterion with respect to the location at which the limit on dose rate is applied. We chose a distance of 1 m from the surface of a waste package instead of the surface itself, because the former is a more likely location of individuals who might receive accidental exposures. For expected sizes of waste packages, however, an analysis in Section A.3.4 of Appendix A suggests that the dose rates at 1 m and at the surface will not differ by more than an order of magnitude. That this difference is relatively insignificant is indicated by the WIPP acceptance criterion which also permits disposal of wastes with surface dose-equivalent rates up to ten times higher than 100 rem/h on an exception basis.[12]

Although the proposal to define one aspect of "highly radioactive" as an external dose-equivalent rate of 100 rem/h (1 Sv/h) is largely arbitrary, we suggest in Section 4.5 below that this choice has desirable consequences with regard to the concentration of the important fission product ^{137}Cs that corresponds to the Highly Radioactive boundary.

4.2.4 *Summary of Definition of "Highly Radioactive"*

Based on the analyses summarized in Sections 4.2.1-4.2.3, we obtain the following quantitative and generally applicable definition of wastes that are highly radioactive:

> "Highly radioactive" means -
>
> (1) a power density greater than 50 W/m^3 or
>
> (2) an external dose-equivalent rate at a distance of 1 m from the waste greater than 100 rem/h (1 Sv/h).

Thus, a waste is highly radioactive if either criterion is met.

4.2.5 *Radionuclide Concentrations Corresponding to Highly Radioactive Boundary*

The levels of power density or external dose rate that define the Highly Radioactive boundary are generally applicable to any waste, and a determination of whether a waste is highly radioactive can be based on direct measurements of these properties without knowledge of radionuclide

compositions. Direct measurements would be particularly appropriate in determining external dose rates relative to the boundary value.

On the other hand, radionuclide concentrations can be estimated for many wastes, in which case it may be more useful to determine radionuclide concentrations that correspond to the Highly Radioactive boundary. This section summarizes the methods and results for converting the boundary values of power density and external dose rate to equivalent radionuclide concentrations.

As described in detail in Section A.2 of Appendix A, the calculation of radionuclide concentrations corresponding to a given power density is quite straightforward. The power density (W/m^3) per unit concentration of a radionuclide (Ci/m^3) is proportional to the total energy (MeV) per disintegration (dis) of all ionizing radiations emitted in the decay, and the constant of proportionality is the product of the conversion factors 1.6×10^{-13} J/MeV and 3.7×10^{10} dis/s per Ci. Thus, the radionuclide concentration C_i corresponding to the Highly Radioactive boundary of 50 W/m^3 is given in terms of the total decay energy E_T by

$$C_i(Ci/m^3) = (8.45 \times 10^3)/E_T(MeV/dis) ,$$

where the constant has units of MeV-Ci/dis-m^3. For example, the total decay energy of ^{90}Sr and its short-lived decay product ^{90}Y is 1.13 MeV,[26] so the concentration of ^{90}Sr corresponding to the Highly Radioactive boundary is about 7×10^3 Ci/m^3.

The calculation of radionuclide concentrations corresponding to a given external dose rate is considerably more complex than the calculation for power density described above. In addition to the decay spectrum of photons, the dose rate per unit concentration of a radionuclide depends on the size, geometrical configuration, and orientation of the waste package, the amount of self-shielding provided by materials in the waste package, and any shielding between the waste package and the assumed receptor location. Thus, a model must be assumed for relating external dose rate to radionuclide concentrations in the waste.

In this analysis, we have assumed that the waste package consists of a 55-gallon drum in which radionuclides are mixed uniformly with dirt, polyethylene, concrete, or air in order to simulate a variety of filler materials. The assumed waste package is typical of those that are used for near-surface land disposal. Thus, the source is is assumed to be a right-circular cylindrical volume, and the self-shielding provided by the source volume is determined by the density of the filler material and the average atomic number of its constituents.

External dose rates from a self-absorbing cylindrical volume source were calculated as described in Section A.3 of Appendix A. The calculations assume a uniform concentration of ^{137}Cs because, as discussed

in Section A.3.3 of Appendix A, this is the only radionuclide that is expected to exist in concentrations sufficient to exceed the Highly Radioactive boundary for which the limit on external dose-equivalent rate of 100 rem/h (1 Sv/h) is more restrictive than the limit on power density of 50 W/m^3. For all other radionuclides of potential importance in waste materials, power density is more restrictive than external dose rate, the expected concentrations in wastes are far below the Highly Radioactive boundary, or the half-life is sufficiently long that the radionuclide cannot reasonably occur in concentrations that would give an external dose-equivalent rate approaching 100 rem/h.

The calculations for ^{137}Cs presented in Section A.3.2 of Apppendix A show that the external dose rate at a distance of 1 m from a cylindrical volume source can vary by about a factor of 4, depending on the assumed filler material in the waste package and the orientation of the cylinder relative to the receptor location. Taking into account this range of values, we estimate that a ^{137}Cs concentration of about 5×10^3 Ci/m^3 provides a nominal external dose-equivalent rate of 100 rem/h (1 Sv/h) at a distance of 1 m from a waste package.

Concentrations of selected radionuclides that correspond to the Highly Radioactive boundary are given in Table 1. All entries are based on a power density of 50 W/m^3, except the entry for ^{137}Cs is based on an external dose-equivalent rate of 100 rem/h (1 Sv/h). In calculating the boundary concentrations based on power density, the total decay energy of radionuclides and their short-lived daughter products was obtained from ref. 26. The correspondence between the Highly Radioactive boundary concentrations for ^{90}Sr and ^{137}Cs and the limit for disposal as Class-C waste is discussed in Section 4.5.

Only radionuclides with half-lives greater than 20 years are listed in Table 1, except ^{241}Pu and ^{244}Cm which decay to longer-lived daughter products. Again, according to the waste classification system described in Section 3.2 and depicted in Fig. 1, radionuclides with half-lives less than about 20 years would be classified as LLW regardless of their concentration (i.e., regardless of whether or not the Highly Radioactive boundary is exceeded), because they cannot exist in sufficient concentrations to exceed the Permanent Isolation boundary. Conversely, no radionuclides with half-lives greater than a few tens of thousands of years are listed in Table 1, because such radionuclides have low specific activities and cannot exist in sufficient concentrations to exceed the Highly Radioactive boundary.

The concentrations in Table 1 define the Highly Radioactive boundary for individual radionuclides. For wastes containing mixtures of radionuclides, the determination of whether the waste is highly radioactive is based on the sum-of-fractions rule; i.e., a mixture of

Table 1. Selected radionuclide concentrations corresponding to Highly Radioactive boundary in waste classification system[a]

Nuclide[b]	Boundary concentration (Ci/m^3)	Nuclide[b]	Boundary concentration (Ci/m^3)
C-14	2E5	U-232 + d	2E2
Ni-63	5E5	Pu-238	2E3
Sr-90 + d	7E3[c]	Pu-239	2E3
Cs-137 + d	5E3[c]	Pu-240	2E3
Sm-151	4E5	Pu-241	2E6
Pb-210 + d	1E3	Am-241	2E3
Ra-226 + d	3E2	Am-243 + d	1E3
Ac-227 + d	2E2	Cm-243	1E3
Th-229 + d	3E2	Cm-244	1E3
Pa-231	2E3	Cm-245	2E3

[a]Boundary concentration for any radionuclide is based on a power density of 50 W/m^3 or an external dose-equivalent rate at a distance of 1 m from the waste of 100 rem/h (1 Sv/h), whichever is more restrictive; for all radionuclides in this table except Cs-137, the boundary concentration is based on power density. Highly Radioactive boundary for wastes containing mixtures of radionuclides is determined from boundary concentrations for each radionuclide using sum-of-fractions rule, or may be determined from direct measurements of power density and external dose rate.

[b]Notation "+ d" means short-lived daughter products are assumed to be in secular equilibrium with parent radionuclide.

[c]Value corresponds to Class-C limit for near-surface land disposal, as specified by the NRC in 10 CFR Part 61 (ref. 1).

radionuclides is highly radioactive if the ratio of each radionuclide concentration to the corresponding boundary concentration in Table 1, summed over all radionuclides, exceeds unity. While this procedure is not strictly correct for wastes that contain ^{137}Cs mixed with other radionuclides, because the basis for the boundary concentration for ^{137}Cs is external dose rate but power density is used for the other radionuclides, use of the sum-of-fractions rule does not lead to serious errors in this case because the boundary concentration for ^{137}Cs which would be based on a power density of 50 W/m^3 is greater than the value in Table 1 by only about a factor of 2.

4.3 Quantification of Permanent Isolation Boundary

As described in Section 3.1.4, the proposed waste classification system associates "requires permanent isolation" with concentrations of long-lived radionuclides greater than those that would be generally acceptable for near-surface land disposal (but would not necessarily require deep geologic repositories or equivalent). The Permanent Isolation boundary separates LLW from HLW and TRU Waste and Equivalent (see Fig. 1 in Section 3.2).

In 10 CFR Part 61, the NRC has established concentration limits for radionuclides that are generally acceptable for near-surface land disposal; these are the concentration limits for Class-C wastes.[1,2] The basis for these concentrations is a limit on annual dose equivalent to whole body for an inadvertent intruder into the disposal facility of 0.5 rem at 500 years after disposal, and the other assumptions used by the NRC to derive the Class-C limits are discussed briefly in Section B.1 of Appendix B.

In this study, the concentration limits for Class-C wastes obtained from 10 CFR Part 61 and its associated methodology are used to define radionuclide concentrations corresponding to the Permanent Isolation boundary. The resulting boundary concentrations for selected long-lived radionuclides are given in Table 2, and were obtained from the following sources:

- Tables 1 and 2 of the Final Rule for 10 CFR Part 61 for ^{14}C, ^{59}Ni, ^{63}Ni, ^{90}Sr, ^{94}Nb, ^{99}Tc, ^{129}I, and ^{137}Cs;[1]

- Section 7 of Appendix C of the Final Environmental Impact Statement (FEIS) for 10 CFR Part 61 for all TRU radionuclides;[2]

Table 2. Selected radionuclide concentrations corresponding to Permanent Isolation boundary in waste classification system[a]

Nuclide	Boundary concentration (Ci/m^3)	Nuclide	Boundary concentration (Ci/m^3)
C-14	8	Th-232	1E-2[c]
C-14[b]	8E1	Pa-231	3E-2[c,e]
Ni-59[b]	2E2	U-232	5E-2[c]
Ni-63	7E2	U-233	4E-1[c]
Ni-63[b]	7E3	U-234	5E-1[c]
Sr-90	7E3	U-235	4E-1
Nb-94[b]	2E-1	U-236	6E-1[c]
Tc-99	3	U-238	5E-1
Ag-108m	3E-2[c]	Np-237	4E-2
Sn-126	1E-2[c]	Pu-238	7
I-129	8E-2	Pu-239	1E-1
Cs-135	8E2	Pu-240	1E-1
Cs-137	5E3	Pu-241	5[f]
Pb-210	2E2[c]	Pu-242	1E-1
Ra-226	3E-2[d]	Am-241	1E-1
Ac-227	1[c]	Am-243	7E-2
Th-229	5E-2[c]	Cm-243	8E1[g]
Th-230	6E-2[c]	Cm-244	4E1[h]

[a]Boundary concentration is defined as Class-C limit that is generally acceptable for near-surface land disposal, as specified by the NRC in 10 CFR Part 61 and supporting documentation (refs. 1-4). Permanent Isolation boundary for wastes containing mixtures of radionuclides is determined from boundary concentration for each radionuclide using sum-of-fractions rule.

[b]Radionuclide in activated metals only.

[c]Value is not included in the NRC's 10 CFR Part 61 and supporting documentation (refs. 1-4) and is provisional.

[d]Value assumes Pb-210 is in secular equilibrium with Ra-226.

[e]Value assumes Ac-227 is in secular equilibrium with Pa-231.

[f]Value is 30 times boundary concentration for Am-241.

[g]Value is 850 times boundary concentration for Pu-239.

[h]Value is 360 times boundary concentration for Pu-240.

- Table 4.5 of the Main Report of the FEIS for 10 CFR Part 61 for ^{135}Cs, ^{235}U, and ^{238}U;[2]

- Table 4-3 of Volume 2 of the revised impacts analysis methodology for 10 CFR Part 61 for ^{226}Ra;[4]

- Calculations of Class-C limits which we performed using the revised impacts analysis methodology for 10 CFR Part 61 for ^{108m}Ag, ^{126}Sn, ^{210}Pb, ^{227}Ac, ^{229}Th, ^{230}Th, ^{232}Th, ^{231}Pa, ^{232}U, ^{233}U, ^{234}U, and ^{236}U.[3,4]

The boundary concentrations in Table 2 are discussed further in Sections B.2 and B.3 of Appendix B, particularly with regard to the provisional nature of the values which we calculated from the NRC's revised impacts analysis methodology.[3,4] The use of separate concentration limits for each TRU radionuclide and for ^{226}Ra in units of Ci/m^3, instead of the single limit for all long-lived, alpha-emitting TRU radionuclides of 100 nCi/g given in Table 1 of the Final Rule for 10 CFR Part 61[1] and the limit for ^{226}Ra of 20 nCi/g given in Table 4-3 of Volume 2 of the revised impacts analysis methodology,[4] is discussed in detail in Appendix D. In essence, we use radionuclide-specific concentration limits in Ci/m^3 for these radionuclides because (1) such concentrations are the measure of activity that is directly related to risk from waste disposal and (2) this approach provides a generally applicable definition of the Permanent Isolation boundary.

The concentration limits for ^{226}Ra and ^{231}Pa in Table 2 include the contributions from their daughter products ^{210}Pb and ^{227}Ac, respectively,[3] and the daughters are assumed to be in secular equilibrium with the parent radionuclides at the time intrusion occurs. The concentration limits for the relatively short-lived radionuclides ^{241}Pu, ^{243}Cm, and ^{244}Cm are determined by the limits for their longer-lived daughter products ^{241}Am, ^{239}Pu, and ^{240}Pu, respectively, and the half-lives of the parent and daughter in each case.

Although the NRC's impacts analysis methodology and the resulting concentration limits of radionuclides for Class-C wastes are well established,[1,2] it should be recognized that there is considerable uncertainty in estimating these concentrations on the basis of a dose limit for an inadvertent intruder. Not only is it somewhat arbitrary to assume that intruder exposures occur at 500 years after disposal, but there also is considerable uncertainty in defining appropriate exposure scenarios for an intruder and in choosing the parameter values used in the models for estimating annual doses per unit radionuclide concentration for the postulated exposure scenarios. Furthermore, for a few of the most

important radionuclides listed in Tables 1 and 2 of the Final Rule for 10 CFR Part 61,[1] subjective judgment evidently was applied in adjusting the concentration limits calculated from the dose-assessment methodology to obtain the final results.[2] Thus, although a determination of the Permanent Isolation boundary from the 10 CFR Part 61 methodology appears to have a sound technical foundation based directly on limitation of risk from waste disposal, the correspondence between the radionuclide concentrations that define this boundary and a limit on risk perhaps is no more rigorous than the correspondence with risk provided by the concentrations that define the Highly Radioactive boundary in Table 1.

The concentrations in Table 2 define the Permanent Isolation boundary for individual radionuclides. As with the results in Table 1, the determination of whether a mixture of radionuclides requires permanent isolation is obtained by use of the sum-of-fractions rule.

4.4 Depiction of Quantitative Waste Classification System

The qualitative definitions of HLW, TRU Waste and Equivalent, and LLW were summarized in Section 3.2 and depicted in Fig. 1. In Section 4.2, we developed the quantitative definition that wastes are highly radioactive if the power density exceeds 50 W/m^3 or the external dose-equivalent rate exceeds 100 rem/h (1 Sv/h). This boundary separates HLW from TRU Waste and Equivalent but is not applied to LLW, since neither power density nor radiation dose is a factor in determining wastes that are generally acceptable for near-surface land disposal.[1,2] In Section 4.3, we developed the quantitative definition that wastes require permanent isolation if the radionuclide concentrations exceed the Class-C limits that are generally acceptable for near-surface land disposal, as specified in the NRC's 10 CFR Part 61.[1-4]

The quantitative waste classification system that results from these definitions is depicted in Fig. 2. Radionuclide concentrations corresponding to the Highly Radioactive boundary of 50 W/m^3 or 100 rem/h (1 Sv/h) are given in Table 1, and concentrations corresponding to the Permanent Isolation boundary are given in Table 2.

With regard to the Permanent Isolation boundary, it is not necessary to define quantitatively what is meant by a "long-lived" radionuclide. Rather, for purposes of the proposed waste classification system, it is sufficient to recognize that a radionuclide is "long-lived" if it can exist in concentrations greater than its Class-C limit. The lower limit for the half-life that is "long-lived" depends on the particular radionuclide, but generally is about 20 years.

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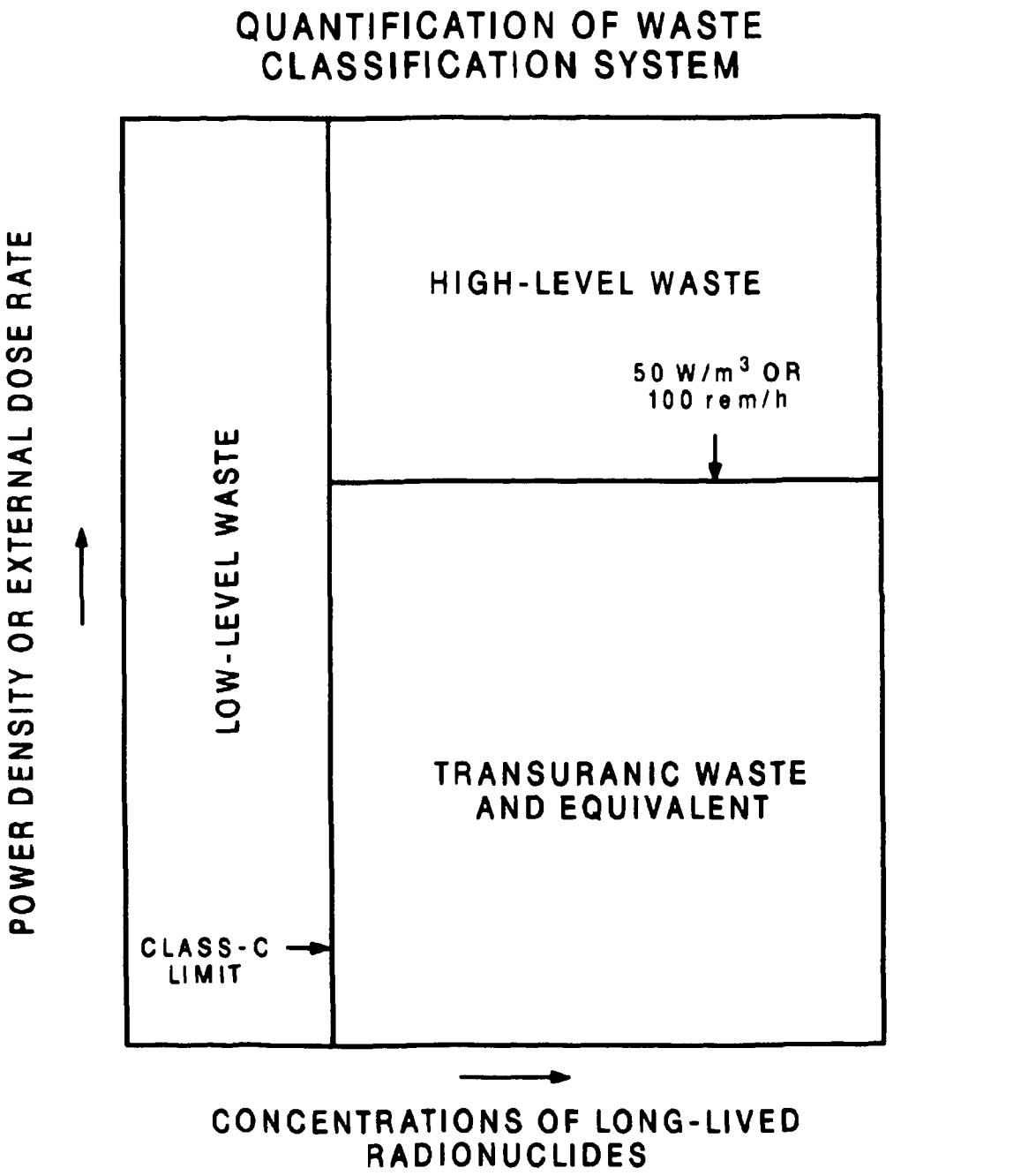

Fig. 2. Depiction of proposed waste classification system. Radionuclide concentrations corresponding to boundaries defining High-Level Waste, Transuranic Waste and Equivalent, and Low-Level Waste are given in Tables 1 and 2.

4.5 Boundary Concentrations for ^{90}Sr and ^{137}Cs

The fission products ^{90}Sr and ^{137}Cs are two of the most important constituents of spent fuel, reprocessing wastes, and a variety of other wastes. In the proposed waste classification system summarized in Tables 1 and 2, these radionuclides are used in defining the Permanent Isolation and the Highly Radioactive boundary; and, for each radionuclide, the same concentration is used to define the two boundaries. Thus, concentrations of either of these radionuclides by themselves that exceed their respective Class-C limits would be classified as HLW.

Inclusion of ^{90}Sr and ^{137}Cs in defining the Permanent Isolation boundary appears somewhat at odds with the historical precedents discussed in Section 2.1 for describing HLW from fuel reprocessing. The attribute "requires permanent isolation" clearly is associated with long-term risks from waste disposal; but, historically, such risks were regarded as resulting principally from high concentrations of long-lived, alpha-emitting TRU radionuclides and not from the shorter-lived ^{90}Sr and ^{137}Cs. However, since we have defined "requires permanent isolation" in terms of the concentration of any radionuclide that exceeds its Class-C limit for near-surface land disposal,[1-4] ^{90}Sr and ^{137}Cs are included in the class of radionuclides that could require permanent isolation.

