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TECHNICAL ASSISTANCE TO THE
U.S. ENVIRONMENTAL PROTECTION AGENCY
ON 40 CFR PART 191

Prepared by:

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CHAPTER 1

INTRODUCTION

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CHAPTER 1

INTRODUCTION

Over the past several years, the U.S. Environmental Protection Agency (EPA) has been working on a revision to its environmental standard for management and disposal of spent nuclear fuel, high-level and transuranic radioactive wastes (40 CFR Part 191) in response to the 1987 remand by the U.S. Court of Appeals. In a December 20, 1991, management meeting between the U.S. Department of Energy (DOE) and the EPA, the DOE volunteered to provide technical assistance to the EPA in developing supporting technical justification for revising sections of 40 CFR Part 191. In a January 7, 1992 letter from M. Oge (EPA) to R. Berube (DOE), the EPA accepted the offer and requested technical assistance in several specific areas. Those areas were: human intrusion, the three-bucket approach, multimode release limits, collective dose, TRU waste equivalence unit, uncertainty propagation, and Carbon-14. The DOE envisioned that this technical assistance would consist of a six-month effort of comprehensive technical analyses and computer modeling exercises that could provide the technical foundation for any proposed revision. However, due to time constraints resulting from the EPA 40 CFR Part 191 repromulgation schedule, the technical studies were compressed to a program having a duration of only approximately six weeks.

In order to guide its contractors in performing the technical studies, the DOE developed task assignments containing statements of work for each area. These task assignments and responsible organizations are:

- **Task 1: Human Intrusion**
Responsible Organization: Sandia National Laboratory

Develop the specifics of an approach that separates human intrusion from the complementary cumulative distribution function (CCDF) and considers it in a qualitative fashion. Information developed from this task can be found in Chapter 3 of this document.

- **Task 2: Three-Bucket Approach**
Responsible Organization: Sandia National Laboratory

Analyze the NRC's suggested "three-bucket approach" (and EPA's modification of NRC's approach), evaluate its usefulness in alleviating problems with the probabilistic analysis, and determine the implementability of the approach. Information developed from this task can be found in Chapter 4 of this document.

- **Task 3: Multimode Release Limits**
Responsible Organization: Sandia National Laboratory

Develop the concept of a multi-column release limit table to cover the possible release modes for generic repositories, including methods for computing limits for each mode and methods for implementation. Information developed from this task can be found in Chapter 5 of this document.

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- **Task 4: Collective Dose**
Responsible Organization: Sandia National Laboratory

Evaluate the feasibility and develop the concept of a collective dose option to the release limits approach, including the implementability of such an option. Information developed from this task can be found in Chapter 6 of this document.

- **Task 5/6: TRU Waste Equivalence Unit**
Responsible Organization: Sandia National Laboratory

Develop a fundamental criteria for disposal of TRU waste and a waste unit that is equivalent to HLW, based on a comparable acceptable collective risk. (This task was originally started as two tasks and later combined because of similarities in scope.) Information developed from this task can be found in Chapter 7 of this document. (Information not available at this time).

- **Task 7: Uncertainty Propagation**
Responsible Organization: CRWMS M&O (TESS)

Conduct the necessary analyses and evaluations to provide a defensible estimate of the uncertainty in repository performance predictions as a function of time, for periods between 1,000 and 100,000 years. Information developed from this task can be found in Chapter 8 of this document.

- **Task 8: Carbon-14**
Responsible Organization: CRWMS TMSS (SAIC)

Develop further information concerning Carbon-14 releases from unsaturated media, including costs of compliance with the present standard, and develop an alternative requirement for regulating such releases. Information developed from this task can be found in Chapter 9 of this document.

For each of these tasks, information was developed to support a possible revision of the standard, with the goal that the overall level of public protection be similar to that provided by the 1985 standard. Four types of material were developed for each task and are presented in this document:

1. Statement of the Problem
2. Recommended Approach
3. Supplementary Information
4. Technical Support Documentation

The Statement of the Problem identifies the concern about the standard that is being addressed in the sections that follow. The Recommended Approach provides example regulatory language to illustrate how the proposed revision might be incorporated into the standard. The Supplementary Information provides a general discussion of the technical and regulatory justification for the proposed revision in a format that is similar to the information that would be required in the Federal Register supplementary information text for the repromulgated standard. The Technical Support Documentation provides the details of the technical analysis

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that support the proposed revision, this type of information would be needed for the Background Information Document (BID) that the EPA would prepare as part of the repromulgation process.