On the other hand, inclusion of ^{90}Sr and ^{137}Cs in defining the Highly Radioactive boundary is in accord with historical precedents for describing HLW from fuel reprocessing, because these radionuclides are the most important sources of high levels of decay heat and external radiation in reprocessing wastes that have been aged for a few years. Nonetheless, use of the Class-C limits for ^{90}Sr and ^{137}Cs in defining the Highly Radioactive boundary appears somewhat arbitrary, because the Class-C limits are based only on consideration of risks from waste disposal and not on consideration of risks from decay heat or external radiation.[1,2] However, we re-emphasize that the analyses in Section 4.2 related to the definition of the Highly Radioactive boundary as a power density of 50 W/m^3 or an external dose-equivalent rate of 100 rem/h (1 Sv/h) were not based on the Class-C limits for ^{90}Sr and ^{137}Cs. Rather, the analyses showed that a range of power densities and external dose rates would provide a reasonable risk-based definition of "highly radioactive," and the Class-C limits for ^{90}Sr and ^{137}Cs correspond to values of power density and external dose rate, respectively, that lie within these ranges. Thus, although the choice of the Class-C limits for ^{90}Sr and ^{137}Cs to define the Highly Radioactive boundary is partly a matter of subjective judgment, the choice still is related to short-term risks resulting from decay heat and external radiation.

Use of the Class-C limits for ^{90}Sr and ^{137}Cs in defining the Permanent Isolation and the Highly Radioactive boundary has several desirable consequences which provide justification for the choice. First, if ^{90}Sr and ^{137}Cs were used in defining only the Highly Radioactive boundary (i.e., were not regarded as "long-lived" for purposes of defining the Permanent Isolation boundary), then these radionuclides would be classified as LLW regardless of concentration. However, there exist ^{90}Sr and ^{137}Cs wastes in which the concentrations exceed the Class-C limits by as much as a factor of 4×10^4;[21] and it seems more reasonable that such wastes should be called HLW than greater than Class-C LLW, particularly since they may require disposal in deep geologic repositories or equivalent for protection of public health and safety (see Section C.1 of Appendix C).

Second, if ^{90}Sr and ^{137}Cs are used in defining both boundaries in the waste classification system, then use of the Class-C limits for each boundary means that these radionuclides by themselves would be classified as either LLW or HLW, but not as TRU Waste and Equivalent. Conversely, if the Highly Radioactive boundary for these radionuclides did not correspond to the Class-C limits, then these radionuclides could exist in any of the three waste classes. The desirable aspects of such a possibility are not apparent, particularly since the exclusion from TRU Waste and Equivalent of ^{90}Sr and ^{137}Cs in concentrations greater than their Class-C limits agrees with the historical precedent that TRU waste contains relatively low concentrations of fission products compared with waste from fuel reprocessing.

Finally, one purpose of the proposed waste classification system is to quantify the historical source-based definitions of HLW, particularly the definition in Clause (A) of the NWPA (see Section 2.1.3) which refers to "highly radioactive material" from fuel reprocessing that "contains fission products in sufficient concentrations." Thus, the waste classification system essentially defines "contains fission products in sufficient concentrations" for aged reprocessing wastes as concentrations of ^{90}Sr and ^{137}Cs that exceed their Class-C limits. This is a reasonable choice, because reprocessing wastes that contain concentrations of ^{90}Sr and ^{137}Cs in excess of their Class-C limits also contain concentrations of long-lived, alpha-emitting TRU radionuclides that exceed their Class-C limits,[21,27] and it seems proper that such wastes should be classified as HLW. Thus, the waste classification system provides a reasonable reconciliation between the definitions in Clauses (A) and (B) of the NWPA.

4.6 Provision for Greater Confinement Disposal

As discussed in Section 3.4, the proposed waste classification system does not associate the three waste classes with requirements for particular disposal technologies, even though LLW generally is associated with near-surface land disposal and HLW and TRU Waste and Equivalent are associated with deep geologic repositories or equivalent. Again, these are the only disposal technologies currently recognized in law and for which regulatory standards and technical criteria have been developed, but the waste classification system should not preclude alternatives for waste disposal that would protect public health and safety.

Alternatives to near-surface land disposal and deep geologic repositories or equivalent would involve technologies for GCD which presumably provide intermediate waste-isolation capabilities. The role of GCD in the proposed waste classification system is specified as follows:

- Wastes classified as HLW or TRU Waste and Equivalent may be acceptable for greater confinement disposal on a site-, waste-, and technology-specific basis provided applicable standards for protection of public health and safety will be met.

Thus, GCD would constitute "permanent isolation" for sufficiently dilute wastes that exceed Class-C limits, just as near-surface land disposal constitutes "permanent isolation" for LLW.

The use of GCD technologies is under active consideration by the DOE[9,28] and the NRC.[29-33] A brief description of GCD technologies and their current status of development is given in Appendix F. GCD technologies currently in use or under investigation include (1) above-grade confinement in engineered structures, (2) below-grade confinement involving deep trenches, augered shafts, concrete structures, underground mines, rock cavities, or hydrofracture, and (3) improved waste forms and high-integrity containers.

The use of GCD is related only to limitation of long-term risks from waste disposal (i.e., to the horizontal axis in Figs. 1 and 2) but is not relevant to limitation of shorter-term risks from wastes that are highly radioactive. For radionuclides with half-lives comparable to or longer than any time period over which continued integrity of waste containers and waste forms may reasonably be assumed (e.g., 500 years),[1,2] the primary benefit of GCD compared with conventional near-surface land disposal is the potential for eliminating particular exposure scenarios for inadvertent intruders (i.e., the so-called intruder-agriculture and intruder-construction scenarios) which were used by the NRC in 10 CFR Part 61 to determine concentration limits of many radionuclides for near-

surface land disposal.[2] A form of GCD involving a facility well below the ground surface would be needed to eliminate these intrusion scenarios for long time periods.

As a means of encouraging further development of GCD technologies, methodologies for health-risk assessments, and appropriate regulatory standards and technical criteria, Section C.1 of Appendix C presents an example analysis for estimating maximum concentrations that would be acceptable for GCD for the long-lived radionuclides listed in Table 2. The analysis assumes intermediate-depth burial as the disposal technology, again because enhanced surface or near-surface land disposal presumably would not be effective in reducing doses to inadvertent intruders for radionuclides with half-lives longer than a few hundred years. Radiation doses to inadvertent intruders per unit concentration of radionuclides in the facility are estimated on the basis of a solid-waste drilling scenario[10] that is assumed to occur at 500 years after disposal. In this scenario, an intruder living on the site drills through the disposal facility (e.g., for the purpose of constructing a well for the intruder's water supply), radionuclides are brought to the surface in the solid drilling wastes, and the radioactive wastes are mixed with native soil in a vegetable garden. Doses to the intruder then result from the following exposure pathways: (1) ingestion of contaminated vegetables from the garden, (2) ingestion of contaminated soil from the garden in conjunction with vegetable intakes, (3) inhalation of suspended radionuclides from the garden, and (4) external exposure to contaminated soil in the garden. The maximum concentrations of radionuclides that would be acceptable for intermediate-depth burial then are obtained by assuming a limit on annual committed effective dose equivalent for an intruder of 0.5 rem. This choice of a dose limit is discussed in Section B.3 of Appendix B.

The analysis in Section C.1 of Appendix C provides reasonable limits on radionuclide concentrations that would be acceptable for intermediate-depth burial, in the sense that the limits for the most important radionuclides in commonly existing wastes lie between the limits for Class-C LLW given in Table 2 and the concentrations typically found in commercial spent fuel and reprocessing wastes[25,27] that probably require deep geologic repositories or equivalent for protection of public health and safety. We emphasize, however, that this analysis does not provide a suitable basis for defining generally applicable concentration limits for GCD (i.e., minimum concentrations of radionuclides that generally would require deep geologic repositories or equivalent). First, while the solid-waste drilling scenario is reasonably generic, the parameters used in the dose analysis for this scenario may be quite site-specific and subject to considerable uncertainty. Second, the analysis of the solid-waste drilling scenario does not take into account potentially important

contributions to dose from radionuclides that are leached from the disposal facility and transported to an aquifer that is used as a source of drinking water for an intruder (see Section C.2 of Appendix C). Third, until regulatory standards and technical criteria are developed for GCD, there is considerable uncertainty over the required performance of waste packages and engineered facilities; and these uncertainties could affect the validity of the exposure scenario chosen for analysis, so that other exposure scenarios might be more appropriate. Finally, the analysis considered only intermediate-depth burial, and similar analyses for other GCD technologies could result in significantly different concentration limits of radionuclides.

Thus, the analysis in Section C.1 of Appendix C is intended only as a demonstration that it is reasonable to consider GCD as an alternative to deep geologic repositories for disposal of relatively dilute wastes classified as HLW or TRU Waste and Equivalent. At present, however, the acceptability of GCD should be evaluated only on a site-, waste-, and technology-specific basis. A number of such evaluations and the development of an appropriate regulatory framework for GCD could lead to the definition of a generally applicable GCD-Permanent Isolation boundary, which would specify HLW or TRU Waste and Equivalent that requires deep geologic repositories or equivalent for protection of public health and safety.

Finally, we re-emphasize that the acceptability of GCD for disposal of some HLW or TRU Waste and Equivalent would not affect the definitions of these wastes in the proposed classification system. However, the waste classification system does not preclude the possibility of defining sub-classes of HLW and TRU Waste and Equivalent corresponding to wastes that are acceptable for GCD vs those that require deep geologic repositories or equivalent. A precedent for defining such sub-classes is provided by the specification of criteria for near-surface land disposal of three classes of waste in the NRC's 10 CFR Part 61.[1,2]

4.7 Classification System for Surface-Contaminated Wastes

The waste classification system developed in this report assumes implicitly that the radionuclides are dispersed throughout a waste volume. This section presents a proposal for classifying surface-contaminated wastes on the basis of the classification system for volume-contaminated wastes.

The need for a classification system for surface-contaminated wastes is indicated by the fact that many wastes for which activity is reported on a per unit volume or mass basis, and for which analyses of risks from

waste disposal assume volume contamination, are surface-contaminated. For example, in many types of LLW (e.g., compactible or noncompactible trash and filter cartridges), radionuclides are deposited on surfaces of glass, paper, metal, clothing, glove boxes, etc.[2] Similarly, an investigation we performed of available data on TRU waste indicates that about 80% by volume of the waste currently in storage probably is surface-contaminated. However, a separate treatment of surface-contaminated wastes in the proposed waste classification system probably is needed only for large waste forms (e.g., glove boxes and large metal forms) that are noncompactible. Otherwise, the surface-contaminated wastes will be effectively dispersed throughout a volume when prepared for disposal and can be treated as volume-contaminated waste without further consideration.

We propose that classification of surface-contaminated wastes needing separate treatment be based on the surface area-to-volume ratio for the waste form; i.e., a given concentration of a radionuclide per unit area on the surface would be multiplied by the ratio of the surface area to the volume of the solid waste form to give the appropriate concentration per unit volume for use in the waste classification system. This method would be applied to the determination of power density in relation to the Highly Radioactive boundary and to the determination of radionuclide concentrations in relation to the Permanent Isolation boundary. However, the determination of external dose rate in relation to the Highly Radioactive boundary for surface-contaminated wastes would be obtained most easily from direct measurement or would require a separate calculation based on consideration of the particular waste form.

For simple geometrical configurations for the waste form, the surface area-to-volume ratio is calculated easily. For example, for a right-circular cylinder of radius r, the ratio is $2/r$ for any height of the cylinder; for a sphere of radius r, the ratio is $3/r$; and for a rectangle of dimensions x, y, and z, the ratio is $2/(x+y+z)$.

The WIPP facility applies limits on removable surface contamination for acceptance of TRU waste of 50 pCi per 100 cm^2 for alpha-emitting radionuclides and 450 pCi per 100 cm^2 for beta/gamma-emitting radionuclides.[12] The limits on surface contamination are based on experience that these levels are reasonably achievable and would maintain an essentially contamination-free environment in a waste-handling facility during continuous operation. One could consider applying these criteria, particularly for gamma-emitting radionuclides, in defining levels of surface contamination that are "highly radioactive." However, a cursory analysis indicates that external dose rates resulting from the specified limits on surface contamination are far too low to provide a reasonable basis for defining "highly radioactive" in the waste classification system.

4.8 Volume of Waste Package for Application of Waste Classification System

The proposed waste classification system does not specify a volume of waste or size of a waste package to which the definitions apply. Since the waste classification system focuses primarily on disposal, we intend that the radionuclide concentrations to be compared with the Highly Radioactive and Permanent Isolation boundaries in Tables 1 and 2 should be obtained by averaging the concentrations over the volume of the waste form or waste package that is to be used for final disposal. Thus, it usually is improper to change a waste classification simply by placing a relatively small-volume waste form in a much larger waste package than is needed for disposal. An exception is that some wastes (e.g., small sources of ^{90}Sr and ^{137}Cs) may be of such small volume but so highly radioactive that it would be reasonable to dispose of the wastes using packages much larger than the source itself in order to provide adequate protection of workers during waste handling operations. In such cases, we propose that the radionuclide concentration can be averaged over a volume not to exceed 1 m^3. This limit corresponds to the nominal volume of a waste package for RH TRU waste at the WIPP facility.[12] The use of such an averaging procedure for very small sources should have no significant effect on the risks that would result from their disposal.

Inhomogeneities in radionuclide concentrations throughout a waste volume could be of concern during storage of liquid wastes or sludges. Thus, if it is desirable to classify wastes on an interim basis prior to final disposal, then the variability of radionuclide concentrations in a given waste storage unit should be taken into account.

5. IMPACTS OF PROPOSED WASTE CLASSIFICATION SYSTEM

This section discusses impacts of the proposed waste classification system, as summarized in Tables 1 and 2 and Section 4.4 and depicted in Fig. 2, on selected commercial and defense wastes. The impacts analysis is restricted to (1) the waste classifications that would apply to commercial spent fuel and reprocessing wastes and to defense wastes that have been called HLW because of their source as waste from fuel reprocessing and (2) a discussion of potential impacts of differences between the waste classification system and the acceptance criteria for disposal of defense TRU waste at the WIPP facility.

5.1 Impacts on Commercial Spent Fuel and Reprocessing Wastes

Tables E-1 through E-4 in Section E.1 of Appendix E present selected data on radionuclide concentrations in 10-year old commercial spent fuel, liquid reprocessing wastes, and reprocessing wastes that have been solidified in borosilicate glass.[25,27] In each table, the reported concentrations are compared with the concentrations that correspond to the Highly Radioactive and Permanent Isolation boundaries, as given in Tables 1 and 2. The waste classification then is determined from application of the sum-of-fractions rule to the two boundaries. The comparison of radionuclide concentrations with the GCD boundary is discussed in Appendix E and is based on the analysis presented in Section C.1 of Appendix C and discussed in Section 4.6.

Irrespective of the differences in the reported radionuclide concentrations for the two types of spent fuel and reprocessing wastes in Tables E-1 through E-4, each of these wastes clearly would be classified as HLW in the proposed classification system; i.e., the radionuclide concentrations greatly exceed the Highly Radioactive and the Permanent Isolation boundary. Such a result intuitively would be required of any reasonable waste classification system.

The data for commercial spent fuel and reprocessing wastes also show, as expected, that these wastes are highly radioactive, primarily because of the high concentrations of the fission products ^{90}Sr and ^{137}Cs. It also is interesting to consider the waste classifications that would result if all fission products were removed and only the TRU radionuclides remained. Commercial spent fuel absent all fission products still would be highly radioactive (and thus HLW), because the concentrations of various isotopes of Pu, Am, and Cm each exceed the boundary concentrations in Table 1. However, the reprocessing waste in borosilicate glass would just barely exceed the Highly Radioactive boundary, due primarily to the

concentration of ^{241}Am, and the liquid reprocessing waste would not be highly radioactive if the ^{244}Cm were allowed to decay for a few years. Thus, the liquid waste without fission products would be classified as TRU Waste and Equivalent, but we caution that these concentrations might not adequately represent those in solidified waste prepared for disposal.

Alkaline (liquid and sludge) and acid wastes from reprocessing of spent fuel are being stored at the West Valley Demonstration Project in New York, and these wastes represent an actual waste inventory requiring disposal. The radionuclide concentrations in the West Valley wastes generally are less than those in the commercial reprocessing wastes discussed above, because some of the wastes arise from thorium-uranium fuel or include DOE reprocessing wastes, both of which generally involve lower fuel burnups than in commercial reactors.[20]

We have not evaluated the West Valley wastes in detail, but data compiled by the DOE[21] indicate that the acid wastes and the alkaline sludges in their present form would be classified as HLW, but the alkaline liquids would be classified as TRU Waste and Equivalent. Again, however, these classifications do not necessarily apply to solid waste prepared for disposal, and they do not take into account that further waste processing may occur (e.g., removal of ^{137}Cs from the supernatant) prior to solidification.[34]

5.2 Impacts on Defense Reprocessing Wastes

Defense wastes currently called HLW, because of their source as waste from fuel reprocessing, are stored at the Savannah River Plant, the Idaho National Engineering Laboratory, and the Hanford Reservation. These wastes occur in a variety of forms and with widely varying radionuclide concentrations, because of differences in the characteristics of the fuels that have been reprocessed at each site and differences in plant operating practices.

We have considered in detail the impacts of the proposed waste classification system only for one type of defense reprocessing waste - namely, the sludge-supernate glass waste at Savannah River,[35] which is in a form appropriate for disposal. The reported radionuclide concentrations in borosilicate glass are compared with the concentrations that correspond to the Highly Radioactive and Permanent Isolation boundaries in Table E-5 in Section E.2 of Appendix E. This waste clearly would be classified as HLW, since both boundaries are exceeded considerably. The reported data on power density and external dose rate[35] also indicate that this waste is highly radioactive. Absent any fission products, the waste would just barely exceed the Highly Radioactive boundary (and thus be HLW), due to

the high concentration of ^{238}Pu.

Data for sludge-only glass waste at Savannah River also have been reported.[35] With the exception of ^{137}Cs, the radionuclide concentrations in this waste generally are somewhat greater than in the sludge-supernate glass waste discussed above. Thus, the sludge-only glass waste also would be classified as HLW.

Data on wastes at the other two sites that currently are called HLW have been compiled by the DOE.[21] The Idaho wastes in calcine form probably would be classified, on average, as TRU Waste and Equivalent rather than HLW, because they do not appear to contain sufficient concentrations of ^{90}Sr and ^{137}Cs to be highly radioactive. Similarly, many of the wastes at Hanford in the form of liquids, sludges, salt cake, and slurries would be classified, on average, as TRU Waste and Equivalent or even LLW. Only the capsules of ^{90}Sr and ^{137}Cs would be classified as HLW.

We re-emphasize, however, that most of the defense reprocessing wastes for which data are reported by the DOE[21] are not in a form appropriate for disposal, and the radionuclide concentrations could change significantly with further processing and solidification prior to disposal. Furthermore, the radionuclide concentrations reported by the DOE generally are averages over a large number of waste storage units, particularly for the Hanford wastes, and these data may not adequately represent the concentrations in a significant number of individual storage units. Therefore, these data should be used only to indicate the possibility that much of the defense waste currently called HLW, because of its source as waste from fuel reprocessing, may be classified according to our proposed system as TRU Waste and Equivalent or even LLW, due to the low fuel burnups compared with those in commercial reactors and to the varieties of processing applied to the wastes. More detailed analysis is needed on particular wastes and on expected waste forms for disposal in reaching definitive conclusions on the classification of these defense reprocessing wastes.

5.3 Impacts on Acceptance Criteria for Disposal of TRU Wastes at the WIPP Facility

Defense wastes currently called TRU waste are being generated and stored at several DOE sites, and retrievable wastes that can be properly certified are intended for disposal at the WIPP facility.[20] We have not evaluated the data on defense TRU waste at the various sites compiled by the DOE[21] because (1) much of the waste is not in a form acceptable for disposal at the WIPP facility and (2) the data generally represent

averages over a large number of individual waste units and, thus, potentially significant differences in radionuclide concentrations among these units are not apparent. Rather, this section discusses the potential impacts of the proposed waste classification system on the waste acceptance criteria for the WIPP facility,[12] which are summarized in Section 2.2.2.

5.3.1 *Potential Impacts of Highly Radioactive Boundary*

The proposed Highly Radioactive boundary, which separates HLW from TRU Waste and Equivalent, is defined as a power density of 50 W/m^3 or an external dose-equivalent rate at a distance of 1 m from the waste package of 100 rem/h (1 Sv/h), whichever is the more restrictive.

The acceptance criterion on external dose-equivalent rate for RH TRU waste at the WIPP facility is a limit of 100 rem/h at the surface of the waste canister, so the WIPP criterion is more restrictive than the limit in the waste classification system due to the different locations at which the limit applies. Thus, some wastes that we would classify as TRU Waste and Equivalent could exceed the WIPP limit for external dose rate. However, the WIPP criterion also allows for acceptance of waste canisters with surface dose-equivalent rates as high as 1000 rem/h on an exception basis. Therefore, since the dose rate at 1 m probably will be within a factor of 10 of the dose rate at the surface,[35] the WIPP criterion appears to be roughly equivalent to the limit in the waste classification system and any differences probably would not have a significant impact on the quantities of TRU waste that could be acceptable for disposal at the WIPP facility.

The acceptance criterion on thermal power for RH TRU waste at the WIPP facility is a limit of 300 W per waste package. When combined with the nominal volume of 1 m^3 for the standard RH waste container, this limit is equivalent to a limit on power density of 300 W/m^3, which is a factor of 6 greater than the limit for TRU Waste and Equivalent in the proposed waste classification system. This difference in the limit on power density could affect waste acceptance at the WIPP facility in two ways.

First, any waste currently classified as RH TRU waste with a power density between 50 and 300 W/m^3 would be reclassified as HLW and, thus, would not be eligible for disposal at the WIPP facility.[20] However, the current volume of waste having a power density between these two limits that also meets all other acceptance criteria for the WIPP facility is only about 20 m^3 and, thus, is only a small fraction of the total volume of RH waste that is potentially certifiable for disposal (M. H. McFadden, private communication). Therefore, the potential impact of eliminating

waste from eligibility for disposal at the WIPP facility on account of a reduced limit on power density appears insignificant, and the small volume of waste involved easily could be disposed of elsewhere, e.g., in a repository for HLW.

Second, as discussed in Section 5.2, the Highly Radioactive boundary of 50 W/m^3 in the proposed waste classification system may result in a reclassification of much of the defense waste currently called HLW, because of its source as waste from fuel reprocessing, as TRU Waste and Equivalent due to the relatively low concentrations of ^{90}Sr and ^{137}Cs. If these wastes also have concentrations of long-lived, alpha-emitting TRU radionuclides in excess of 100 nCi/g, which is likely, then they probably would meet the acceptance criteria for the WIPP facility. The primary impact on the WIPP facility then would be the possibility that the volume of waste that would be eligible for disposal would be significantly greater than previously assumed in planning for waste handling and disposal capacity.[8] It also is noteworthy that the volume of defense reprocessing waste that could be reclassified as TRU Waste and Equivalent would increase even more if the Highly Radioactive boundary were increased to 300 W/m^3 to agree with the WIPP criterion.

However, it is not evident without further analysis that all defense reprocessing wastes currently in storage that would be reclassified as TRU Waste and Equivalent could be retrieved and properly certified for disposal at the WIPP facility. For example, some wastes, particularly those with high concentrations of ^{238}Pu, may not meet the acceptance criterion of a limit on ^{239}Pu-equivalent activity of 1000 Ci per waste package. Furthermore, even if wastes are eligible for disposal at the WIPP facility, it is neither necessary nor desirable to require disposal there if serious distortions of existing agreements or planned operations would result. As emphasized in Sections 3.4 and 4.6, many of these wastes may be suitable candidates for GCD, either *in situ* at the current storage location or in another facility developed specifically for these wastes. Decisions regarding wastes that would be sent to the WIPP facility then could be based on analyses of the tradeoffs between expanding an existing facility vs developing new disposal technologies at different sites.

5.3.2 *Potential Impacts of Permanent Isolation Boundary*

The proposed Permanent Isolation boundary, which separates LLW from HLW and TRU Waste and Equivalent, is defined in terms of Class-C limits on radionuclide concentrations that are generally acceptable for near-surface land disposal.[1-4] The potential impacts of the Permanent Isolation boundary on disposal of TRU waste at the WIPP facility arise from (1) use

in the waste classification system of radionuclide-specific concentration limits for long-lived TRU radionuclides in Ci/m^3, rather than the WIPP limit of 100 nCi/g for all long-lived, alpha-emitting TRU radionuclides, and (2) the inclusion of long-lived, non-TRU radionuclides in TRU Waste and Equivalent.

The use in the waste classification system of radionuclide-specific concentration limits for long-lived TRU radionuclides in Ci/m^3 is discussed in detail in Appendix D. Our choice follows essentially from the recognition that limitation of long-term risk to inadvertent intruders, which is the basis for the definition of the Permanent Isolation boundary, depends on limitation of radionuclide concentrations per unit volume rather than concentrations per unit mass; i.e., analyses of doses to an intruder from waste concentrations expressed in nCi/g must involve a conversion to activity per unit volume using an assumed density for the waste material. Furthermore, for existing TRU wastes, the most important TRU radionuclides usually are ^{239}Pu, ^{240}Pu, and ^{241}Am,[21] and we show in Appendix D that the radionuclide-specific concentration limits for these radionuclides in Ci/m^3 in Table 2 that correspond to the Permanent Isolation boundary are essentially equivalent to a limit of 100 nCi/g for all long-lived, alpha-emitting TRU radionuclides. Thus, the WIPP definition of the lower boundary for TRU waste (i.e., 100 nCi/g) is consistent with and supported by the waste classification system proposed herein. The one exception occurs with wastes that contain the shorter-lived ^{238}Pu as a principal constituent. In this case, the concentration in Table 2 that corresponds to the Permanent Isolation boundary is one-to-two orders of magnitude greater than 100 nCi/g for expected densities of waste materials. However, the boundary concentration for ^{238}Pu in Table 2 is greater than the minimum concentration for disposal at the WIPP facility, and the waste classification system does not preclude the WIPP facility from accepting ^{238}Pu-contaminated wastes in concentrations less than the Class-C limit we have adopted but greater than 100 nCi/g.

The inclusion of long-lived, non-TRU radionuclides in TRU Waste and Equivalent means that these wastes could contain little or no TRU radionuclides. For example, wastes that contained ^{90}Sr, ^{137}Cs, and long-lived Pu isotopes each in concentrations one-third of their Class-C limits or wastes that contained only such radionuclides as ^{14}C, ^{94}Nb, ^{99}Tc, ^{126}Sn, and ^{129}I in concentrations greater than their Class-C limits would be classified as TRU Waste and Equivalent. This consequence of the waste classification system apparently conflicts with the definition of TRU waste in current regulations and in the acceptance criteria for the WIPP facility, which specify a minimum concentration of long-lived, alpha-emitting TRU radionuclides of 100 nCi/g (i.e., the Class-C limit for the TRU radionuclides only), and the WIPP facility currently may not accept

waste with concentrations of TRU radionuclides less than 100 nCi/g.[8,12,20]

However, as emphasized in Sections 3.4 and 4.6, we do not regard the proposed definitions of waste classes as equivalent to waste acceptance criteria for particular disposal facilities. In particular, the waste classification system does not preclude the WIPP facility from maintaining its current requirement that wastes must have concentrations of long-lived, alpha-emitting TRU radionuclides greater than 100 nCi/g. Wastes that do not meet this criterion but would be classified as TRU Waste and Equivalent in our system then would require disposal elsewhere, presumably using some form of GCD unless the concentrations of the non-TRU radionuclides were so high that GCD were not acceptable, in which case a deep geologic repository or equivalent would be required.

6. SUMMARY AND CONCLUSIONS

The primary purpose of this report has been to develop a quantitative and generally applicable risk-based definition of high-level radioactive waste (HLW), which has been defined historically as waste from reprocessing of spent nuclear fuel. The need for such a definition arises from a description in the Nuclear Waste Policy Act (NWPA) of 1982 that HLW is "other highly radioactive material that....requires permanent isolation."

In developing a quantitative and generally applicable definition of HLW, similar definitions of other waste classes also are obtained. The proposed waste classification system presented herein supersedes the summaries of preliminary versions of this work that were published previously.[36,37]

6.1 Summary of Proposed Waste Classification System

On the basis of the description of HLW in the NWPA, and other historical precedents, and the characteristics of reprocessing wastes involving (1) high levels of decay heat and external radiation due to high concentrations of shorter-lived fission products and (2) high concentrations of long-lived, alpha-emitting TRU radionuclides, we developed the following conceptual definition of HLW:

HLW is waste that is –
(1) highly radioactive and
(2) requires permanent isolation.

Thus, HLW is assumed to have two distinct attributes; and "highly radioactive" is associated with shorter-term risks due to high levels of decay heat and external radiation, and "requires permanent isolation" is associated with long-term risks from waste disposal.

The conceptual definition of HLW then led to the following conceptual definitions of Transuranic (TRU) Waste and Equivalent and low-level waste (LLW):

- TRU Waste and Equivalent is waste that requires permanent isolation but is not highly radioactive;

- LLW is waste that does not require permanent isolation, without regard to whether or not it is highly radioactive.

TRU Waste and Equivalent may include non-TRU radionuclides; and the

definition of LLW is consistent with the NRC's 10 CFR Part 61,[1,2] which classifies waste only in relation to risks associated with near-surface land disposal.

Development of a quantitative definition of "highly radioactive" was based on analyses of levels of power density and external radiation that would limit system design or operation in controlling short-term risks in a variety of waste management activities, including disposal. From these analyses, we proposed the following generally applicable definition:

> "Highly radioactive" means -
>
> (1) a power density greater than 50 W/m^3 or
>
> (2) an external dose-equivalent rate at a distance of 1 m from the waste greater than 100 R/h (1 Sv/h).

A determination of whether wastes are highly radioactive can be based directly on estimates of power density and external dose rate, but it may be more convenient in some cases to base this determination on known radionuclide concentrations in the waste. Simple models were used to derive concentrations of radionuclides that are equivalent to the limits on power density or external dose rate and that correspond to the Highly Radioactive boundary. These concentrations are given in Table 1.

The proposed quantification of "requires permanent isolation" in relation to limitation of long-term risks from waste disposal was based on the following definition:

> "Requires permanent isolation" means concentrations of radionuclides that exceed the Class-C limits that are generally acceptable for near-surface land disposal, as defined by the NRC in 10 CFR Part 61 and its supporting documentation and methodology.[1-4]

Thus, a radionuclide is "long-lived" if it can occur in concentrations greater than its Class-C limit, and knowledge of the concentrations of the most important long-lived radionuclides in the waste is needed in determining if the waste requires permanent isolation. The concentrations of radionuclides that correspond to the Permanent Isolation boundary are given in Table 2.

The proposed waste classification system that provides quantitative and generally applicable definitions of HLW, TRU Waste and Equivalent, and LLW is depicted in Fig. 2. The definition of HLW also embodies and quantifies the historical source-based definition of HLW as waste from fuel reprocessing. We intend that the waste classification system be applied to expected radionuclide compositions and waste forms at the time of final disposal.

6.2 Summary of Issues in Developing the Waste Classification System

In Section 1.2, a number of important constraints are described that were applied in developing the proposed waste classification system. In attempting to comply with these constraints, a number of fundamental issues were encountered. These issues are discussed in this section.

6.2.1 *Risk Basis for Definitions of Waste Classes*

An important goal of this study was to develop definitions of waste classes from considerations of risks associated with waste management and disposal, with primary emphasis on disposal. Furthermore, the definitions should have a sound technical foundation.

In the course of this study, however, it became apparent that rigorous risk-based definitions of waste classes based primarily on defensible and objective technical analyses probably are not achievable. The technical analyses in support of the definitions of the Highly Radioactive and Permanent Isolation boundaries indicated a range of reasonable quantifications rather than definitive values. Thus, the definitions of the two boundaries also involved subjective judgments based on consideration of the consequences of possible choices. More generally, our experience indicates that any efforts to define generally applicable waste classes using alternative conceptual models also will involve a significant degree of subjective judgment that cannot be based directly on rigorous technical analysis.

6.2.2 *Number of Waste Classes to be Defined*

In response to the description of HLW in the NWPA, it would be reasonable to develop a quantitative and generally applicable definition for HLW only, but to leave other wastes defined essentially as they are in current regulations. However, it is natural to define other waste classes from the proposed definition for HLW, so that a consistent set of generally applicable definitions of all wastes would be obtained and a reasonable framework for decision-making in waste management would be established.

From the discussions of current definitions of HLW, TRU waste, and LLW in Section 2, it is apparent that none of these wastes are defined adequately at present. All definitions of HLW are based on the source of the waste, but these definitions have not yet been quantified. Then,

since current definitions of TRU waste and LLW explicitly exclude HLW, the definitions of these waste classes also have not been quantified. The interrelationships between current definitions of HLW, TRU waste, and LLW argue strongly in favor of developing an all-encompassing waste classification system at this time.

6.2.3 *Relationship Between Waste Definitions and Choice of Disposal Technologies*

An important issue that must be considered in developing any waste classification system is whether the definitions of waste classes should be associated with particular disposal technologies. This study has adopted the position that such an association is neither necessary nor desirable, primarily because it could limit the flexibility of waste management programs in developing disposal systems that protect public health and safety in a cost-effective manner.

There are two potential disadvantages with defining waste classes in association with particular disposal technologies. First, there would be a disincentive to distinguish between existing wastes that contain high concentrations of both fission products and long-lived, alpha-emitting TRU radionuclides (e.g., commercial spent fuel and reprocessing wastes) and wastes with similar concentrations of TRU radionuclides but much lower concentrations of fission products, because both types of waste would require disposal in deep geologic repositories or equivalent due to the concentrations of TRU radionuclides. However, not distinguishing between these types of waste would be incompatible with existing law and regulations and with historical definitions of waste classes, and might have unnecessary adverse impacts on current plans for disposal of defense TRU wastes. Furthermore, as discussed in Section 3.1.2, there are important technical considerations in the design of disposal systems, based on consideration of heat generation rates, that indicate the desirability of distinguishing between HLW and TRU waste even if both types of waste require deep geologic repositories or equivalent for long-term protection of public health and safety.

Second, an association of waste classes with particular disposal technologies might discourage disposal options involving technologies more confining than are necessary for protection of public health and safety. This possibility is undesirable, because cost-effective solutions to disposal problems could involve co-disposal of lower- and higher-activity wastes in a facility designed for the higher-activity component.

On the other hand, a potentially desirable aspect of associating waste classes with specific disposal technologies arises with HLW, because this type of waste generally is associated with disposal in deep geologic repositories or equivalent. However, we have emphasized that the proposed definition of HLW covers a broad spectrum of possible radionuclide compositions and concentrations (e.g., many forms of HLW would contain radionuclide concentrations considerably lower than those in commercial spent fuel and reprocessing wastes), and wastes in this class could be associated with a variety of disposal technologies of differing waste-isolation capabilities and still protect public health and safety.

6.2.4 *Role of Greater Confinement Disposal*

Although the proposed waste classification system does not associate each waste class with a particular disposal technology, at the present time LLW generally is associated with near-surface land disposal and HLW and TRU Waste and Equivalent with deep geologic repositories or equivalent, primarily because these are the only disposal technologies for which generally applicable regulatory standards and technical criteria have been developed. Again, however, the development of alternatives for waste disposal is desirable and should not be precluded by the waste classification system.

Alternatives to near-surface land disposal and deep geologic repositories or equivalent would involve technologies for greater confinement disposal (GCD) which provide intermediate waste-isolation capabilities. The role of GCD in the proposed waste classification system is specified as follows:

- Wastes classified as HLW or TRU Waste and Equivalent may be acceptable for greater confinement disposal on a site-, waste-, and technology-specific basis provided applicable standards for protection of public health and safety are met.

The essential aspect of this statement is that the waste classification system encourages but does not require GCD. If GCD technologies were well developed and regulatory standards well established, then it would be reasonable to define HLW based on the concept that such wastes are not generally acceptable for GCD; i.e., HLW then would be defined in association with a requirement for disposal in deep geologic repositories or equivalent. At the present time, however, GCD is not sufficiently developed to provide a basis for defining waste classes, and disposal of any wastes using GCD must be considered on a case-by-case basis.

In order to encourage further development of GCD technologies, regulatory standards, and methodologies for health-risk analysis, Section C.1 of Appendix C presents an example analysis of maximum concentrations of radionuclides that could be acceptable for GCD assuming intermediate-depth burial. The analysis provides encouraging results because the boundary concentrations generally are intermediate between the limits that are generally acceptable for near-surface land disposal and the concentrations occurring in commercial spent fuel and reprocessing wastes which probably require deep geologic repositories or equivalent for protection of public health and safety. However, as discussed in Section 4.6, this analysis does not yet provide a defensible basis for defining a generally applicable set of concentration limits for GCD.

Finally, we have emphasized that waste disposal by any method requires site-specific performance assessments to determine compliance with applicable standards and technical criteria, regardless of how waste classes are defined, and the performance assessments may lead to development of waste acceptance criteria for that site. However, the proposed waste classification system is not equivalent to waste acceptance criteria for any disposal technology at any site, but serves mainly to indicate those technologies that may be acceptable for disposal of various wastes.

6.2.5 *Classification of Non-TRU Radionuclides*

This section considers the classification of long-lived, non-TRU radionuclides. The most important of these are the shorter-lived fission products ^{90}Sr and ^{137}Cs, which are important constituents of many existing wastes, and such longer-lived radionuclides as ^{14}C, ^{94}Nb, ^{99}Tc, ^{126}Sn, and ^{129}I.

The classification of wastes containing primarily ^{90}Sr and ^{137}Cs in concentrations greater than their Class-C limits is an important consideration because of the substantial quantities of such wastes that presently exist. However, the classification of these wastes is a difficult issue to resolve on technical grounds alone because of the relatively short half-lives of ^{90}Sr and ^{137}Cs. As discussed in Section 4.5, one choice would be to use concentrations of these radionuclides only in defining the Highly Radioactive boundary in the waste classification system, in which case these radionuclides probably would be classified as LLW in any concentrations. However, we have included these radionuclides in defining the Permanent Isolation boundary as well because they can exist in concentrations greater than their Class-C limits.

Our choice has the consequence that concentrations of ^{90}Sr and ^{137}Cs greater than their Class-C limits are classified as HLW. Support for this choice is provided by the existence of wastes with concentrations of these radionuclides more than 10^4 times greater than their Class-C limits; and it seems reasonable that such high concentrations of these radionuclides should be classified as HLW, rather than LLW, due to the long time period required for these wastes to decay to levels that would be generally acceptable for near-surface land disposal. In addition, use of the Class-C limits for ^{90}Sr and ^{137}Cs in defining the Highly Radioactive boundary provides a reasonable basis for quantifying one aspect of source-based HLW.

The classification of concentrations of longer-lived, non-TRU radionuclides that exceed their Class-C limits also is a matter of choice that does not have a firm technical basis. One possibility would be to classify these radionuclides in any concentration as LLW, but to recognize that some form of GCD involving burial well below the surface probably would be required for concentrations exceeding the Class-C limits. However, we have classified concentrations of these radionuclides greater than their Class-C limits as TRU Waste and Equivalent, primarily because the concentrations of the non-TRU and TRU radionuclides in this class would involve comparable risks from waste disposal.

6.3 Impacts of Waste Classification System

An important requirement of any reasonable waste classification system is that it not impose unnecessary adverse distortions on current waste management and disposal programs. A brief analysis of the impacts of the proposed waste classification system on selected commercial spent fuel and reprocessing wastes and defense wastes from fuel reprocessing was presented in Section 5. As expected, the commercial wastes clearly would be classified as HLW. The defense wastes from the Savannah River Plant that are encapsulated in a glass waste form appropriate for disposal, although they are derived from fuel with lower burnups than commercial wastes, also would be classified as HLW. On the other hand, substantial quantities of defense wastes that have not been solidified in a form for disposal apparently would be classified in their present state as TRU Waste and Equivalent or even LLW. Again, however, the waste classification system does not preclude disposing of any of these wastes as if they were HLW, but it also encourages development of safe and cost-effective alternative disposal methods.

This report also discussed the potential impacts of the proposed waste classification system on the acceptance criteria for defense TRU waste at the WIPP facility. Both the Highly Radioactive and the Permanent Isolation boundary involve definitions that differ from the WIPP acceptance criteria. The resulting impacts on the quantities of waste that might be acceptable for disposal at the WIPP facility could be substantial, primarily because of the existing defense reprocessing wastes that might be classified as TRU waste according to the WIPP criteria. However, since one of the constraints of this study is not to disrupt existing plans for waste disposal at the WIPP facility, the preferred solution to this apparent conflict is to retain the generally applicable definitions of waste classes proposed in this report, but to emphasize that the waste classification system does not preclude the application of different criteria for disposal of wastes at the WIPP facility. The same general principle would be applied to waste disposal at any other facility, since the waste classification system does not associate waste classes with specific disposal technologies.

An important general conclusion was obtained from the analysis of impacts of the waste classification system on defense reprocessing and TRU wastes. Because of the nature of the WIPP acceptance criteria and the historical precedents for defining HLW as waste from fuel reprocessing, it became apparent that any generally applicable, risk-based definitions of HLW and the other waste classes necessarily would either conflict with current definitions of defense HLW and TRU waste or could significantly affect the quantities of waste that might be acceptable for disposal at the WIPP facility. This general conclusion again emphasizes the importance of distinguishing between a generally applicable waste classification system and site-specific waste acceptance criteria.

6.4 Conclusion

The waste classification system developed in this report is potentially useful because it does not appear to have arbitrary or unnecessary adverse impacts on existing plans and methods for management or disposal of commercial and defense radioactive wastes. The change from a source-based to a risk-based definition for HLW would have the desirable effect of removing any legal obstacles to partitioning and other advanced waste management technologies. However, the use of such technologies is not mandatory in the waste classification system, because lower-activity wastes always can be combined with higher-activity wastes for more confining disposal if such methods would reduce risks in a cost-effective manner. Furthermore, the proposed waste classification system has a

reasonably firm basis in health and safety considerations, offers reasonable compatibility with existing law, and can be applied early and unambiguously in any waste management program.

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APPENDIX A

ANALYSES RELATED TO QUANTIFICATION OF HIGHLY RADIOACTIVE BOUNDARY

This Appendix discusses the analyses used in Section 4.2 to develop a quantitative and generally applicable definition of waste that is highly radioactive. The definition of the Highly Radioactive boundary is based on levels of power density and external dose rate that necessitate control measures for limiting shorter-term risks in a variety of waste management and disposal activities. Three aspects of the quantification of the Highly Radioactive boundary are discussed in this appendix: (1) data on levels of power density and external dose rate that provide the basis for the proposed definition, (2) the calculation of power density for a given concentration of a radionuclide, and (3) the calculation of external dose rate for a given concentration of a radionuclide.

A.1 Data to Support Definition of "Highly Radioactive"

The quantitative and generally applicable definition of "highly radioactive" developed in Section 4.2 - i.e., a power density greater than 50 W/m^3 or an external dose-equivalent rate at a distance of 1 m from the waste greater than 100 rem/h (1 Sv/h) - is based on data discussed in the following sections.

A.1.1 *Package Stacking Limits for Waste Containers*

Waste packages often are stacked together for storage or disposal, in which case the heat generated in the waste can result in a higher temperature in the interior of the stack than on the outside. This temperature difference depends on the diameter of the stack and the heat generation rate per unit volume of waste (i.e., the power density). The maximum size of a stack then should be limited by the temperature rise in the interior that would exceed the boiling point of water or would be sufficient to decompose typical organic waste materials.

A heat transfer calculation was performed based on the assumption that the stack is a cylinder of infinite length. The heat transfer equation in this case is[1]

$$(d^2/4)P_D = 4K_f T_r \ ,$$

where d is the diameter of the stack in m, P_D is the power density in

W/m^3, K_f is the thermal conductivity of the waste in $W/m\text{-}^oC$, and T_r is the temperature rise from the center of the stack to the outside edge in ^oC. The thermal conductivity in the waste is assumed to be 1 BTU/h-ft-^oF (1.7 $W/m\text{-}^oC$), which is a value typical of inorganic solids, and the maximum allowable temperature rise in the waste is assumed to be 100 ^oF (55 ^oC) in order to prevent boiling of water or degradation of the waste. [illegible] ...ptions described above, the [illegible] function of stack diameter was [illegible] ...ults are given in Table A-1. Wastes stored in caverns and other facilities seldom are piled more than a few meters in any direction, due to size limitations of fork-lift trucks and other package-handling equipment. The results in Table A-1 show, for example, that a nominal stacking diameter of 5 m, which is a reasonable maximum stack size, corresponds to a limit on power density of about 50 W/m^3.