Since the DOE intends that the recommendations in this document be considered as a whole, the suggested revisions to the standard resulting from each task have been consolidated, and are presented in Chapter 2.

The information provided for each individual task within this document represents approximately six weeks of concentrated effort on the part of the DOE and its various contractors. As discussed earlier, the original scope of these studies provided for approximately six months of technical analysis and computer modeling. However, in order to support the early May deadline requested by the EPA, it was necessary to provide preliminary or incomplete information, because several important analyses have not been completed. The Recommended Approach, Supplementary Information, and Technical Support Documentation for Task 5/6 (TRU Waste Equivalence Unit) will be completed by June 1992. The technical analyses being conducted in support of Task 2 (Three-Bucket Approach) and Task 7 (Uncertainty Propagation) are scheduled for completion in August 1992. These analyses are described in Chapters 4 and 8 of this document. When this material becomes available, it will be provided to the EPA.

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CHAPTER 2

SUMMARY OF RECOMMENDED CHANGES

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CHAPTER 2

SUMMARY OF RECOMMENDED CHANGES

2.1 OVERVIEW

Chapters 3 through 9 of this document contain recommended changes to EPA's environmental radiation protection standards for the management and disposal of spent nuclear fuel, high-level, and transuranic wastes (40 CFR Part 191). Each chapter presents and discusses a separate set of changes in order to describe each recommendation clearly and to allow the EPA to choose from the recommendations those that it wishes to incorporate in the revised standards. The DOE intends, however, for the recommendations be considered as a whole. In formulating each recommendation, the DOE has considered its effect on the other recommendations. Furthermore, the intentions of the DOE can be understood fully only if the recommendations are thought of as constituting a single overall recommendation. The recommendations contained in each of the chapters that follow are summarized below:

- Chapter 3 describes a formulation of the containment requirements that eliminates some difficulties with the inclusion of human-initiated events and processes in the demonstration of compliance. The recommendation allows for such processes and events to be separated from the CCDF and treated qualitatively. The DOE intends that this formulation be a part of each option for demonstrating compliance with the containment requirements. These options, three in all, are discussed in item 3 below.
- Chapter 4 describes the DOE objections to the proposed "three-bucket approach" to demonstrating compliance with the containment requirements. The DOE recommends that this approach not be incorporated into the next revision of the standard.
- Chapters 5 and 6 describe additional options for the containment requirements. These options are: (a) a multimode option that includes limits for all release modes to be considered in the containment requirements (land, well, river, and ocean), and (b) a collective dose option that would apply to population doses resulting from the same four release modes. The DOE recommends that both of these options appear in the standard in addition to the current requirement, after it has been modified according to the recommendation for human intrusion in item 1 above. The DOE recommends that the standard allow the DOE to choose any one of these three options for the demonstration of compliance. Furthermore, the DOE recommends that the standard also allow the DOE to choose the use of a combination of two of these options in generating the CCDF: the DOE may elect to use a combination of the original (but reworded) release limit option and the collective dose option (described in Chapter 6), or a combination of the multimode release limit option (described in Chapter 5) and the collective dose option.

In addition, it is recommended that none of these options (or combination of options) be used to regulate gaseous radionuclide releases. In order to be consistent with other EPA regulations that address similar releases from other facilities, these gaseous releases should be regulated as part of the individual protection requirements in 40 CFR Part 191, as discussed in item 6 below.

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Implementation of the multimode release limit or collective dose options discussed in Chapters 5 and 6 may result in the need to obtain more information regarding site characteristics. However, even though this may be viewed as a disadvantage, these options have the advantage of allowing site-specific considerations to be taken into account while at the same time retaining the generic nature of the standard. It is also important to note that each of the three resulting options for the containment requirements has its advantages and disadvantages. For that reason, the revised standard should not require the use of any one of the options by itself. Table 2-1 provides a comparison of the various containment options being recommended, as well as an example evaluation of the effects of just using one of the options (e.g., collective dose).