A.1.2 *Limits on Power Density in Liquid Waste Tanks*

Liquid wastes from fuel reprocessing at the Hanford site have been characterized as self-heating or non-heating, depending on whether the decay heat would raise the temperature to the boiling point when the waste is placed in large, underground tanks. If the temperature could reach the boiling point, then the wastes were placed in special tanks with large cooling systems to prevent boiling. In non-heating wastes, the natural thermal conductivity from the tank to the surrounding earth is sufficient to keep temperatures below the boiling point.

The limiting values of power density that would cause liquid wastes at the Hanford site to be self-boiling have been estimated as 8-40 W/m^3 and 20-50 W/m^3.[2,3] Thus, the power density that would require active cooling measures in large liquid waste storage tanks appears to be in the range 10-50 W/m^3.

A.1.3 *Limits on Power Density in Waste Transport Containers*

Special casks are used to transport radioactive materials, and the heat generation rate in the waste may be important in determining design requirements. For example, casks for shipping of spent fuel or defense reprocessing wastes are designed to accommodate power densities in the range 500-28,000 W/m^3,[4-6] and such power densities are a major consideration in design of the casks.

Table A-1. Power density vs diameter of waste stack for a maximum temperature rise in the center of the stack of 100 °F (55 °C)[a]

Power density (W/m^3)	Diameter (m)
1	39
10	12
50	5.6
100	3.9
500	1.8
1,000	1.2
10,000	0.4

[a]Calculations are described in Section A.1.1.

Of greater relevance to a determination of the Highly Radioactive boundary is the limit on power density in a transport container for contact-handled (CH) defense TRU waste, since heat generation is not a major consideration in the design of these containers. The limit on power density in a transport container for CH TRU waste is about 40 W/m^3.[7]

A.1.4 *Waste Acceptance Criteria for the WIPP Facility*

The acceptance criteria for defense TRU wastes at the WIPP facility[8] were reviewed in Section 2.2.2. As summarized in Section 4.2.1, the power density for CH TRU waste is limited to 15 W/m^3 for close stacking of containers for disposal. Power densities less than 15 W/m^3 should not affect the waste except under very unusual circumstances. For remote-handled (RH) TRU wastes, which have higher power densities, the limit for the standard waste container is about 300 W/m^3. At this level, heat generation will be an important consideration in waste disposal, and the areal density of RH waste containers is limited accordingly.[8]

As described in Section 4.2.3, the waste acceptance criteria for the WIPP facility also include limits on external radiation dose. For RH TRU waste, the dose-equivalent rate at the surface of a waste package is limited to 100 rem/h. This limit is based on the maximum size and weight of shielding for waste packages that can be accommodated routinely at the facility. However, wastes with surface dose-equivalent rates up to

1000 rem/h also may be accepted on an exception basis.

A.1.5 *Limits on Power Density in Geologic Repositories*

A recent report has reviewed options for management and disposal of low- and intermediate-level solid radioactive wastes.[9] This report suggests that a nominal power density of 100 W/m^3 is a limit above which heat generation would require special considerations in the design of deep geologic repositories.

A.2 Relationship Between Power Density and Radionuclide Concentrations

Calculation of radionuclide concentrations corresponding to a given power density is quite straightforward, because the power density per unit concentration depends only on the total energy of all ionizing radiations emitted in the decay. The radiations that must be taken into account include alpha particles, electrons (discrete Auger and internal conversion electrons and the continuous spectrum of electrons from beta decay), and photons (including X-rays from atomic de-excitations). Possible contributions from nuclear recoil and the emission of neutrons or spontaneous fission products generally can be neglected.

If C_i denotes the concentration of a radionuclide in Ci/m^3 and E_T the total decay energy in MeV per disintegration (dis), then the power density, P_D, in W/m^3 is given in terms of the conversion factors from MeV to joules and from curies to dis/s by the following expression:

$$P_D = (1.6 \times 10^{-13}\ J/MeV)(3.7 \times 10^{10}\ dis/Ci\text{-}s)E_T C_i$$
$$= (5.92 \times 10^{-3}\ W\text{-}dis/MeV\text{-}Ci)E_T C_i \ .$$

Thus, for the power density of 50 W/m^3 that defines the Highly Radioactive boundary, the radionuclide concentration in Ci/m^3 corresponding to this power density is given by

$$C_i = (50\ W/m^3)/[(5.92 \times 10^{-3}\ W\text{-}dis/MeV\text{-}Ci)E_T]$$
$$= (8.45 \times 10^{3}\ MeV\text{-}Ci/dis\text{-}m^3)/E_T \ .$$

This equation is used to calculate the radionuclide concentrations corresponding to the Highly Radioactive boundary in Table 1 in Section 4.2.5, except the value for ^{137}Cs. The total decay energy for each radionuclide was obtained from a published compilation.[10]

A.3 Relationship Between External Dose Rate and Radionuclide Concentrations

A.3.1 *Description of Calculational Method*

Calculation of the external dose rate for a given concentration of a radionuclide in the waste is considerably more complex than the calculation of power density described above. In addition to the decay spectrum of photons, the dose rate per unit concentration of a radionuclide depends on the composition, geometrical configuration, and size of the waste package, the location relative to the waste package at which exposures occur, and the thickness and composition of any shielding materials between the source and receptor locations.

In this analysis, we assume that exposures occur at a distance of 1 m from a 55-gallon drum in which radionuclides are mixed uniformly with dirt or other materials that could be used as filler in the waste package. Thus, the source is assumed to be a self-absorbing, right-circular cylinder, and the self-shielding provided by the source is determined by the density of the material and the average atomic number of its constituents as well as the thickness and composition of the walls of the drum.

External dose rates from a self-absorbing cylindrical volume source are estimated using the point-kernel method.[11] For the assumed source configuration, the point-kernel method does not yield a closed-form solution for the external dose rate, so numerical solutions must be used. In order to simplify the calculations, we assume that the receptor is located either along the perpendicular bisector of the axis of the cylinder (i.e., at the side of the source) or along the axis itself (i.e., at the end of the source). For exposures along the perpendicular bisector of the axis of the cylinder, eq. (6.4.-38) of ref. 11 approximates the photon flux density as a function of concentration for a monoenergetic photon emitter. For exposures along the axis of the cylinder, eqs. (6.4.-40)-(6.4.-43) of ref. 11 give two pairs of equations that provide upper and lower bounds for the photon flux density, with the particular pair that is appropriate depending on the product of the photon linear attenuation coefficient in the filler material and the height of the cylinder. We then assume that the photon flux density is given by the average of the appropriate upper- and lower-bound estimates.

The point-kernel method for estimating external dose rates from the self-absorbing cylindrical drum was implemented using the CONDOS II computer code,[12] and Appendix B of the code documentation lists the equations and parameters used in the calculations. Since the exposures are assumed to occur at a distance of only 1 m from the source with no

shielding materials outside the drum other than air, the photon buildup factor in air can be neglected compared with the buildup factor in the filler material and the walls of the drum and is set to unity in all calculations.

The cylindrical drum is assumed to have a height of 0.89 m and a diameter of 0.61 m. The walls of the drum are assumed to be iron of thickness 0.13 cm and density 7.86 g/cm^3. Shielding provided by the walls of the drum is included in all calculations.

Calculations were performed for four different filler materials in the source volume. The base case assumes that the radionuclides are mixed with soil of density 1.6 g/cm^3 and a composition by weight of 49.6% O, 7.8% Al, 34.5% Si, and 8.1% Fe. Calculations also were performed assuming concrete, polyethylene, or air as filler materials; air was included in order to investigate the effect on the external dose rate of a significant fraction of void spaces in the source volume. Concrete is assumed to have a density of 2.3 g/cm^3 and a composition by weight of 0.6% H, 49.8% O, 1.7% Na, 0.2% Mg, 4.6% Al, 31.6% Si, 0.1% S, 1.9% K, 8.3% Ca, and 1.2% Fe. Polyethylene is assumed to have a density of 0.92 g/cm^3 and to be composed of C and H in an atom ratio of 1:2. Air is assumed to have a density of 0.0012 g/cm^3 and to be composed principally of N and O in the approximate atom ratio of 4:1. The linear attenuation coefficients as a function of photon energy for all elements in the filler materials are given in data libraries in the CONDOS II code.[12]

A.3.2 *Results of Calculations for ^{137}Cs*

Calculations of external dose rates were performed assuming a ^{137}Cs source of concentration 1 Ci/m^3 uniformly distributed throughout the source volume. The results of these calculations are given in Table A-2 as effective dose equivalents,[13] which are weighted sums of dose-equivalent rates to different body organs with the weighting factor for each organ being proportional to the risk from uniform whole-body irradiation.

The calculations in Table A-2 show that the external dose rate per unit concentration of ^{137}Cs varies by about a factor of 4 depending on the assumed filler material in the drum and the location of the exposed individual. Taking into account these variations, we conclude that a ^{137}Cs concentration of 5 x 10^3 Ci/m^3, which corresponds to the Class-C limit for near-surface land disposal in the NRC's 10 CFR Part 61,[14] nominally yields an external dose-equivalent rate of 100 rem/h (1 Sv/h), which is one of the definitions of the Highly Radioactive boundary proposed in Section 4.2.3.

Table A-2. Estimated external dose-equivalent rates at a distance of 1 m from a 55-gallon drum containing 1 Ci/m^3 of ^{137}Cs

	Dose-equivalent rate (rem/h)[a]	
Filler material	Top of drum	Side of drum
Soil	0.008	0.013
Concrete	0.006	0.011
Polyethylene	0.011	0.018
Air	0.030	0.034

[a]The values calculated are effective dose equivalents[13] to exposed individuals at the receptor location.

A.3.3 *Calculations for Other Radionuclides*

An analysis similar to the one for ^{137}Cs presented above can provide estimates of concentrations of any radionuclide that would yield an external dose-equivalent rate of 100 rem/h (1 Sv/h). However, as discussed below, the concentration giving this dose rate will be greater than the concentration giving a power density of 50 W/m^3, which is the other criterion for defining "highly radioactive," unless a substantial fraction of the decay energy is in the form of high-energy photons (i.e., photons with energies of a few hundred keV or more). Thus, for most radionuclides that could be classified as either HLW or TRU Waste and Equivalent (i.e., those that can exist in concentrations greater than their Class-C limits), the concentration corresponding to the Highly Radioactive boundary is determined by the limit on power density rather than external dose rate.

For ^{137}Cs, the concentration limit for Class-C wastes[14] of 5 x 10^3 Ci/m^3 corresponds to a power density of nearly 25 W/m^3, and about 70% of the decay energy occurs as high-energy photons.[10] Thus, if there were sufficient additional decay energy from non-penetrating radiations to increase the power density to 50 W/m^3, the fraction of the decay energy in the form of high-energy photons would be about 35%; i.e., about one-third of the total decay energy of a radionuclide must be in the form of high-energy photons for the external dose rate to be more restrictive than the power density in determining the concentration corresponding to the Highly Radioactive boundary.

The minimum half-life of radionuclides that can exist in concentrations greater than their Class-C limits is about 20 years, but there are very few such radionuclides expected to occur in radioactive wastes that have at least one-third of their total decay energy in the form of high-energy photons. Of the radionuclides listed in Tables 1 and 2 of Sections 4.2.5 and 4.3, respectively, including any short-lived daughter products, the only radionuclides in addition to ^{137}Cs that meet these two criteria are ^{94}Nb, ^{108m}Ag, and ^{126}Sn.[10] However, ^{108m}Ag generally is an unimportant constituent of radioactive wastes[15] and, thus, is not likely to occur in sufficiently high concentrations to yield external dose-equivalent rates approaching 100 rem/h; and the half-lives of ^{94}Nb and ^{126}Sn are too long for these radionuclides to occur in sufficient concentrations to yield such a high external dose rate. Thus, we expect that ^{137}Cs will be the principal radionuclide of concern in waste materials with regard to the limit on external dose-equivalent rate that defines the Highly Radioactive boundary.

A.3.4 *Variation of External Dose Rate with Distance from Waste Package*

As noted in Section 4.2.3, the proposed definition of the Highly Radioactive boundary in terms of an external dose-equivalent rate of 100 rem/h (1 Sv/h) at a distance of 1 m from the waste package differs from the waste acceptance criterion for the WIPP facility of a limit of 100 rem/h at the surface of the waste container.[8] Thus, it is of interest to compare expected dose rates at the surface with the dose rate at 1 m.

We have not performed calculations of external dose rate vs distance for the waste package in the form of a 55-gallon drum assumed in this analysis. However, for exposures at the side of the drum, the dose rate varies as $1/(a+z)$, where a is the distance from the surface of the drum to the receptor location and z is the self-absorption distance, which is the distance from the surface of the drum to an interior line source that would yield the same photon flux and which depends only on the absorbing properties of the filler materials in the drum.[11] Thus, the variation of external dose rate with distance from the surface of the drum varies less rapidly than the inverse of the distance.

Calculations have been presented of external dose rates at various distances from cylindrical canisters containing defense reprocessing wastes encapsulated in glass from the Savannah River Plant.[16] While the dimensions of the canister are somewhat different from those for the 55-gallon drum assumed in our analysis, the calculations show that the dose rate at the surface is no more than a factor of 10 greater than the dose rate at 1 m. This difference seems substantial, but we note again that

the WIPP facility may accept wastes on an exception basis with surface dose-equivalent rates up to 10 times greater than the normal limit of 100 rem/h.[8]

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APPENDIX B

ANALYSES RELATED TO QUANTIFICATION OF PERMANENT ISOLATION BOUNDARY

In Section 4.3, a quantitative and generally applicable definition of wastes that require permanent isolation was developed on the basis of the assumption that such wastes have concentrations of long-lived radionuclides greater than the Class-C limits that are generally acceptable for near-surface land disposal, as specified in the NRC's 10 CFR Part 61.[1-4] Thus, in the waste classification system depicted in Figs. 1 and 2 in Sections 3.2 and 4.4, respectively, the Permanent Isolation boundary separates LLW from HLW or TRU Waste and Equivalent. Furthermore, the definition of this boundary does not depend on the particular technology that would be used for disposal of wastes in which radionuclide concentrations exceed Class-C limits. The radionuclide concentrations corresponding to the Permanent Isolation boundary are given in Table 2 in Section 4.3.

This Appendix reviews the bases for the concentration limits for Class-C wastes developed by the NRC in 10 CFR Part 61.[1,2] Then, the sources for the particular concentration limits of radionuclides that correspond to the Permanent Isolation boundary are described. Finally, we discuss the provisional nature of the concentration limits for Class-C wastes, which arises from (1) the use of different methodologies for various radionuclides that are not entirely consistent with one another and (2) the different choices for a dose limit to an inadvertent intruder at a near-surface land disposal facility as one of the bases for defining the Permanent Isolation boundary.

B.1 Bases for Concentration Limits for Class-C Wastes in 10 CFR Part 61

The concentration limits of radionuclides that are generally acceptable for near-surface land disposal, as developed in the NRC's 10 CFR Part 61, were based on the requirement that any individual who might inadvertently intrude into the disposal facility after loss of active institutional controls could not receive an annual dose equivalent to whole body greater than 0.5 rem.[1,2] Inadvertent intruders were assumed to be exposed to the waste according to postulated scenarios, i.e., the intruder-construction, intruder-agriculture, and leaching and migration scenarios.[2,5] The intruder-construction scenario is acute (i.e., occurs only once in an intruder's lifetime with an assumed duration of 500 hours)

and was based on the assumption that an intruder digs a foundation hole for a house at the location of the buried wastes. The intruder-agriculture scenario is chronic (i.e., occurs continuously over an intruder's lifetime) and was based on the assumption that an intruder lives on the facility and consumes food grown in contaminated soil. The leaching and migration scenario also is chronic and was based on the assumption that an intruder uses contaminated ground water from a well on the disposal site. The annual dose per unit concentration of radionuclides in the waste for each scenario was estimated from an analysis of the relevant ingestion, inhalation, and external exposure pathways.

The concentration limit of a radionuclide that is generally acceptable for near-surface land disposal then was based on the exposure scenario that is most restrictive, i.e., gives the highest dose per unit concentration in the waste, combined with the limit on annual dose equivalent of 0.5 rem. For most radionuclides, either the intruder-construction or intruder-agriculture scenario was the most restrictive.

The NRC developed concentration limits for near-surface land disposal for three classes of waste, i.e., Class A, B, and C.[1,2] The concentration limits for all classes were based on the assumption that active institutional controls prevent exposures of inadvertent intruders for a period of 100 years. In addition, requirements were placed on the disposal of Class-B and -C wastes that reduce estimated doses to intruders per unit concentration of radionuclides in the waste compared with doses from Class-A wastes and, thus, increase the concentration limits that are acceptable for disposal.

The requirements for disposal of Class-C wastes are the most stringent and include two aspects that are important for reducing intruder doses: (1) rigorous requirements on the stability of the waste form to inhibit mobilization of radionuclides into soil or water and (2) disposal at depths greater than a few meters or the use of engineered barriers to prevent intruder exposures for a time period as long as 500 years. For all radionuclides, the requirements on stability of the waste form result in concentration limits for Class-C wastes that are a factor of 10 higher than the limits for Class-A wastes. However, prevention of intruder exposures for as long as 500 years affects the concentration limits for Class-C wastes relative to Class-A wastes only for those radionuclides that decay significantly over that time period (e.g., ^{90}Sr and ^{137}Cs) but not for longer-lived radionuclides (e.g., ^{99}Tc and ^{239}Pu).

Some radioactive wastes occur as activated metals which are likely to be less accessible to an intruder than other solid wastes. For activated metals, the NRC set the concentration limit for disposal as any waste class at a factor of 10 higher than the corresponding limit for other

solid wastes.[1,2]

B.2 Sources of Radionuclide Concentrations Corresponding to Permanent Isolation Boundary

The concentration limits for Class-C wastes that correspond to the Permanent Isolation boundary in Table 2 in Section 4.3 include values for radionuclides that are not given in the Final Rule for 10 CFR Part 61.[1] However, all of the additional radionuclides have been considered in the NRC's impacts analysis methodology.[2,3] These radionuclides are included in Table 2 because they could be important in wastes that are not common in existing commercial LLW, and a goal of the proposed waste classification system is that it be generally applicable to any wastes. This section describes the sources for the radionuclide concentrations that correspond to the Permanent Isolation boundary.

The boundary concentrations for the following radionuclides were obtained directly from Tables 1 and 2 of the Final Rule for 10 CFR Part 61: ^{14}C, ^{59}Ni, ^{63}Ni, ^{90}Sr, ^{94}Nb, ^{99}Tc, ^{129}I, and ^{137}Cs.[1] As discussed in Section B.1 above, the distinction between the two tables in 10 CFR Part 61 is related strictly to whether or not the radionuclides have half-lives sufficiently short that the assumed 500-year intruder barriers are effective in reducing doses. However, this distinction is not important in the proposed waste classification system, because the only concern in defining the Permanent Isolation boundary for a radionuclide is whether the half-life is sufficiently long that it could exist in concentrations exceeding its Class-C limit.

The boundary concentrations for all TRU radionuclides were obtained from tables in Section 7 of Appendix C of the Final Environmental Impact Statement (FEIS) for 10 CFR Part 61.[2] Thus, we did not use the limit of 100 nCi/g for all long-lived, alpha-emitting TRU radionuclides as given in Table 1 of the Final Rule itself.[1] The rationale for choosing radionuclide-specific concentration limits in Ci/m^3 from the FEIS, rather than the single value in nCi/g for many TRU radionuclides from the Final Rule, is discussed in Appendix D.

The boundary concentrations for ^{135}Cs, ^{235}U, and ^{238}U were obtained from Table 4.5 of the Main Report of the FEIS for 10 CFR Part 61.[2] These limits were not included in the Final Rule because of the NRC's evaluation that existing commercial wastes do not contain concentrations of these radionuclides approaching their Class-C limits.

The boundary concentration for ^{226}Ra was obtained from Table 4-3 of Vol. 2 of the documentation for the revised impacts analysis methodology.[4] The Class-C limit is given in that report as 20 nCi/g, and this value was

converted to Ci/m^3 using an assumed waste density of 1.6 g/cm^3.[2]

The boundary concentrations for the remaining radionuclides ^{108m}Ag, ^{126}Sn, ^{210}Pb, ^{227}Ac, ^{229}Th, ^{230}Th, ^{232}Th, ^{231}Pa, ^{232}U, ^{233}U, ^{234}U, and ^{236}U were obtained from calculations which we performed using the NRC's revised impacts analysis methodology.[3,4] The calculations assumed that the wastes do not occur as activated metals, and the results were based on the more restrictive of the intruder-construction and intruder-agriculture scenarios and a limit on annual committed effective dose equivalent[6] to an intruder of 0.5 rem. Concentration limits were calculated for Class-A wastes assuming an institutional control period of 100 years and prevention of intruder exposures for 500 years by the disposal system. The concentration limits for Class-C wastes then were assumed to be 10 times the Class-A limits.[2]

B.3 Provisional Nature of Concentration Limits for Class-C Wastes

The concentration limits for disposal of radionuclides as Class-C wastes, which are used to obtain the Permanent Isolation boundary in the proposed waste classification system, may be provisional and thus subject to future change. The provisional nature of these limits arises from two sources: (1) inconsistencies in the methodologies used in deriving the concentration limits for various radionuclides and (2) questions concerning the most appropriate dose limit for an inadvertent intruder at a disposal facility for LLW.

B.3.1 *Inconsistencies in Calculational Methodologies*

The concentration limits of various radionuclides corresponding to the Permanent Isolation boundary in Table 2 in Section 4.3 were obtained using methodologies that differ in some respects. First, the revised impacts analysis methodology,[3,4] which we used to calculate concentration limits for a large number of radionuclides for which limits have not been given by the NRC, contains models and parameter values for estimating intakes of radionuclides and external exposures per unit concentration in the disposal facility for the various exposure scenarios that differ in some cases from the assumptions used in developing the Class-C concentration limits in the Final Rule for 10 CFR Part 61.[2,5] The extent of inconsistencies in results arising from the use of different exposure-assessment methodologies is difficult to evaluate but probably is not large for most radionuclides.

Second, the concentration limits we obtained from the revised impacts analysis methodology[3,4] were based on an assumed limit on annual committed effective dose equivalent to an inadvertent intruder of 0.5 rem, whereas the concentration limits developed by the NRC in 10 CFR Part 61 were based on a limit on annual dose equivalent to whole body of 0.5 rem.[1,2] The effective dose equivalent is a weighted sum of doses to several body organs and is intended to be proportional to risk for either uniform or nonuniform irradiations of the body.[6] The effective dose equivalent from intakes of a radionuclide by ingestion or inhalation may be substantially different from the dose equivalent to whole body for radionuclides that deposit preferentially in particular organs and emit mostly non-penetrating radiations, since such situations do not result in uniform whole-body irradiations. Important examples of radionuclides for which the effective dose equivalent from internal exposures is substantially different from the dose equivalent to whole body include the bone-seeking radionuclides ^{90}Sr, ^{239}Pu, and other TRU radionuclides, and ^{99}Tc and ^{129}I which deposit preferentially in the thyroid.

Finally, the whole-body doses per unit intakes of radionuclides used in the methodology for 10 CFR Part 61[5] were based on outdated methods for calculating internal dose,[7] but these dosimetry data have been replaced in the revised impacts analysis methodology[3] by results based on current methods.[8] Thus, even for radionuclides that irradiate the body reasonably uniformly following ingestion or inhalation, the doses calculated for the Final Rule in 10 CFR Part 61 and those obtained from the revised methodology may differ somewhat.

It clearly would be desirable to develop all Class-C concentration limits of radionuclides that correspond to the Permanent Isolation boundary on the basis of the same exposure- and dose-assessment methodologies and the same dose limit for an inadvertent intruder. However, as indicated by the following discussion, this goal is not easily achievable.

Since the concentration limits for Class-C wastes in 10 CFR Part 61 are well established, one way of obtaining a consistent set of radionuclide concentrations corresponding to the Permanent Isolation boundary would be to base the calculations for all radionuclides on the methodologies and the dose limit that were used in developing the current regulations.[1,2,5] However, this option has two drawbacks. First, some of the long-lived radionuclides which probably should be included in defining the Permanent Isolation boundary (i.e., ^{108m}Ag, ^{126}Sn, and ^{232}U) were not considered by the NRC in developing 10 CFR Part 61, and it was not possible to augment the data base for the NRC's calculations to include these radionuclides. Second, it is unreasonable and undesirable to use outdated calculational methodologies for radionuclides for which

concentration limits are not listed in the Final Rule or FEIS for 10 CFR Part 61, when the NRC recently has revised the methodologies to incorporate current recommendations.[3]

A reasonable alternative would be to base all concentration limits for Class-C wastes on the revised impacts analysis methodology[3] and a limit on annual committed effective dose equivalent for an intruder of 0.5 rem, since all aspects of the calculations would incorporate current dose-assessment methodologies. However, this option also has two drawbacks. First, for many of the radionuclides in Tables 1 and 2 of the Final Rule for 10 CFR Part 61,[1] the concentration limits based on the revised methodology would not be the same as the limits in the current regulations that are well established and widely accepted. When we consider that one of the constraints for this study is to maintain consistency with existing regulations to a reasonable extent, then there is no apparent advantage in attempting to establish a different set of Class-C limits for these radionuclides without concurrence of the NRC even when the methodology associated with the revised limits is more defensible. Second, in calculating Class-C limits for some of the important radionuclides in Tables 1 and 2 of the Final Rule, the NRC evidently applied subjective judgments in adjusting calculated values to obtain the final results given in the regulations.[2] In attempting to calculate revised concentration limits for these radionuclides using the NRC's updated methodology, we would not know how to adjust these values to reflect the subjective judgments previously applied by the NRC, and the result could be revised limits that have unnecessary adverse impacts on current disposal practices for LLW.

Thus, there is no entirely satisfactory option for developing the concentration limits for Class-C wastes that correspond to the Permanent Isolation boundary if the goal is to obtain results for all radionuclides based on a single, self-consistent methodology and set of assumptions. Our choices in defining the Permanent Isolation boundary seem the most reasonable, because they preserve the concentration limits that are well established in 10 CFR Part 61 and its FEIS while using current dose-assessment methodologies for the remaining radionuclides. Because of the inconsistencies in methodologies, however, we regard the concentration limits in Table 2 in Section 4.3 that we calculated from the revised impacts analysis methodology as provisional.

B.3.2 *Choice of Dose Limit for Inadvertent Intruder*

There are two important questions regarding the dose limit that should be applied to an inadvertent intruder in establishing the concentration limits for Class-C wastes that correspond to the Permanent Isolation boundary. The first involves the manner in which the dose limit is expressed, and the second involves the magnitude of the dose limit.

The manner in which the dose limit is expressed refers to the option of a limit on dose equivalent to whole body, as used by the NRC in developing 10 CFR Part 61,[1,2] vs a limit on committed effective dose equivalent, as recommended by the International Commission on Radiological Protection.[8] The potential impact of this choice on the concentration limits for Class-C wastes was discussed in Section B.3.1 above.

The use of a limit on dose equivalent to whole body in 10 CFR Part 61 is patterned after current radiation protection standards of the NRC in 10 CFR Part 20.[9] However, proposed revisions of these radiation protection standards would specify limits on committed effective dose equivalent.[10] If we make the reasonable assumption that the Final Rule for the revised 10 CFR Part 20 will contain dose limits in the latter form, then the NRC may need to revise 10 CFR Part 61 by calculating concentration limits for Class-C wastes based on use of the committed effective dose equivalent in order to maintain consistency between the two regulations. Again, as discussed previously, this revision could result in substantial changes in the Class-C concentration limits for some radionuclides that do not irradiate the body uniformly following inhalation or ingestion. On the other hand, the NRC could choose to maintain the existing concentration limits in 10 CFR Part 61 if revisions would have unnecessary adverse impacts on current and future disposal practices without a commensurate reduction in risks to the general public.

The numerical value of the dose limit to an inadvertent intruder, i.e., an annual dose equivalent of 0.5 rem, also is patterned after the radiation protection standards for the public in 10 CFR Part 20,[9] and this value is maintained in the proposed revisions of the standards.[10] However, national and international authorities have recommended that the limit on annual dose equivalent for members of the public be lowered to 0.1 rem for chronic exposures,[8,11,12] and the lower dose limit has been adopted in revisions of the DOE's radiation protection orders for the public.[13] Since most of the Class-C concentration limits of radionuclides in 10 CFR Part 61 were based on scenarios involving chronic exposures,[2] the lower dose limit perhaps should be considered for application to inadvertent intruders.

However, there are four reasons why it is reasonable to retain a limit on annual dose equivalent of 0.5 rem for an inadvertent intruder even if the dose limit for chronic exposures of members of the public is reduced to 0.1 rem in radiation protection standards. First, dose limits for the public are intended, strictly speaking, only for application to routine exposure situations that are expected to occur with a probability that is essentially unity. In this case, a limit on annual dose equivalent of 0.1 rem then corresponds to an assumed limit on acceptable risk from a lifetime's exposure. For waste disposal, however, the probability of exposures of inadvertent intruders according to the postulated scenarios probably will not be unity and may be considerably less. Thus, retention of the higher dose limit of 0.5 rem still may result in a limit on risk from a lifetime's exposure that is well within acceptable bounds, because risk is the product of the probability that a dose will be received and the probability that the dose will give rise to a deleterious health effect.[14] Second, the dose limits themselves are somewhat arbitrary because of large uncertainties in the assumed dose-response relation at low doses, and a limit on annual dose equivalent of 0.5 rem or any lower limit thus does not represent a well defined limit on acceptable risk. Third, even if inadvertent intruders receive much higher doses than off-site individuals, whose annual dose equivalents from disposal of LLW are limited to 25 mrem,[1] the effect on the population dose probably will be negligible because of the small number of inadvertent intruders compared with the size of the off-site population that would be exposed. Finally, retention of a limit on annual dose equivalent of 0.5 rem for an inadvertent intruder maintains consistency with the value used in developing the Class-C concentration limits in 10 CFR Part 61,[1,2] and there is no evident need of changing the dose limit for our analysis unless the NRC chooses to do so and revises the limits in 10 CFR Part 61 accordingly.

References for Appendix B

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2. U.S. Nuclear Regulatory Commission, *Final Environmental Impact Statement on 10 CFR Part 61 "Licensing Requirements for Land Disposal of Radioactive Waste,"* NUREG-0945, Vol. 1-3 (1982).

3. O. I. Oztunali and G. W. Roles, *Update of Part 61 Impacts Analysis Methodology - Methodology Report*, NUREG/CR-4370, Vol. 1, Envirosphere Company and U.S. Nuclear Regulatory Commission (1986).

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7. International Commission on Radiological Protection, *Recommendations of the International Commission on Radiological Protection*, ICRP Publication 2, Pergamon Press, Oxford (1960).

8. International Commission on Radiological Protection, "Limits for Intakes of Radionuclides by Workers," ICRP Publication 30, Part 1, *Ann. ICRP* 2, No. 3/4 (1979).

9. U.S. Nuclear Regulatory Commission, "Part 20 - Standards for Protection Against Radiation," p. 253 in *Code of Federal Regulations, Title 10, Parts 0 to 199*, U.S. Government Printing Office (1986).

10. U.S. Nuclear Regulatory Commission, "10 CFR Parts 19, 20, 30, 31, 32, 34, 40, 50, 61, and 70 - Standards for Protection Against Radiation," Proposed Rule, *Fed. Registr.* 51, 1092 (1986).

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13. U.S. Department of Energy, "Radiation Standards for Protection of the Public in the Vicinity of DOE Facilities" (August 5, 1985).

14. International Commission on Radiological Protection, "Radiation Protection Principles for the Disposal of Solid Radioactive Waste," ICRP Publication 46, *Ann. ICRP* 15, No. 4 (1985).

APPENDIX C

ANALYSES RELATED TO QUANTIFICATION OF GCD-PERMANENT ISOLATION BOUNDARY

Sections 3.4 and 4.6 of this report discuss the role of greater confinement disposal (GCD) in the proposed waste classification system. At the present time, near-surface land disposal (for LLW) and deep geologic repositories (for HLW and TRU Waste and Equivalent) are the only disposal options that are recognized in law and for which regulatory standards and technical criteria have been developed. However, the waste classification system explicitly does not preclude the use of technologies for GCD, which would provide waste-isolation capabilities intermediate between those for near-surface land disposal and deep geologic repositories or equivalent. Thus, some forms of GCD could be appropriate for relatively dilute wastes in which the concentrations of radionuclides exceed the Class-C limits that are generally acceptable for near-surface land disposal[1,2] and that define the Permanent Isolation boundary in the waste classification system. These concentrations are listed in Table 2 in Section 4.3 and depicted in Fig. 2 in Section 4.4.

This Appendix presents an example analysis that provides estimates of limits on radionuclide concentrations that would be acceptable for GCD. These concentration limits could be used to define a generally applicable GCD-Permanent Isolation boundary, analogous to the Permanent Isolation boundary in the proposed waste classification system. If such a GCD-Permanent Isolation boundary could be defined, then the concept of "permanent isolation" would refer to disposal in deep geologic repositories or equivalent, whereas in this report "permanent isolation" refers to any disposal technology more confining than near-surface land disposal (see Section 3.1.4).

As described in Appendix F, a number of GCD technologies are under consideration or active development involving above-grade confinement, below-grade confinement, improved waste forms, and high-integrity containers. In the example analysis presented in this Appendix, we assume that intermediate-depth burial (i.e., burial at depths greater than about 10 m but less than the depth of a geologic repository) generally would be the most appropriate disposal technology for wastes in which radionuclide concentrations exceed their Class-C limits. The primary benefit of this form of GCD compared with near-surface land disposal is the elimination of the intruder-construction and intruder-agriculture scenarios that usually are the most important in determining the concentration limits for Class-C wastes (see Appendix B). The alternative of developing a near-surface land disposal facility that would include improved waste forms, high-

integrity containers, or other engineered features to delay the possibility for onset of human intrusion could be effective in reducing doses to intruders for shorter-lived radionuclides (e.g., ^{90}Sr and ^{137}Cs) but does not appear to be a reasonable option for the longer-lived radionuclides that are important in many wastes (e.g., ^{239}Pu), because prevention of intrusion using engineered barriers for the long times that would be required for significant decay of these radionuclides to occur probably cannot be demonstrated with reasonable assurance.

The example analysis of the GCD-Permanent Isolation boundary for intermediate-depth burial assumes that the wastes are placed in soil in the unsaturated zone. In a manner similar to the determination of the Class-C concentration limits of radionuclides that are generally acceptable for near-surface land disposal,[1,2] we assume a hypothetical solid-waste drilling scenario for an inadvertent intruder in which an intruder living on the site drills through the disposal facility (e.g., for the purpose of constructing a well for the intruder's water supply), radionuclides are brought to the surface in the solid drilling wastes, and the radioactive wastes are mixed with native soil in a vegetable garden.[3] An analysis of ingestion, inhalation, and external exposure pathways is performed which yields annual doses per unit concentration of radionuclides in the waste at the time of disposal. The limits on radionuclide concentrations that would be acceptable for intermediate-depth burial then are based on a limit on annual committed effective dose equivalent[4] to an intruder of 0.5 rem. Use of the committed effective dose equivalent, rather than the dose equivalent to whole body used by the NRC in determining the concentration limits for Class-C wastes in 10 CFR Part 61,[1,2] is discussed in Section B.3 of Appendix B. The estimated concentration limits of radionuclides for intermediate-depth burial then define the example GCD-Permanent Isolation boundary.

An alternative means of exposure of inadvertent intruders from intermediate-depth burial is a well-water scenario in which radionuclides are leached from the solid waste by infiltrating water and transported to an underlying aquifer, and contaminated water is withdrawn through a well for use by the intruder.[5] This scenario is discussed briefly in Section C.2 of this Appendix but is not used in obtaining the example GCD-Permanent Isolation boundary.

C.1 Analysis of Solid-Waste Drilling Scenario

The solid-waste drilling scenario for an inadvertent intruder at an intermediate-depth burial site was proposed in developing disposal criteria for ^{239}Pu at the Hanford site.[3] This scenario was not used by

the NRC in developing concentration limits of radionuclides that are generally acceptable for near-surface land disposal in 10 CFR Part 61,[1,2] because the scenario generally is less restrictive than the intruder-construction or intruder-agriculture scenarios for near-surface land disposal. The analysis of the solid-waste drilling scenario is based on models and parameter values described in the following section. Section C.1.2 then summarizes the example analysis and presents the radionuclide concentrations corresponding to the example GCD-Permanent Isolation boundary that result from the analysis. Finally, Section C.1.3 discusses some of the sources of uncertainty in analyzing the solid-waste drilling scenario.

C.1.1 *Model Equations and Parameter Values*

The solid-waste drilling scenario assumes that 0.5 m^3 of contaminated soil from the disposal facility is brought to the surface by drilling activity and is mixed uniformly with native soil in a vegetable garden to a depth of 0.15 m (i.e., the depth of the plowed layer of surface soil) over an area of 2500 m^2.[3] Thus, the concentration of a radionuclide in soil in the vegetable garden relative to the concentration in the waste at the time of disposal is given by the following equation:

$$C_s = (0.5\ m^3)/[(0.15\ m)(2500\ m^2)] \times f_o \times f_L = (1.3 \times 10^{-3}) \times f_o \times f_L , \quad \text{(C-1)}$$

where

C_s = radionuclide concentration in soil in the vegetable garden per unit concentration in the waste at time of disposal,
f_o = time delay factor, and
f_L = waste leachability/accessibility factor.

The time delay factor, f_o, takes into account the assumed time delay between waste disposal and the onset of drilling intrusion. If t_d denotes the time delay for intrusion and $T_{1/2}$ the radionuclide half-life, then the time delay factor is given by

$$f_o = \exp[-(\ln 2)t_d/T_{1/2}] . \quad \text{(C-2)}$$

We assume that the disposal system for intermediate-depth burial contains engineered barriers that prevent intrusion for 500 years, which is the same delay time assumed by the NRC for near-surface land disposal of Class-C wastes in 10 CFR Part 61.[1,2] Thus,

$$f_o = \exp(-347/T_{1/2}) , \quad \text{(C-3)}$$

where $T_{1/2}$ is expressed in years.

The waste leachability/accessibility factor for drilling into solid wastes also was developed by the NRC in establishing concentration limits for near-surface land disposal.[2] This parameter takes into account that radionuclides in the form of activated metals are less accessible to removal by drilling intrusion than radionuclides in the form of bulk solid wastes mixed with soil. Based on the assumption used by the NRC for the leachability of activated metals into soils relative to the leachability of bulk solid wastes,[2] the waste leachability/accessibility factor is assigned the following values:

$$f_L = 1, \text{ bulk solid wastes,}$$
$$= 0.01, \text{ activated metals.} \qquad \text{(C-4)}$$

In the analyses for near-surface land disposal, the NRC also used a peak-to-average concentration ratio of 10 in establishing concentration limits for disposal of bulk solid wastes, in order to account for the expected inhomogeneities in radionuclide concentrations over the large disposal volume that could be accessed by an intruder.[2] However, this peak-to-average ratio for large waste volumes is not applied to the solid-waste drilling scenario, because only a small volume of waste (i.e., 0.5 m^3) is assumed to be accessed by an intruder.

An intruder is assumed to be exposed to contaminated soil in the vegetable garden by means of the following pathways:

- ingestion of vegetables grown in contaminated soil in the garden;
- ingestion of contaminated soil from the garden in conjunction with the vegetable intakes;
- inhalation of suspended radionuclides in contaminated soil from the garden; and
- external exposure to contaminated soil in the garden.

With the exception of ingestion of contaminated soil, these pathways also were considered in the analysis of disposal criteria for ^{239}Pu at the Hanford site[3] (but external exposure is not important for ^{239}Pu). The equations and parameter values for each exposure pathway are described in the following paragraphs.

Ingestion of Contaminated Vegetables. All vegetables consumed by an intruder are assumed to be contaminated by root uptake of radionuclides from soil in the garden. The annual dose from ingestion of vegetables grown in contaminated soil per unit concentration of a radionuclide in the

waste at the time of disposal is given by the following equation:

$$H_{ing} = (B_v/\rho_s) \times U_v \times D_{ing} \times C_s \ , \qquad (C\text{-}5)$$

where

H_{ing} = annual committed effective dose equivalent from ingestion of contaminated vegetables per unit concentration of a radionuclide in the waste at time of disposal (rem/y per Ci/m^3),

B_v = radionuclide plant-to-soil concentration ratio from root uptake (Ci/kg wet weight in vegetation per Ci/kg dry weight in soil),

ρ_s = density of soil (kg/m^3),

U_v = annual consumption of vegetables (kg per year),

D_{ing} = committed effective dose equivalent per unit activity of a radionuclide ingested (rem per Ci ingested),

and C_s is the radionuclide concentration in soil in the vegetable garden relative to the concentration in the waste at the time of disposal and is obtained from eqs. (C-1), (C-3), and (C-4).

The data used in estimating the annual dose from ingestion of contaminated vegetables in eq. (C-5) are described as follows:

- the radionuclide plant-to-soil concentration ratios are the underlined values in Table D-11 of ref. 5, except the value for ^{14}C is reduced by a factor of 10 in accordance with footnote (b) of that table;

- the density of soil is 1600 kg/m^3, as given in Table D-16 of ref. 5;

- the annual consumption of contaminated vegetables is 60 kg;[3] and

- the committed effective dose equivalent per unit activity of a radionuclide ingested is given in Table D-6 of ref. 5.

The assumed annual consumption of vegetables is a value appropriate for an average adult, rather than the maximum value of 190 kg assumed by the NRC in evaluating intruder scenarios for near-surface land disposal.[5] The use of an average annual consumption for an intruder is consistent with the recommendation of the International Commission on Radiological Protection (ICRP) that dose limits should apply to <u>average</u> individuals within the critical group of maximally exposed individuals, rather than those individuals who might receive the highest dose.[4] The committed effective dose equivalent per unit activity of a radionuclide ingested from

Table D-6 of ref. 5 is the entry labelled "ICRP;" and if values are given for more than one solubility class, then the value for the class of lowest solubility is used. Relatively insoluble forms of radionuclides are expected to be contained in wastes prepared for GCD, in order to minimize the potential for mobilization and transport in water.

Ingestion of Contaminated Soil. An intruder is assumed to ingest contaminated soil from the garden in conjunction with intakes of vegetables. The annual dose from ingestion of contaminated soil per unit concentration of a radionuclide in the waste at the time of disposal is given by the following equation:

$$H_{ing} = (1/\rho_s) \times U_s \times D_{ing} \times C_s \ , \qquad \text{(C-6)}$$

where

H_{ing} = annual committed effective dose equivalent from ingestion of contaminated soil per unit concentration of a radionuclide in the waste at time of disposal (rem/y per Ci/m^3),

ρ_s = density of soil (kg/m^3),

U_s = annual consumption of contaminated soil (kg per year),

D_{ing} = committed effective dose equivalent per unit activity of a radionuclide ingested (rem per Ci ingested),

and C_s again is the radionuclide concentration in soil in the vegetable garden relative to the concentration in the waste at the time of disposal and is obtained from eqs. (C-1), (C-3), and (C-4).

The data used in estimating the annual dose from ingestion of contaminated soil in eq. (C-6) are described as follows:

- the density of soil is 1600 kg/m^3, as given in Table D-16 of ref. 5;
- the annual consumption of contaminated soil is 0.037 kg;[6] and
- the committed effective dose equivalent per unit activity of a radionuclide ingested is given in Table D-6 of ref. 5.

The assumed annual consumption of contaminated soil corresponds to a daily consumption of 0.1 g and is a value appropriate for an average adult. Again, the committed effective dose equivalent per unit activity of a radionuclide ingested from Table D-6 of ref. 5 is the entry labelled "ICRP," and the value for the lowest solubility class is used.

Inhalation of Suspended Activity. An intruder is assumed to inhale contaminated soil suspended from the vegetable garden. The annual dose from inhalation of contaminated soil suspended in air per unit concentration of a radionuclide in the waste at the time of disposal is

given by the following equation:

$$H_{inh} = f_a \times U_a \times D_{inh} \times C_a \ , \qquad \text{(C-7)}$$

where

H_{inh} = annual committed effective dose equivalent from inhalation of contaminated air per unit concentration of a radionuclide in the waste at time of disposal (rem/y per Ci/m^3),
f_a = fraction of the year during which inhalation exposure occurs,
U_a = annual air intake (m^3 per year),
D_{inh} = committed effective dose equivalent per unit activity of a radionuclide inhaled (rem per Ci inhaled), and
C_a = radionuclide concentration in air per unit concentration in the waste at time of disposal.

Concentrations of suspended radionuclides in air are estimated using a mass-loading approach,[7] which is based on observations of airborne concentrations of naturally occurring uranium and thorium relative to their concentrations in surface soils. In this model, the concentration of a radionuclide in air per unit concentration in the waste at the time of disposal is given by the following equation:

$$C_a = (L_a/\rho_s) \times C_s \ , \qquad \text{(C-8)}$$

where

L_a = mass loading of soil in the atmosphere (kg/m^3),
ρ_s = density of soil (kg/m^3),

and C_s again is the radionuclide concentration in soil in the vegetable garden relative to the concentration in the waste at the time of disposal and is obtained from eqs. (C-1), (C-3), and (C-4).

The data used in estimating the annual dose from inhalation of contaminated air in eqs. (C-7) and (C-8) are described as follows:

- the fraction of the year during which inhalation exposure occurs is 25%, i.e., approximately 2000 hours per year;[3]

- the annual air intake is 8000 m^3;[8]

- the committed effective dose equivalent per unit activity of a radionuclide inhaled is given in Table D-7 of ref. 5;

- the mass loading of soil in the atmosphere is 10^{-7} kg/m^3;[7] and

- the density of soil is 1600 kg/m^3, as given in Table D-16 of ref. 5.

The assumed annual air intake is a value appropriate for an average adult. The assumed atmospheric mass loading of suspended soil is approximately the average background level.[7] The combination of assumed exposure time and atmospheric mass loading of soil takes into account that inhalatic exposures can occur at times when the intruder is residing near the garden as well as when working in the garden, and that the residence time near the garden is likely to be the greater of the two. The committed effective dose equivalent per unit activity of a radionuclide inhaled from Table D-7 of ref. 5 is the entry labelled "ICRP," and the value for the lowest solubility class again is used.

External Exposure to Contaminated Soil. An intruder is assumed to receive an external exposure while working in or residing near the vegetable garden. This exposure pathway is considered only for radionuclides that emit significant intensities of photons with energies of a few hundred keV or greater. The annual dose from external exposure to contaminated soil per unit concentration of a radionuclide in the waste at the time of disposal is given by the following equation:

$$H_{ext} = f_e \times D_{ext} \times C_s \ , \qquad \text{(C-9)}$$

where

H_{ext} = annual effective dose equivalent from external exposure to contaminated soil per unit concentration of a radionuclide in the waste at time of disposal (rem/y per Ci/m^3),

f_e = fraction of the year during which external exposure occurs,

D_{ext} = effective dose equivalent for external exposure per unit concentration of a radionuclide in contaminated soil (rem/y per Ci/m^3),

and C_s again is the radionuclide concentration in soil in the vegetable garden relative to the concentration in the waste at the time of disposal and is obtained from eqs. (C-1), (C-3), and (C-4).

The data used in estimating the annual dose from external exposure to contaminated soil in eq. (C-9) are described as follows:

- the fraction of the year during which external exposure occurs is 25%, i.e., approximately 2000 hours per year;[3]

- the effective dose equivalent for external exposure per unit concentration of a radionuclide in a uniformly contaminated slab source of thickness 0.15 m is obtained from the absorbed dose rates

in air above ground given in Appendix H of ref. 9,* multiplied by a factor of about 0.7 which converts absorbed dose in air to effective dose equivalent.[10-12]

The assumed fraction of the year during which external exposure occurs is the same as the value for inhalation exposures and takes into account the time spent residing near the garden as well as working in the garden. This assumption probably overestimates external dose, because the dose received while residing near the garden would be less than the dose received while working in the garden and it is the latter that is calculated in eq. (C-9). The absorbed dose rates in air above ground per unit concentration of a radionuclide in a uniformly contaminated slab source of thickness 0.15 m, which is the depth of the plowed layer of surface soil in the garden, were calculated according to the model in ref. 13. The external dose rate for each long-lived radionuclide in the waste includes contributions from any short-lived daughter products, which are assumed to be in secular equilibrium with the parent. The external dose rates per unit concentration in soil in the garden differ somewhat from those in Table D-8 of ref. 5, because the latter apply to a volume source of infinite thickness.

C.1.2 *Radionuclide Concentrations Corresponding to GCD-Permanent Isolation Boundary*

Summary of Dose Analysis. As presented in Section C.1.1, the dose analysis for an inadvertent intruder for the solid-waste drilling scenario is comprised of two separate factors:

[1] the concentration of a radionuclide in soil in an intruder's vegetable garden relative to the concentration in the waste at the time of disposal; and

[2] the annual dose to an intruder per unit concentration of a radionuclide in the vegetable garden from the different ingestion, inhalation, and external exposure pathways.

These two factors are summarized in Tables C-1 and C-2, respectively, and their product gives the annual dose to an intruder per unit concentration of a radionuclide in the waste at the time of disposal. The radionuclides

* The data in Appendix H of ref. 9 have been increased by a factor of 920 to correct an error in the tabulation.

Table C-1. Concentrations of radionuclides in soil in an intruder's vegetable garden relative to concentrations in the waste at time of disposal assumed for solid-waste drilling scenario[a]

Nuclide	Half-life[b]	f_o[c]	f_L[d]	C_s[e]
C-14	5730 y	0.94	1	1.2E-3
C-14[f]	5730 y	0.94	0.01	1.2E-5
Ni-59[f]	7.5E4 y	1.0	0.01	1.3E-5
Ni-63	100.1 y	3.1E-2	1	4.1E-5
Ni-63[f]	100.1 y	3.1E-2	0.01	4.1E-7
Sr-90	28.6 y	5.5E-6	1	7.1E-9
Nb-94[f]	2.03E4 y	0.98	0.01	1.3E-5
Ag-108m	127 y	6.5E-2	1	8.5E-5
Cs-137	30.17 y	1.0E-5	1	1.3E-8
Pb-210	22.26 y	1.7E-7	1	2.3E-10
Ra-226	1600 y	0.81	1	1.1E-3
Ac-227	21.773 y	1.2E-7	1	1.6E-10
Th-229	7.34E3 y	0.95	1	1.2E-3
U-232	72 y	8.1E-3	1	1.1E-5
Pu-238	87.75 y	1.9E-2	1	2.5E-5
Pu-241[g]	14.4 y	-	-	-
Am-241	432.2 y	0.45	1	5.8E-4
Am-243	7.38E3 y	0.95	1	1.2E-3
Cm-243[h]	28.5 y	-	-	-
Cm-244[i]	18.11 y	-	-	-
Others	-	1.0	1	1.3E-3

See following page for footnotes.

Footnotes for Table C-1

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[a]Calculations are described in eqs. (C-1) through (C-4) in Section C.1.1.

[b]Values from ref. 14.

[c]Time delay factor, based on assumed delay of 500 years between waste disposal and onset of intrusion.

[d]Waste accessibility/leachability factor.

[e]Concentration in soil in vegetable garden relative to concentration in waste at time of disposal, based on values of f_o and f_L and dilution factor of 1.3×10^{-3} for mixing of contaminated soil from solid drilling waste with native soil of vegetable garden.

[f]Radionuclide in activated metals only.

[g]Radionuclide decays to longer-lived Am-241; maximum concentration of Am-241 resulting from decay of Pu-241 will be 1/30 of the concentration of Pu-241 at time of disposal.

[h]Radionuclide decays to longer-lived Pu-239; maximum concentration of Pu-239 resulting from decay of Cm-243 will be 1/850 of the concentration of Cm-243 at time of disposal.

[i]Radionuclide decays to longer-lived Pu-240; maximum concentration of Pu-240 resulting from decay of Cm-244 will be 1/360 of the concentration of Cm-244 at time of disposal.

Table C-2. Annual committed effective dose equivalents to an intruder per unit concentration of radionuclides in soil in vegetable garden[a]

Nuclide	Annual dose per unit concentration (rem/y per Ci/m^3)				
	Vegetable ingestion	Soil ingestion	Inhalation	External exposure	Total
C-14	3.1E1	3.5E-2	1.4E-6	-	3.1E1
Ni-59	1.7E-1	4.9E-3	1.2E-4	-	1.7E-1
Ni-63	4.6E-1	1.3E-2	2.9E-4	-	4.7E-1
Sr-90	3.1E1	2.5E-1	1.9E-1	-	3.1E1
Nb-94	2.5	1.6E-1	5.1E-2	1.4E3	1.4E3
Tc-99	4.1E1	2.3E-2	9.1E-4	-	4.1E1
Ag-108m	4.3E1	1.8E-1	3.5E-2	1.4E3	1.4E3
Sn-126	1.9	4.6E-1	1.3E-2	1.7E3[b]	1.7E3
I-129	3.9E1	5.3	1.9E-2	-	4.4E1
Cs-135	2.1	2.5E-1	8.4E-4	-	2.4
Cs-137	1.5E1	1.9	6.0E-3	5.0E2	5.2E2
Pb-210	1.2E2	1.8E1	3.3E-1	-	1.4E2
Ra-226	8.6E2[c]	5.0E1[c]	1.4[c]	1.4E3[d]	2.3E3
Ac-227	5.2E2	1.3E2	6.5E1	2.9E2[e]	1.0E3
Th-229	2.1E2	3.0E1	8.0E1	2.2E2[f]	5.4E2
Th-230	9.9E1	1.5E1	3.3E1	-	1.5E2
Th-232	5.6E2[g]	3.9E1[g]	5.0E1[h]	2.1E3[i]	2.8E3
Pa-231	1.4E3[j]	3.5E2[j]	1.5E1[j]	2.9E2[k]	2.1E3
U-232	6.6E1[m]	1.3E1[m]	5.6E1[m]	1.4E3[n]	1.5E3
U-233	2.3	5.8E-1	1.4E1	-	1.7E1
U-234	2.3	5.8E-1	1.4E1	-	1.7E1
U-235	2.3	5.6E-1	1.3E1	9.6E1[o]	1.1E2
U-236	2.3	5.6E-1	1.3E1	-	1.6E1
U-238	2.1	5.1E-1	1.2E1	1.5E1[p]	3.0E1
Np-237	1.1E4	1.1E2	4.4E1	1.7E2[q]	1.1E4
Pu-238	2.9	3.2	3.9E1	-	4.5E1
Pu-239	3.4	3.7	4.4E1	-	5.1E1
Pu-240	3.4	3.7	4.4E1	-	5.1E1
Pu-242	3.2	3.5	4.3E1	-	5.0E1
Am-241	9.7E2	1.1E2	4.4E1	3.8	1.1E3
Am-243	9.9E2	1.1E2	4.4E1	1.1E2[r]	1.3E3

See following page for footnotes.

Footnotes for Table C-2

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[a]Model equations and parameter values for each exposure pathway are described in eqs. (C-5) through (C-9) in Section C.1.1, but calculations in this table exclude the factor C_s that is given in Table C-1.

[b]Value assumes Sb-126m and Sb-126 are in secular equilibrium with Sn-126.

[c]Value assumes Pb-210 is in secular equilibrium with Ra-226.

[d]Value assumes Pb-214 and Bi-214 are in secular equilibrium with Ra-226.

[e]Value assumes Th-227, Ra-223, Rn-219, Pb-211, and Bi-211 are in secular equilibrium with Ac-227.

[f]Value assumes Fr-221, Bi-213, and Tl-209 are in secular equilibrium with Th-229.

[g]Value assumes Ra-228 and Th-228 are in secular equilibrium with Th-232.

[h]Value assumes Th-228 is in secular equilibrium with Th-232.

[i]Value assumes Ac-228, Pb-212, Bi-212, and Tl-208 are in secular equilibrium with Th-232.

[j]Value assumes Ac-227 is in secular equilibrium with Pa-231.

[k]Value assumes daughter products of Ac-227 are in secular equilibrium with Pa-231 (see footnote e).

[m]Value assumes Th-228 is in secular equilibrium with U-232.

[n]Value assumes Pb-212, Bi-212, and Tl-208 are in secular equilibrium with U-232.

[o]Value assumes Th-231 is in secular equilibrium with U-235.

[p]Value assumes Th-234, Pa-234m, and Pa-234 are in secular equilibrium with U-238.

[q]Value assumes Pa-233 is in secular equilibrium with Np-237.

[r]Value assumes Np-239 is in secular equilibrium with Am-243.

included in the analysis are those listed in Table 2 in Section 4.3. Again, these radionuclides are sufficiently long-lived that they can exist in concentrations greater than the Class C limits that are generally acceptable for near-surface land disposal[1,2] and that define the Permanent Isolation boundary in the proposed waste classification system (see Fig. 2 in Section 4.3).

Table C-1 presents the concentration of radionuclides in soil in the vegetable garden per unit concentration in the waste at the time of disposal, which is denoted by C_s. This parameter is developed in eqs. (C-1) through (C-4) and consists of three factors: (1) the dilution factor for mixing of contaminated soil from the solid drilling wastes into native soil in the vegetable garden, which is calculated to be 1.3×10^{-3} for all radionuclides, (2) the time delay factor, f_o, which takes into account reductions in radionuclide concentrations in the waste due to radioactive decay over an assumed delay time of 500 years before the onset of intrusion, and (3) the waste accessibility/leachability factor, f_L, which is unity for all radionuclides in the form of bulk solid wastes but is assumed to be 0.01 for radionuclides in the form of activated metals. A separate entry is given for a radionuclide only if the time delay factor or the waste accessibility/leachability factor differs from unity; otherwise, C_s has the value 1.3×10^{-3} for all radionuclides. As noted in the table, the dose to an intruder from the relatively short-lived ^{241}Pu, ^{243}Cm, and ^{244}Cm after a time delay of 500 years will be determined by the concentrations of the longer-lived daughter products ^{241}Am, ^{239}Pu, and ^{240}Pu, respectively, resulting from decay of the parent radionuclides.

Table C-2 presents the annual doses to an intruder per unit concentration of radionuclides in the vegetable garden from the different exposure pathways, and the sum of the doses from all pathways is given in the last column of the table. These results are obtained from eqs. (C-5) through (C-9), except the factor C_s listed in Table C-1 is not included. The parameter values assumed in the equations for the different pathways are described in Section C.1.1. Significant contributions to the dose for each pathway from relatively short-lived daughter products are included whenever the half-lives of the daughters are less than the assumed time delay for the onset of intrusion after disposal of 500 years, and all such daughters are assumed to be in secular equilibrium with the parent. No entries are given in this table for ^{241}Pu, ^{243}Cm, and ^{244}Cm because, as noted in Table C-1, the doses from these radionuclides are determined by the contributions from their longer-lived daughter products which are listed separately.

The results in Table C-2 show that the relative importance of the different exposure pathways depends on the particular radionuclide. Direct ingestion of contaminated soil is important relative to ingestion

of contaminated vegetables only for radionuclides with low values for the plant-to-soil concentration ratio, B_v. The inhalation pathway is important relative to the ingestion pathways only for the alpha-emitting actinides and is the most important pathway in many cases. Finally, external exposure often is the dominant pathway when a radionuclide and its short-lived daughter products in secular equilibrium emit high intensities of high-energy photons.

GCD-Permanent Isolation Boundary. As indicated above, the annual dose to an inadvertent intruder per unit concentration of a radionuclide in the waste at the time of disposal, denoted by H_T, is given by the product of the factor C_s from Table C-1 and the total dose from Table C-2; and H_T has units of rem per year per Ci/m^3. Then, since the limit on annual committed effective dose equivalent for an intruder is assumed to be 0.5 rem, the limit on concentration of a radionuclide that would be acceptable for disposal, denoted by C_w, in units of Ci/m^3 is given by

$$C_w = 0.5/H_T \quad . \tag{C-10}$$

The resulting concentration limits of radionuclides that would be acceptable for intermediate-depth burial, based on the solid-waste drilling scenario, are given in Table C-3. These concentration limits define the example GCD-Permanent Isolation boundary. The notation "No limit" indicates a calculated concentration that exceeds the specific activity of the pure radioisotope. Again, the concentration limits for the relatively short-lived radionuclides ^{241}Pu, ^{243}Cm, and ^{244}Cm are determined by the limits for their longer-lived daughter products and the half-lives of the parent and daughter in each case.

Table C-3 also compares the radionuclide concentrations corresponding to the example GCD-Permanent Isolation boundary with the Class-C concentration limits that correspond to the Permanent Isolation boundary in the waste classification system, as obtained from Table 2 in Section 4.3. In most cases, we obtain the expected result that the concentration limit that is generally acceptable for GCD is greater than the limit for near-surface land disposal. Only for ^{14}C, ^{135}Cs, and ^{237}Np is the ratio of the GCD boundary concentration to the Class-C limit less than or equal to unity, and the largest excursion below unity is only a factor of 3. Given that the concentration limits for GCD were estimated on the basis of an exposure scenario that was not considered by the NRC in obtaining Class-C limits for near-surface land disposal,[1,2] given the differences in the dosimetric models for ingestion and inhalation used in the two analyses (see Section B.3 of Appendix B), and given the uncertainties in parameter values contained in the models (see Section C.1.3), the few results that give GCD-Permanent Isolation boundary concentrations at or below Class-C limits are not cause for concern.

Table C-3. Concentration limits of radionuclides that are acceptable for greater confinement disposal via intermediate-depth burial assuming a solid-waste drilling scenario[a]

Nuclide	Concentration (Ci/m^3)	Ratio to Class-C[b]	Nuclide	Concentration (Ci/m^3)	Ratio to Class-C[b]
C-14	1E1	1	Th-232	1E-1	1E1
C-14[c]	1E3	1E1	Pa-231	2E-1[e]	7
Ni-59[c]	2E5	1E3	U-232	3E1	6E2
Ni-63	3E4	4E1	U-233	2E1	5E1
Ni-63[c]	3E6	4E2	U-234	2E1	4E1
Sr-90	2E6	3E2	U-235	4	1E1
Nb-94[c]	3E1	2E2	U-236	2E1	3E1
Tc-99	9	3	U-238	No limit	-
Ag-108m	4	1E2	Np-237	4E-2	1
Sn-126	2E-1	2E1	Pu-238	4E2	6E1
I-129	9	1E2	Pu-239	8	8E1
Cs-135	2E2	3E-1	Pu-240	8	8E1
Cs-137	7E4	1E1	Pu-241	2E1[f]	8
Pb-210	2E7	1E5	Pu-242	8	8E1
Ra-226	2E-1[d]	7	Am-241	8E-1	8
Ac-227	3E6	3E6	Am-243	3E-1	4
Th-229	8E-1	2E1	Cm-243	6E3[g]	8E1
Th-230	3	5E1	Cm-244	3E3[h]	8E1

[a]Calculations are described in Sections C.1.1 and C.1.2. Concentration limits define example GCD-Permanent Isolation boundary, and boundary for wastes containing mixtures of radionuclides is determined from boundary concentration for each radionuclide using sum-of-fractions rule.

[b]Class-C concentration limits for near-surface land disposal are given in Table 2 in Section 4.3.

[c]Radionuclide in activated metals only.

[d]Value assumes Pb-210 is in secular equilibrium with Ra-226.

[e]Value assumes Ac-227 is in secular equilibrium with Pa-231.

[f]Value is 30 times concentration limit for Am-241.

[g]Value is 850 times concentration limit for Pu-239.

[h]Value is 360 times concentration limit for Pu-240.

The role of the example GCD-Permanent Isolation boundary in the waste classification system is depicted in Fig. C-1. The GCD-Permanent Isolation boundary, which corresponds to the concentrations in Table C-3, generally is a vertical line that is displaced toward higher concentrations from the Permanent Isolation boundary corresponding to the Class-C limits for near-surface land disposal. The depiction of the GCD-Permanent Isolation boundary as a cross-hatched bar, rather than a line, is intended to represent the uncertainty that is inherent in its determination, due primarily to uncertainties in the analyses used in defining the boundary (see Section C.1.3), the possible site-specific nature of the assumed exposure scenario, and the lack of similar analyses for other possible GCD technologies.

The depiction in Fig. C-1 also emphasizes that the example analysis for obtaining a generally applicable GCD-Permanent Isolation boundary has no bearing on the definitions of HLW and TRU Waste and Equivalent in the proposed waste classification system. This boundary would be used only to distinguish between relatively dilute HLW and TRU Waste and Equivalent that would be acceptable for GCD and relatively concentrated wastes in these classes that would require deep geologic repositories or equivalent for protection of public health and safety.

C.1.3 *Uncertainties in Analysis of Solid-Waste Drilling Scenario*

The analysis of the solid-waste drilling scenario in Section C.1.1, which was used to obtain an example GCD-Permanent Isolation boundary, was based to a large extent on models and parameter values used by the NRC in 10 CFR Part 61 in developing the Class-C concentration limits of radionuclides that are generally acceptable for near-surface land disposal,[1,2,5] and which correspond to the Permanent Isolation boundary in the proposed waste classification system. This approach was adopted in order to provide a measure of consistency in the determinations of the two sets of concentration limits. However, the analysis of the solid-waste drilling scenario involves a number of important sources of uncertainty which could affect the validity of the results.

This section discusses some of the sources of uncertainty in the models and parameter values for the solid-waste drilling scenario. The discussion emphasizes uncertainties or possible errors in the estimates of annual dose to an inadvertent intruder. It is important to bear in mind that, from a regulatory perspective, the objective of such a dose analysis is to obtain estimates of dose that are not likely to be exceeded, rather than best estimates of actual doses that would be received. Therefore, uncertainties or possible errors in the analysis that would result in

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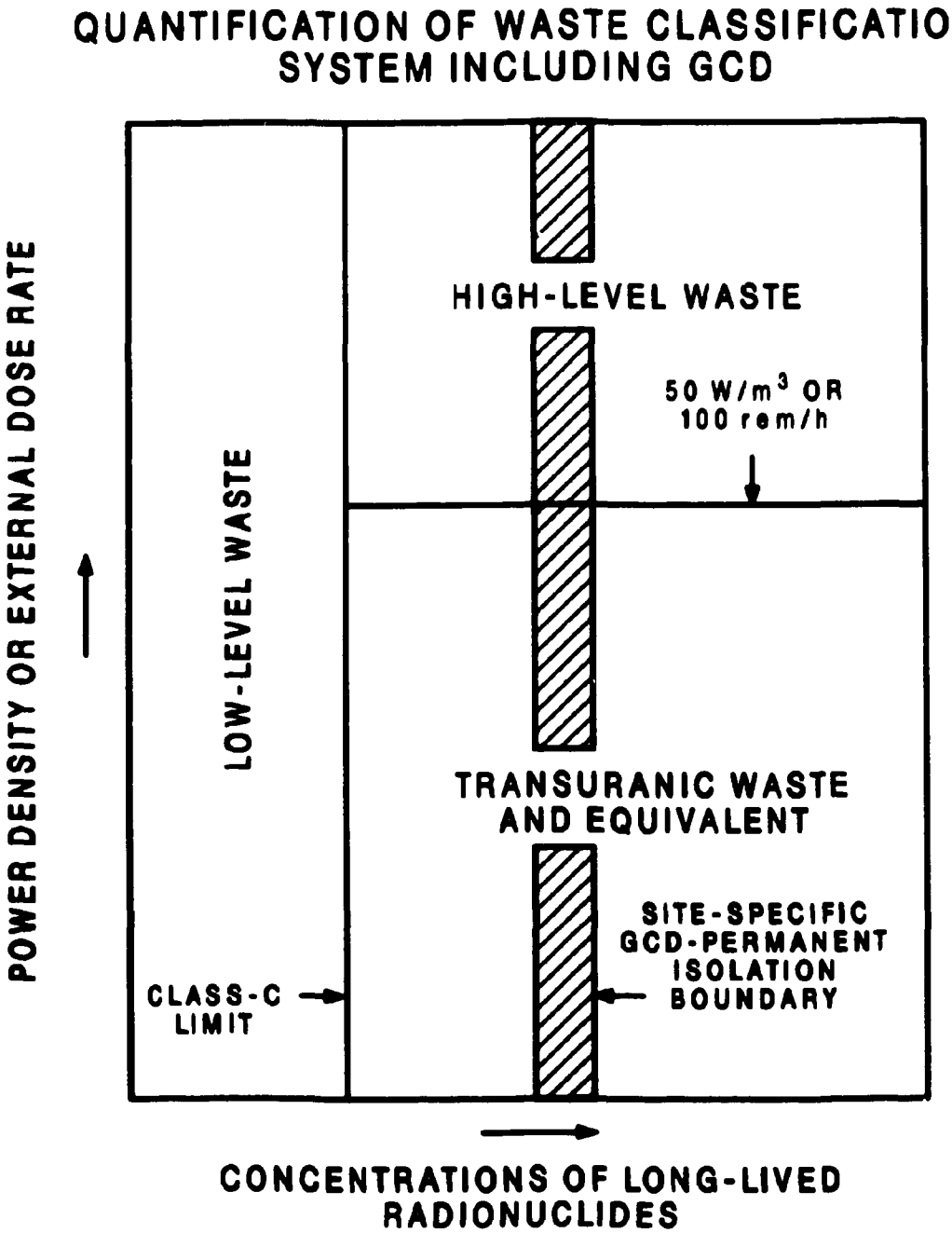

Fig. C-1. Depiction of proposed waste classification system including site-specific GCD-Permanent Isolation boundary. The waste classification system is the same as depicted in Fig. 2, and radionuclide concentrations corresponding to the example GCD-Permanent Isolation boundary are given in Table C-3.

underestimates of dose are of greater concern than those that would result in overestimates. As indicated in eq. (C-10), underestimates of dose would result in overestimates of concentration limits of radionuclides that would be acceptable for intermediate-depth burial, and vice versa. Some of the sources of uncertainty or possible error in analyzing the solid-waste drilling scenario are discussed in the following paragraphs.

The value of the dilution factor for mixing of contaminated soil from the solid drilling wastes into native soil in an intruder's vegetable garden, which was assumed to be 1.3×10^{-3} for this scenario[3] [see eq. (C-1)], is highly subjective and depends on the assumed volume of contaminated soil brought to the surface by drilling and the size of the vegetable garden. This dilution factor conceivably could be uncertain by as much as an order of magnitude, although a value much smaller than assumed in this analysis seems unlikely because the assumed size of the vegetable garden (2500 m^2) is quite large. Thus, the assumed dilution factor may result in underestimates of dose.

In this analysis, the committed effective dose equivalents from ingestion or inhalation of a unit activity of radionuclides, which also are referred to as dose conversion factors, ostensibly were calculated by the NRC[5] on the basis of models and parameter values currently recommended by the ICRP.[4,15] However, we have noted several discrepancies between the dose conversion factors given by the NRC and an independent set of values obtained from the ICRP methodology.* In particular, the ingestion dose conversion factors for ^{210}Pb, ^{227}Ac, ^{229}Th, and ^{232}Th used in this analysis apparently are underestimated by factors of 3-7, the value for ^{232}U is overestimated by a factor of 5, and the inhalation dose conversion factors for ^{210}Pb, ^{227}Ac, ^{228}Th, ^{229}Th, and ^{232}Th are underestimated by factors of 3-5. Furthermore, the ingestion dose conversion factors for all isotopes of plutonium used in this analysis do not take into account the recent recommendation of the ICRP that the fraction of ingested plutonium absorbed in the gastrointestinal (GI) tract should be increased to 10^{-3} in estimating dose to members of the public, unless the plutonium is known to be in the form of insoluble oxides and free of very small particles;[16] and the exception conditions cannot reasonably be assumed at times far into the future. Thus, the ingestion dose conversion factors for all isotopes of plutonium may to be underestimated by a factor of about 25. Underestimates of dose conversion factors for ingestion or inhalation would result in underestimates of dose.

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* The calculations of dose conversion factors for ingestion and inhalation kindly were provided by D. E. Dunning, Jr., of Maxima Corporation and K. F. Eckerman of Oak Ridge National Laboratory.

For many elements, the plant-to-soil concentration ratio from root uptake, which is important in determining dose from ingestion of contaminated vegetables, is highly uncertain. In particular, the values used in this analysis[5] for isotopes of Nb, Tc, Th, U, Pu, Am, and Cm differ by factors of 5-250 from mean values obtained from published evaluations of available data.[17,18] However, the values used in this analysis may be overestimates for all elements except Nb and Tc and, thus, would result in overestimates of dose from the vegetable pathway in most cases. Furthermore, as indicated by the results in Table C-2, uncertainties in annual dose from the vegetable pathway for isotopes of the elements listed above would have a significant effect on the total dose from all pathways only for ^{99}Tc, ^{230}Th, ^{241}Am, and ^{243}Am, due to the greater importance of the inhalation and external exposure pathways for the other radionuclides. Thus, the uncertainty in the plant-to-soil concentration ratio for ^{99}Tc is of greatest concern for this analysis. In addition, the concentration ratio for ^{14}C used in this analysis may be overestimated by at least an order of magnitude, since most of the carbon in plants results from photosynthesis of atmospheric carbon rather than root uptake from soil, and the vegetable pathway is the only one of importance for this radionuclide. Finally, reliable data on plant-to-soil concentration ratios for many elements probably can be obtained only from site-specific measurements, particularly in cases where the values are relatively low and the available data for different food crops and types of soil vary by an order of magnitude or more.

In estimating dose from inhalation of suspended activity from the vegetable garden, the values of the fraction of the year during which inhalation exposure occurs and the mass loading of contaminated soil in the atmosphere are highly subjective and uncertain. In this analysis, we assumed that an intruder is exposed to background levels of suspended contaminated soil while residing near the garden for a substantial fraction of the year (25%). This assumption may lead to erroneous estimates of dose because an intruder also will receive inhalation exposures while working in the garden, and the atmospheric mass loading of contaminated soil during gardening activities likely will be greater than background levels by an order of magnitude or more.[3,5] However, the higher concentrations of radionuclides inhaled likely will be compensated by a much smaller time spent working in the garden compared with the time spent residing near the garden.[5] Reliable data on atmospheric mass loadings of contaminated soil probably require site-specific measurements, particularly since the values may vary greatly between arid, sparsely vegetated locations and locations with plentiful rainfall and extensive vegetation.

The dose from the external exposure pathway also is uncertain due to the subjective assumption for the fraction of the year that an intruder spends working in or residing near the garden. As emphasized in Section C.1.1, our analysis probably overestimates dose from this pathway, because the calculations are based on an exposure in the garden for 25% of the time.

There are three additional noteworthy points concerning the sources of uncertainty in the solid-waste drilling scenario. First, for some radionuclides, possible errors in the calculations resulting from the different sources of uncertainty may compensate one another; i.e., some factors in estimating dose may be overestimated while others are underestimated. Second, many of the sources of uncertainty in developing the concentration limits of radionuclides for intermediate-depth burial in Table C-3 also occur in estimating the Class-C limits of radionuclides that are generally acceptable for near-surface land disposal in Table 2 in Section 4.3. Thus, the ratio of the two concentration limits for some radionuclides may be relatively insensitive to uncertainties in the models and parameter values. Third, there always will be a significant degree of subjective scientific judgment involved in any dose analysis performed for the purpose of establishing generally applicable concentration limits of radionuclides for disposal, and these judgments may be more important than some sources of uncertainty that can be quantified.

Finally, there are other important sources of uncertainty in developing a generally applicable GCD-Permanent Isolation boundary besides uncertainties in the models and parameters for estimating dose to an inadvertent intruder. Some of these sources of uncertainty are discussed in Section 4.6.

C.2 Discussion of Well-Water Scenario

A well-water scenario for exposure of inadvertent intruders also can be analyzed to obtain concentration limits of radionuclides that would be acceptable for intermediate-depth burial. This scenario assumes that radionuclides in solid wastes in the unsaturated zone are leached by infiltrating water and migrate downward to an aquifer, and contaminated water is withdrawn from a well at the disposal site for use by an intruder.

The well-water scenario can be analyzed using the methodology developed by the NRC for near-surface land disposal.[5] However, for the reasons discussed below, we have not used this scenario in the example analysis for obtaining a generally applicable GCD-Permanent Isolation boundary.

- The downward flux of infiltrating water through the unsaturated zone, the flux of water in the underlying aquifer, and the location of the solid wastes relative to the aquifer are expected to be highly site-specific.

- The solution/solid partition coefficients for radionuclides in solid wastes in saturated soils and the correction factors to the partition coefficients that take into account the transient and partially saturated conditions under which water contacts the waste in the unsaturated zone[5] are highly uncertain and likely to be highly site-specific. Thus, the source term describing rates of release of radionuclides from the disposal facility would be very poorly known without site-specific analysis.

- For many radionuclides, the retardation coefficient used in describing transport in water in the unsaturated and saturated zones is highly uncertain and likely to be highly site-specific.[19]

- The concentration of a radionuclide at any location in an aquifer underlying the disposal facility is not simply related to the concentration in solid wastes, but depends in a relatively complicated way on the total activity of the radionuclide and the size of the disposal facility.[5] Thus, generic estimates of radionuclide concentrations in an aquifer are highly speculative.

On the basis of the factors discussed above, we conclude that analysis of a well-water scenario is so site-specific that a generic analysis for developing an example GCD-Permanent Isolation boundary would be largely meaningless. However, a site-specific analysis of a well-water scenario probably will be an essential aspect of performance assessments for determining compliance of any GCD facility with applicable standards for protection of public health and safety, i.e., for determining waste acceptance criteria for particular disposal technologies at particular sites. For particular combinations of site and type of facility, such an analysis may result in concentration limits for disposal of some radionuclides that are significantly less than the example limits in Table C-3 for the more generic solid-waste drilling scenario.

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APPENDIX D

CONCENTRATION LIMITS FOR TRU RADIONUCLIDES THAT CORRESPOND TO PERMANENT ISOLATION BOUNDARY

An important aspect of the Permanent Isolation boundary developed in Section 4.3 of this report is the inclusion of radionuclide-specific concentration limits for TRU radionuclides in units of Ci/m^3, rather than the single concentration limit of 100 nCi/g for all alpha-emitting TRU radionuclides with half-lives greater than 5 years contained in Table 1 of the Final Rule for 10 CFR Part 61.[1] The single limit of 100 nCi/g for these radionuclides also agrees with current definitions of TRU waste used by the DOE[2] and the EPA,[3] as reviewed in Section 2.2.1. This Appendix discusses (1) the rationale for using radionuclide-specific concentration limits for TRU radionuclides in Ci/m^3 in the proposed waste classification system and (2) the essential equivalence of the radionuclide-specific concentration limits in Ci/m^3 with the single limit of 100 nCi/g for many existing wastes containing TRU radionuclides.

The use of radionuclide-specific concentration limits for TRU radionuclides in units of Ci/m^3 for purposes of defining the Permanent Isolation boundary in the proposed waste classification system is based essentially on the rationale described by the NRC in Section 7 of Appendix C of the Final Environmental Impact Statement (FEIS) for 10 CFR Part 61.[4] The NRC's rationale for development of the Class-C limits for near-surface land disposal of TRU radionuclides is described as follows.

First, the NRC's methodology for analyzing the intruder-construction and intruder-agriculture scenarios for exposures of inadvertent intruders at a near-surface land disposal facility yields concentration limits for disposal of all radionuclides that depend on activity per unit volume, rather than activity per unit mass.[4,5] (The leaching and migration scenarios were not considered important for TRU radionuclides because of their relatively low solution/solid partition coefficients and relatively high retardation coefficients for transport in water.) Thus, radionuclide activity per unit volume is the measure that is directly related to long-term risk from waste disposal, not activity per unit mass.

Based on analyses of the relevant exposure scenarios for an inadvertent intruder, the NRC developed Class-C concentration limits for near-surface land disposal for a number of TRU radionuclides,[4] and these limits are given in Table D-1. The concentration limits for the longer-lived radionuclides that do not decay significantly within the 500-year time period during which intruder exposures are assumed to be prevented by the disposal system[1,4] vary only from about 0.04 to 0.11 Ci/m^3, or by less than a factor of 3. Furthermore, the concentration limit for ^{241}Am, for

Table D-1. Class-C concentration limits for near-surface land disposal of TRU radionuclides developed by the NRC[a]

Nuclide	Concentration (Ci/m^3)
Np-237	0.041
Pu-238	6.8
Pu-239	0.11
Pu-240	0.11
Pu-241	4.9[b]
Pu-242	0.11
Am-241	0.14
Am-243	0.068
Cm-243	78[c]
Cm-244	41[d]

[a]Values obtained from Section 7 of Appendix C of the Final Environmental Impact Statement for 10 CFR Part 61 (ref. 4).

[b]Value is based on concentration limit for longer-lived daughter product Am-241 and half-lives of Pu-241 and Am-241.

[c]Value is based on concentration limit for longer-lived daughter product Pu-239 and half-lives of Cm-243 and Pu-239.

[d]Value is based on concentration limit for longer-lived daughter product Pu-240 and half-lives of Cm-244 and Pu-240.

which the initial inventory is reduced by slightly more than a factor of 2 by radioactive decay over 500 years, is barely outside the range of concentration limits for the longer-lived radionuclides. On the other hand, the concentration limit for ^{238}Pu is significantly higher than the limits for the longer-lived radionuclides, because its half-life of 87.75 years is considerably less than 500 years. The concentration limits in Table D-1 were used directly in defining the Permanent Isolation boundary for the proposed waste classification system in Table 2 in Section 4.3.

Second, in the interest of easing compliance by disposal site operators with the Class-C concentration limits in Table D-1, the NRC investigated the desirability of combining the limits for individual isotopes into a single limit. The NRC concluded that it still would be necessary to maintain a limit for ^{241}Pu separate from the limit for its longer-lived daughter product ^{241}Am, because of the importance of ^{241}Pu in various commercial wastes containing TRU radionuclides. However, the NRC also concluded that maintaining separate limits for the longer-lived TRU isotopes was not cost-effective for most licensees.

A single concentration limit for long-lived, alpha-emitting TRU radionuclides could be based on the smallest value in Table D-1, i.e., the limit for ^{237}Np. However, the NRC concluded that this approach would be overly restrictive, because ^{237}Np was expected to occur in commercial wastes only in very small quantities. The preferred alternative was to consider variations in expected isotopic compositions of TRU radionuclides for individual commercial waste streams. On the basis of data assembled for the FEIS for 10 CFR Part 61,[4] the equivalent gross Class-C concentration limit for long-lived, alpha-emitting TRU radionuclides for 14 commercial waste streams was found to be in the range 0.11-0.62 Ci/m^3, but 12 of the 14 waste streams had Class-C concentration limits in the range 0.11-0.30 Ci/m^3. Furthermore, the most important TRU radionuclides in the commercial wastes generally were ^{239}Pu, ^{240}Pu, and ^{241}Am.

An exercise of judgment then was required by the NRC in obtaining a single Class-C concentration limit for long-lived, alpha-emitting TRU radionuclides. First, the NRC concluded that the single concentration limit should be expressed in units of nCi/g, rather than Ci/m^3, in order to be consistent with historical definitions of TRU waste. Second, the conversion of concentration limits from Ci/m^3 to nCi/g required an assumption for the density of the waste. The NRC's analysis of existing commercial wastes led to the conclusion that the densities possibly could be in the range 1-6 g/cm^3 but more typically should be 1-2 g/cm^3. The NRC then assumed an average waste density of 1.6 g/cm^3, which resulted in Class-C concentration limits for long-lived, alpha-emitting TRU radionuclides in the range 60-190 nCi/g.

From the result given above, the NRC concluded that a reasonable gross Class-C concentration limit for long-lived, alpha-emitting TRU radionuclides would be about 100 nCi/g, and this value was adopted for use in Table 1 of the Final Rule for 10 CFR Part 61.[1] Other considerations, such as differences in waste masses, dilution by lower activity wastes, use of volume reduction, improvements in health physics considerations, and site-specific environmental conditions could provide rationales for raising or lowering this concentration limit. However, the NRC concluded that there are about an equal number of factors tending to raise or lower the limit, and that the limit of 100 nCi/g will result in a high probability that the performance objective for protection of inadvertent intruders (i.e., a limit on annual dose equivalent to whole body of 0.5 rem)[1,4] will not be exceeded at any new site.

The rationale for use of radionuclide-specific concentration limits in Ci/m^3 for long-lived, alpha-emitting TRU radionuclides in defining the Permanent Isolation boundary in the proposed waste classification system then may be summarized as follows.

- Radionuclide concentrations in Ci/m^3 are the appropriate measure of activity for estimating risk to an inadvertent intruder, and separate limits for all radionuclides would provide a classification system that is generally applicable to any wastes.

- With a separate concentration limit for ^{241}Pu based on the limit for the longer-lived daughter product ^{241}Am, the Class-C limits for all long-lived, alpha-emitting TRU radionuclides, excluding ^{238}Pu, vary by less than a factor of 3.

- The most important TRU radionuclides in existing commercial wastes, other than ^{241}Pu, are ^{239}Pu, ^{240}Pu, and ^{241}Am. If a waste density of 1.6 g/cm^3 is assumed, then the Class-C concentration limit for most existing commercial wastes is well approximated by the single limit of 100 nCi/g for all long-lived, alpha-emitting TRU radionuclides.

Thus, radionuclide-specific Class-C concentration limits in Ci/m^3 are essentially equivalent to a single limit of 100 nCi/g for all long-lived, alpha-emitting TRU radionuclides. However, the advantage of the former approach is that the concentration limits provide a risk-based definition of the Permanent Isolation boundary which is generally applicable to wastes containing any compositions of TRU radionuclides.

The NRC's analysis described above applies only to expected commercial wastes but not to defense wastes that contain significant concentrations of TRU radionuclides. However, a cursory examination of

published data on defense TRU wastes[6] indicates that the most important alpha-emitting isotopes are ^{238}Pu, ^{239}Pu, ^{240}Pu, and ^{241}Am. Thus, if we assume that the density of defense wastes does not differ greatly from the average value of 1.6 g/cm^3 assumed by the NRC for commercial wastes, then the radionuclide-specific concentration limits for ^{239}Pu, ^{240}Pu, and ^{241}Am that define the Permanent Isolation boundary in Table 2 in Section 4.3 also should be essentially equivalent for most defense TRU wastes to the single limit of 100 nCi/g for all long-lived, alpha-emitting TRU radionuclides. Exceptions will occur for wastes containing significant concentrations of ^{238}Pu, due to the relatively short half-life of this isotope. In these cases, a limit of 100 nCi/g for ^{238}Pu would correspond to a risk to an inadvertent intruder that is considerably less than the risk from disposal of 100 nCi/g of the longer-lived, alpha-emitting TRU isotopes. Thus, the single limit of 100 nCi/g for all long-lived, alpha-emitting TRU isotopes again appears to provide reasonable protection of inadvertent intruders from disposal of existing defense TRU wastes.

References for Appendix D

1. U.S. Nuclear Regulatory Commission, "Part 61 – Licensing Requirements for Land Disposal of Radioactive Waste," p. 628 in *Code of Federal Regulations, Title 10, Parts 0 to 199*, U.S. Government Printing Office (1986); see also *Fed. Registr.* 47, 57446 (1982).

2. U.S. Department of Energy, "Radioactive Waste Management," Order 5820.2 (1984).

3. U.S. Environmental Protection Agency, "Part 191 – Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Wastes," p. 7 in *Code of Federal Regulations, Title 40, Parts 190 to 399*, U.S. Government Printing Office (1986); see also *Fed. Registr.* 50, 38066 (1985).

4. U.S. Nuclear Regulatory Commission, *Final Environmental Impact Statement on 10 CFR Part 61 "Licensing Requirements for Land Disposal of Radioactive Waste,"* NUREG-0945, Vol. 1-3 (1982).

5. O. I. Oztunali and G. W. Roles, *Update of Part 61 Impacts Analysis Methodology – Methodology Report*, NUREG/CR-4370, Vol. 1, Envirosphere Company and U.S. Nuclear Regulatory Commission (1986).

6. U.S. Department of Energy, *Spent Fuel and Radioactive Waste Inventories, Projections, and Characteristics*, DOE/RW-0006, Rev. 1 (1985).

APPENDIX E

DATA TO SUPPORT ANALYSES OF IMPACTS OF WASTE CLASSIFICATION SYSTEM ON SELECTED COMMERCIAL AND DEFENSE WASTES

Sections 5.1 and 5.2 of this report discussed impacts of the proposed waste classification system on selected commercial and defense wastes. Since the primary purpose of this study was to develop a quantitative and generally applicable definition of HLW, the impacts analysis focused on the resulting waste classifications that would apply to commercial spent fuel and reprocessing wastes and to defense wastes that have been called HLW because of their source as waste from fuel reprocessing. Further, the impacts analysis for defense wastes focused on sludge-supernate waste encapsulated in borosilicate glass from the Savannah River Plant, since this waste form is appropriate for disposal. This Appendix presents the data on radionuclide concentrations in the selected commercial and defense wastes that were discussed in Sections 5.1 and 5.2 and compares the concentrations with the different boundaries in the proposed waste classification system.

The data on radionuclide concentrations in existing wastes and the relationship of these concentrations to the proposed waste classification system are presented in tabular form. Each table for a particular type of waste lists reported radionuclide concentrations and a comparison of these concentrations with those that correspond to the Highly Radioactive and Permanent Isolation boundaries, as given in Table 1 in Section 4.2 and Table 2 in Section 4.3, respectively. This comparison involves a calculation of the ratio of reported radionuclide concentrations to the corresponding values for each boundary. According to the sum-of-fractions rule, the determination of whether a particular type of waste is "highly radioactive" or "requires permanent isolation" then is obtained by summing these ratios over all radionuclides and comparing with unity. Thus, as summarized in Section 4.4, a waste is classified as HLW if the sum-of-fractions exceeds unity for the Highly Radioactive and the Permanent Isolation boundary.

Each table also contains a comparison of reported radionuclide concentrations with those that correspond to the example GCD-Permanent Isolation boundary, as calculated in Section C.1 of Appendix C and listed in Table C-1. A sum-of-fractions less than unity indicates that the waste could be a candidate for GCD via intermediate-depth burial, whereas a value greater than unity indicates that a deep geologic repository or equivalent may be required for protection of public health and safety. However, as discussed in Section 4.6 and in Section C.1.3 of Appendix C, comparisons of radionuclide concentrations with the sum-of-fractions for

the example GCD-Permanent Isolation boundary do not yet provide a firm basis for decisions on appropriate disposal technologies. There are large uncertainties in the calculation of the GCD-Permanent Isolation boundary due to uncertainties in the models and parameter values for estimating annual dose to an inadvertent intruder at the disposal site, the site-specific nature of the dose analysis, the absence of an appropriate regulatory framework for GCD, and the consideration of only a single technology for GCD.

E.1 Data on Commercial Spent Fuel and Reprocessing Wastes

Tables E-1 through E-4 present selected data on concentrations of radionuclides in 10-year old commercial spent fuel, liquid reprocessing wastes, and reprocessing wastes that have been solidified in borosilicate glass.[1,2] In comparing these data with the concentrations that correspond to the Highly Radioactive, Permanent Isolation, and GCD-Permanent Isolation boundaries, results for a particular radionuclide are given only if the reported concentration is at least 0.1% of the corresponding boundary concentration.

The radionuclide concentrations for spent fuel reported by the NRC[1] in Table E-1 generally are about a factor of 3 greater than those reported by the Waste Isolation Systems Panel[2] in Table E-2. However, the NRC notes that their data do not take into account the diluting effects of cladding, hardware, and void spaces between fuel pins and, thus, overestimate expected radionuclide concentrations in a waste package containing spent fuel. Considerable differences also are observed between the data for reprocessing wastes in Tables E-3 and E-4, but the magnitude of the difference depends on the radionuclide. These differences undoubtedly result in part from the different waste forms assumed in the two sets of data; i.e., the data compiled by the NRC apply to liquid wastes that are not in a form appropriate for disposal, whereas the data compiled by the Waste Isolation Systems Panel apply to solidified wastes in the expected form for disposal.

Each of the wastes characterized in Tables E-1 through E-4 clearly is highly radioactive and requires permanent isolation and, thus, would classified as HLW according to the waste classification system proposed in this report. The comparison of radionuclide concentrations with the example GCD-Permanent Isolation boundary also suggests that none of these wastes are likely to be suitable candidates for GCD and, thus, would require disposal in deep geologic repositories or equivalent.

Table E-1. Comparison of radionuclide concentrations in commercial spent fuel with boundary concentrations in proposed waste classification system

Nuclide	Concentration (Ci/m^3)[a]	Ratio to boundary concentration		
		Highly radioactive[b]	Permanent isolation[c]	GCD[d]
Sr-90	5E5	7E1	7E1	3E-1
Tc-99	1E2		3E1	1E1
Sn-126	1E1		1E3	5E1
I-129	3E-1		4	3E-2
Cs-135	3		4E-3	2E-2
Cs-137	8E5	2E2	2E2	1E1
Sm-151	1E4	3E-2		
Np-237	3		8E1	8E1
Pu-238	2E4	1E1	3E3	5E1
Pu-239	3E3	2	3E4	4E2
Pu-240	5E3	3	5E4	6E2
Pu-241	7E5	4E-1	1E5	4E4
Am-241	2E4	1E1	2E5	3E4
Am-243	1E2	1E-1	1E3	3E2
Cm-244	9E3	9	2E2	3
Sum		3E2	4E5	7E4

[a]Values for 10-year old spent fuel from Table 1 of ref. 1.

[b]Radionuclide concentrations corresponding to Highly Radioactive boundary are given in Table 1 in Section 4.2.

[c]Radionuclide concentrations corresponding to Permanent Isolation boundary are given in Table 2 in Section 4.3.

[d]Radionuclide concentrations corresponding to GCD-Permanent Isolation boundary are given in Table C-1 in Appendix C.

Table E-2. Comparison of radionuclide concentrations in commercial spent fuel from pressurized-water reactors with boundary concentrations in proposed waste classification system

Nuclide	Concentration (Ci/m^3)[a]	Ratio to boundary concentration		
		Highly radioactive[b]	Permanent isolation[c]	GCD[d]
C-14	4		5E-1	4E-1
Sr-90	2E5	3E1	3E1	1E-1
Tc-99	3E1		1E1	3
Sn-126	2		2E2	1E1
I-129	8E-2		1	9E-3
Cs-135	9E-1		1E-3	5E-3
Cs-137	2E5	4E1	4E1	3
U-234	3		6	2E-1
U-238	8E-1		2	
Np-237	8E-1		2E1	2E1
Pu-238	5E3	3	7E2	1E1
Pu-239	8E2	4E-1	8E3	1E2
Pu-240	1E3	5E-1	1E4	1E2
Pu-241	2E5	1E-1	4E4	1E4
Pu-242	5		5E1	6E-1
Am-241	4E3	2	4E4	5E3
Am-243	4E1	4E-2	6E2	1E2
Sum		8E1	1E5	2E4

[a]Values for 10-year old spent-fuel assemblies from Table 4-4 of ref. 2.

[b]Radionuclide concentrations corresponding to Highly Radioactive boundary are given in Table 1 in Section 4.2.

[c]Radionuclide concentrations corresponding to Permanent Isolation boundary are given in Table 2 in Section 4.3.

[d]Radionuclide concentrations corresponding to GCD-Permanent Isolation boundary are given in Table C-1 in Appendix C.

Table E-3. Comparison of radionuclide concentrations in commercial liquid reprocessing waste with boundary concentrations in proposed waste classification system

Nuclide	Concentration (Ci/m^3)[a]	Ratio to boundary concentration		
		Highly radioactive[b]	Permanent isolation[c]	GCD[d]
Sr-90	9E4	1E1	1E1	5E-2
Tc-99	2E1		7	2
Sn-126	2		2E2	1E1
I-129	3E-4		4E-3	
Cs-135	5E-1			3E-3
Cs-137	1E5	2E1	2E1	2
Sm-151	2E3	5E-3		
Np-237	8E-1		2E1	2E1
Pu-238	5E1	3E-2	7	1E-1
Pu-239	2	1E-3	2E1	3E-1
Pu-240	6	3E-3	6E1	8E-1
Pu-241	6E2	3E-4	1E2	3E1
Am-241	6E2	3E-1	6E3	8E2
Am-243	2E1	2E-2	3E2	7E1
Cm-244	1E3	1	3E1	3E-1
Sum		3E1	7E3	9E2

[a]Values for 10-year old reprocessing wastes from Table 1 of ref. 1.

[b]Radionuclide concentrations corresponding to Highly Radioactive boundary are given in Table 1 in Section 4.2.

[c]Radionuclide concentrations corresponding to Permanent Isolation boundary are given in Table 2 in Section 4.3.

[d]Radionuclide concentrations corresponding to GCD-Permanent Isolation boundary are given in Table C-1 in Appendix C.

Table E-4. Comparison of radionuclide concentrations in commercial reprocessing waste in borosilicate glass with boundary concentrations in proposed waste classification system

Nuclide	Concentration (Ci/m^3)[a]	Ratio to boundary concentration		
		Highly radioactive[b]	Permanent isolation[c]	GCD[d]
C-14	2E-2		3E-3	2E-3
Sr-90	6E5	9E1	9E1	3E-1
Tc-99	1E2		3E1	1E1
Sn-126	8		8E2	4E1
I-129	3E-4		4E-3	
Cs-135	3		4E-3	2E-2
Cs-137	8E5	2E2	2E2	1E1
U-234	9E-2		2E-1	5E-3
U-238	2E-2		4E-2	
Np-237	3		8E1	8E1
Pu-238	1E3	5E-1	1E2	3
Pu-239	2E1	1E-2	2E2	3
Pu-240	4E1	2E-2	4E2	5
Pu-241	4E3	2E-3	8E2	2E2
Pu-242	9E-2		9E-1	1E-2
Am-241	2E3	1	2E4	3E3
Am-243	2E2	2E-1	3E3	7E2
Sum		3E2	3E4	4E3

[a]Values for 10-year old reprocessing waste from Table 4-6 of ref. 2.

[b]Radionuclide concentrations corresponding to Highly Radioactive boundary are given in Table 1 in Section 4.2.

[c]Radionuclide concentrations corresponding to Permanent Isolation boundary are given in Table 2 in Section 4.3.

[d]Radionuclide concentrations corresponding to GCD-Permanent Isolation boundary are given in Table C-1 in Appendix C.

E.2 Data on Defense Reprocessing Wastes in Borosilicate Glass

Defense reprocessing wastes are being prepared at the Savannah River Plant in the form of borosilicate glass, which is the intended form for disposal. Table E-5 presents data on concentrations of radionuclides in one form of Savannah River waste, i.e., the sludge-supernate glass waste.[3] A comparison of the data in this table with the data for commercial spent fuel and reprocessing wastes in Tables E-1 through E-4 shows that the defense waste generally contains lower concentrations of fission products and TRU radionuclides, which is the expected result due to the lower fuel burnups involved with the defense waste. Nonetheless, the radionuclide concentrations in this particular form of defense waste exceed the Highly Radioactive and Permanent Isolation boundaries by substantial amounts and, thus, would be classified as HLW according to the proposed waste classification system. Furthermore, the radionuclide concentrations also exceed the example GCD-Permanent Isolation boundary by a large factor, which suggests that this waste also would require disposal in deep geologic repositories or equivalent.

Table E-5. Comparison of radionuclide concentrations in sludge-supernate defense waste in borosilicate glass from Savannah River Plant with boundary concentrations in proposed waste classification system

Nuclide	Concentration (Ci/m^3)[a]	Ratio to boundary concentration		
		Highly radioactive[b]	Permanent isolation[c]	GCD[d]
Ni-59	3		2E-1	2E-3
Ni-63	4E2		6E-1	1E-2
Sr-90	7E4	1E1	1E1	4E-2
Nb-94	2E-3		1E-1	7E-3
Tc-99	3		1	3E-1
Sn-126	3E-1		3E1	2
Cs-137	6E4	1E1	1E1	1
Sm-151	4E2	1E-3		
U-232	2E-1	1E-3	4	7E-3
U-234	8E-1		2	4E-2
U-235	3E-3		8E-3	
U-236	6E-2		1E-1	3E-3
U-238	2E-2		4E-2	
Np-237	2E-2		5E-1	5E-1
Pu-238	2E3	1	3E2	5
Pu-239	2E1	1E-2	2E2	3
Pu-240	1E1	5E-3	1E2	1
Pu-241	2E3	1E-3	4E2	1E2
Pu-242	1E-2		1E-1	1E-3
Am-241	2E1	1E-2	2E2	3E1
Am-243	1E-2		1E-1	3E-2
Cm-244	3E-1		8E-3	
Sum		2E1	1E3	1E2

[a]Values from Table 11 of ref. 3.

[b]Radionuclide concentrations corresponding to Highly Radioactive boundary are given in Table 1 in Section 4.2.

[c]Radionuclide concentrations corresponding to Permanent Isolation boundary are given in Table 2 in Section 4.3.

[d]Radionuclide concentrations corresponding to GCD-Permanent Isolation boundary are given in Table C-1 in Appendix C.

References for Appendix E

1. D. J. Fehringer, *An Evaluation of Radionuclide Concentrations in High-Level Radioactive Wastes*, NUREG-0946, U.S. Nuclear Regulatory Commission (1985).

2. Waste Isolation Systems Panel, *A Study of the Isolation System for Geologic Disposal of Radioactive Wastes*, National Academy Press, Washington, DC (1983).

3. R. G. Baxter, *Description of Defense Waste Processing Facility Reference Waste Form and Canister*, DP-1606, Rev. 1, Savannah River Plant (1983).

APPENDIX F

DESCRIPTION OF TECHNOLOGIES FOR GREATER CONFINEMENT DISPOSAL

A number of alternatives, ranging from planned but undeveloped concepts to demonstrated practices, currently are being considered as technologies for greater confinement disposal (GCD). This Appendix presents a summary description of various GCD technologies and of the health-risk assessments that have been performed for GCD.

A number of publications have discussed proposed, planned, or operating technologies for GCD.[1-6] These sources indicate that GCD technologies may be grouped into six categories: (1) augered shafts, (2) deep trenches, (3) engineered structures, (4) hydrofracture, (5) improved waste forms, and (6) high-integrity containers.

The NRC has provided descriptions of general design concepts for several alternative disposal methods[6] to assist in defining the range of design characteristics that are considered to be within the framework of existing regulatory requirements in 10 CFR Part 61 for near-surface land disposal.[7,8] Descriptions are given for below-ground vaults, above-ground vaults, earth-mounded concrete bunkers, and shaft disposal. Each of these disposal alternatives is included in one of the six categories listed above.

F.1 Description of GCD Technologies

This section presents a general description of each of the six categories of GCD technologies listed above. This information has been summarized from ref. 2.

F.1.1 *Augered Shafts (Boreholes)*

An augered shaft is a hole bored in the earth which has a large ratio of length to diameter and is of sufficient depth that the waste is highly unlikely to be accessed by plant roots, animals, and human intruders. Although the term "augered shaft" reflects the type of equipment that normally is used in making the excavation, the term applies to any hole of this general description that is constructed by any method. The concept is illustrated by two demonstrations that are currently in progress in the U.S., both of which have been developed to the point where wastes are being emplaced.

The type of shaft used at the Savannah River Plant[9] has a depth of 9 m and a diameter of 2.7 m. The waste layer is 6 m in thickness, and wastes are emplaced in a fiberglass liner of volume 22 m^3. The shaft is backfilled with soil and capped with clay. The fiberglass liner, which is fixed into cement at the bottom of the shaft, could be considered a waste container as well as a liner.

The type of shaft used at the Nevada Test Site[10] has a depth of 37 m, a diameter of 3 m, and a waste layer 12 m in thickness. The disposal volume thus is about 90 m^3. The shaft has no liner and is backfilled with soil.

F.1.2 *Deep Trenches*

The concept of a deep trench described here was suggested in an early study of alternative methods for disposal of LLW.[11] The design differs from the ordinary trench for shallow-land burial mainly in having twice the depth. Thus, the bottom of the trench was about 16 m in depth and would have a waste layer about 7 m in thickness.

A concern regarding deep trenches is the stability of the walls during the emplacement period. To keep the walls from crumbling, they must either be shored or have a gentle slope equal to or less than the maximum safe slope determined from a slope-stability analysis of the soil. If a gentle slope is used, then a large area is required for the open trench. The unusually large width of a deep, unshored trench may impose special requirements on equipment and procedures if wastes are to be emplaced from the edges using cranes.

The deep trench discussed in ref. 11 employs a floor liner that is capable of ion exchange to retard the migration of radionuclides. Design features include a floor with small end-to-end and side-to-side slopes, a layer of sand or gravel for drainage, and a French drain along the lower side to conduct any seepage of water to a sump. If a French drain were used, then pipes standing upright in the drain might permit monitoring after facility closure. The wastes would be covered with layers of clay and topsoil of total thickness about 9 m. The outermost layer of soil would be covered with vegetation. No special intruder barriers are considered necessary because of the depth of the trench.

Another concept of a deep disposal unit involves a circular pit rather than a trench.[12] The pit would have a depth of 34 m, a bottom diameter of 410 m, and a top diameter of 480 m. This concept has not been developed beyond a preliminary suggestion.

F.1.3 *Engineered Structures*

An engineered structure is a disposal unit in which the most important barrier for prevention of human intrusion and leakage of radionuclides from the facility is a chamber with a volume of several hundred to several thousand cubic meters that is constructed with a synthetic material, usually concrete. The most important performance requirements for such a structure are long-term stability and low permeability. The latter is a requirement that concrete structures cannot be expected to fulfill, because they normally develop cracks over time. Thus, the design of engineered structures usually specifies that concrete should be coated with asphalt to reduce its permeability. Drainage is an important element of design to preserve waste containers and to provide stability for the engineered structure, and most designs include both external and internal drainage systems.

Because of the variety of designs, description of a reference concept for an engineered structure is not particularly useful. Instead, we describe several specific examples including the Canadian concrete-walled trench, the French tumulus, the concrete-shored trench at the Savannah River Plant, the concrete-walled trench discussed by the NRC, and a concrete chamber proposed by the University of Arizona.

The Canadian concept[3] consists of a rectangular trench with walls of reinforced concrete. The floor is a layer of gravel over a layer of a bentonite and sand mixture. The emplaced wastes are capped with a layer of compacted clay, then an arched concrete cover, and finally a layer of soil.

The French tumulus[13] is a structure that is situated partly above and partly below the surrounding land surface. The subsurface portion is a rectangular, compartmented structure of poured concrete floors and walls. After being filled with waste, the compartments are backfilled with grout and covered with a layer of asphalt. The asphalt surface is at the same level as the surrounding land, and serves as the floor for an above-grade structure with walls of stacked concrete cylinders. The waste-filled above-grade portion is backfilled with gravel and capped with a layer of clay and finally a layer of soil.

The engineered structure at the Savannah River Plant[9] is formed by excavating a trench 3 m in depth with boundaries 15-30 m by 60-150 m. Shoring walls of concrete with a thickness of 0.5-1.5 m then are inserted into the ground, outlining the trench, in order to support the surrounding earth while a second trench is excavated within the first to an additional depth of 6 m. Wastes are emplaced in the deeper trench onto compacted earth or a concrete floor, which is sloped to a sump for drainage collection.

The concrete-walled trench discussed by the NRC[12] is formed by concrete walls set onto a concrete slab lying at about the same depth as the bottom of a shallow trench (8 m). After filling the unit to a depth of 7 m, it is capped with a layer of concrete and then a layer of soil. The void spaces in the wastes are filled with soil or grout.

The Arizona concept[14] is a reinforced-concrete shell with an arched roof that is set on the top edges of the walls after the wastes are emplaced. This structure would be placed entirely underground in arid regions or on the ground surface in humid regions. For placement on the ground surface, the structure would be mounded with a layer of soil.

F.1.4 *Hydrofracture*

In the hydrofracture technique, wastes are mixed with cement and the resulting grout slurry is injected into approximately horizontal fractures previously induced into rocks at depths far below the ground surface. The cement solidifies as a thin sheet that is fixed in the host rock. Progressive grout injections are made at several levels at the same wellhead, resulting in a stack of grout sheets that are separated by vertical distances of about 3 m. Each grout sheet is typically 1 cm thick and several hundred meters wide.

The hydrofracture technique has been practiced at Oak Ridge National Laboratory for several years. Although the process was developed to dispose of a special type of waste at a specific site, it has been suggested that several types of waste could be disposed of by hydrofracture at other appropriate sites.[15]

F.1.5 *Improved Waste Forms*

Several processes for incorporating LLW into matrices of other materials in order to produce consolidated waste forms have been used for many years. Some of these processes provide volume reduction, while others result in a disadvantageous volume increase. The primary reasons for converting wastes to consolidated forms include (1) reduction of the dispersibility of wastes in case of accidents during handling and transport and (2) reduction of the leachability of radionuclides in contact with water. Because no single consolidation process has been entirely satisfactory, the development of improved techniques is ongoing.

The most commonly used solidification agents are cement, and its many modifications, and bitumen. Other solification agents that have been investigated include polyethylene, polyester resins, epoxy resin,

synthetic minerals, glass, polymer-modified gypsum cement (Envirostone), and polymer-impregnated concrete.

F.1.6 *High-Integrity Containers*

A high-integrity container is any waste container that is capable of providing structural stability and containment of radionuclides over long time periods. The primary purpose of requiring container stability is to preserve the stability of the disposal unit by preventing settling and subsidence. General use of high-integrity containers has been suggested for wastes containing relatively high concentrations of radionuclides and radionuclides with relatively long half-lives (i.e., greater than 5 years).

Efforts to develop high-integrity containers have involved the formulation of performance criteria and the fabrication and testing of models by industrial corporations. Organizations that have defined criteria on acceptable performance include the NRC,[16] the State of South Carolina,[17] and EG&G Idaho, Inc.[18] The U.S. Department of Transportation (DOT) is involved indirectly in the definition of acceptable high-integrity containers, because some of the criteria developed by the other organizations specify compliance with selected DOT regulations on packaging. It is not likely that any of the containers that have been commonly used for transportation and disposal of LLW would meet all of the proposed criteria for high-integrity containers. The construction materials that have been proposed for most container designs are either concrete or polyethylene, because of the desirability of using inert materials.

The purpose of using a high-integrity container is that the container, rather than the surrounding geologic medium, should provide isolation of the waste from the environment. Thus, it should be possible to place appropriately designed containers in a conventional shallow trench. This assumption is expected to be clarified in rules for acceptance, handling, and emplacement developed by the NRC for commercial wastes and by individual facilities for DOE wastes.

F.2 Health-Risk Assessments of GCD Technologies

Assessments of potential health risks to the public from the use of particular GCD technologies at specific sites generally have not been performed. The EPA has performed generic health-risk assessments for sanitary landfills, shallow-land burial, and improved shallow-land

disposal, as well as some analyses on hydrofracture.[19] Other generic assessments of the impacts of GCD technologies are presented in ref. 1. In the latter study, estimated doses for various GCD technologies were accompanied with the cautionary statement that the associated uncertainties are very large and that individual case studies, rather than a generic treatment, are needed.

Thus, while it remains a reasonable presumption that the use of various GCD technologies can result in reductions in doses to the public compared with the doses from conventional near-surface land disposal, the extent of these reductions is not well established. We support the recommendation that health-risk assessments of particular technologies at specific sites are needed.[1]

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