- Chapter 7 (not available at this time) describes the DOE recommendation of a new equivalence unit for TRU waste, which can be used as the fundamental criterion for disposal of TRU waste. This is based upon the same acceptable level of risk that was used for spent fuel and HLW, and upon the same concept of a reference-size repository. The DOE intends that this recommendation be a part of all options for demonstrating compliance.
- Chapter 8 discusses the propagation of uncertainty as it relates to demonstration of compliance for different time periods. These discussions support the DOE recommendation that the time period for individual and groundwater protection be limited to 1,000 years after disposal, as it was in the 1985 standard. Furthermore, the discussions in Chapter 8 support the recommendation that assessments of cumulative radionuclide releases or collective doses should not be required for time periods greater than 10,000 years or, in the case of individual doses, time periods greater than 1,000 years.
- Chapter 9 describes the DOE recommendation for dealing with releases of radionuclides in gaseous form, with special focus on Carbon-14. In order to be consistent with the manner in which the EPA regulates similar releases from other facilities, the DOE recommends that gaseous releases from a repository be governed by the limits established in 40 CFR Part 191 for individual protection, with some modifications. This recommendation was developed in conjunction with the recommendations for containment, individual protection, and groundwater protection. The DOE intends that this recommendation be considered in conjunction with any revision of the requirements that govern those three topics.

Each of the chapters discussed above contains a recommended approach that suggests how the EPA standard could be revised, consistent with the DOE intentions embodied in the recommendations. As mentioned above, the DOE intends that these recommendations be considered as a whole, since they are interrelated. To assist the EPA in this, the rest of this chapter presents a consolidation of all the recommended changes. For the most part, the recommended changes refer to the 1985 standard. However, there are several instances where reference is made to some provisions being considered by the EPA that are contained in Draft Federal Register Notice, dated 2/3/92.

Table 2-1. Comparison of Present Single Generic Release Limits and Alternatives

Characteristic	Present Single Generic Release Limits	Alternative		
		Multimode Generic Release Limits	Collective Dose Standard (without release limit option)	Collective Dose Option (with release limit option)
Uniform Biosphere	Yes	Yes	Only if standard biosphere specified	Only if standard biosphere specified
Uses Appropriate Release Modes	No	Yes	Yes	Yes
Uniform Assessment of All Repositories and Pathways	No	Yes	Yes	Yes
All Repository Components in Evaluations	No	Yes	Yes	Yes
Inaccuracies Due to Generic Derivations	Major	Minor	None	None
Corrections for Repository Locations	No	Yes	Yes	Yes
Traceable to Fundamental Criteria	No	Yes	Yes	Yes
Site Specific	No, but risk uniform	No, with nearly uniform risk	No	No
Additional Site Characterization	No	Moderate	Extensive	None to Extensive
Compatible with 191 Format	Yes	Yes	Yes	Yes
Philosophy Change	No	No	Extensive	Moderate
PA Change	No	Moderate	Extensive	None to Extensive
Status	Complete	Minor derivations	Minor derivations	Minor derivations

2.2 RECOMMENDED CHANGES

The changes recommended below reflect an outline for Subpart B of 40 CFR Part 191 that is similar to the 1985 standard, with some modification of the appendices. Other outline changes being considered, as reflected in the Draft Federal Register Notice (2/3/92), are not addressed here. To assist the reader in understanding the recommended changes, the modified outline is shown below:

Subpart B - Environmental Standards for Disposal

- 191.11 Applicability
- 191.12 Definitions.
- 191.13 Containment requirements.
- 191.14 Assurance requirements.
- 191.15 Individual protection requirements.
- 191.16 Groundwater protection requirements.
- 191.17 Alternative provisions for disposal.
- 191.18 Effective date.
- Appendix A Table for Subpart B
- Appendix B Alternative Tables for Subpart B
- Appendix C Calculation of Annual Committed Effective Dose
- Appendix D Guidance for Implementation of Subpart B

The following new definitions should be added to Section 191.12, Definitions:

"Point of compliance" means the location, for a given release mode, where radionuclides enter the biosphere. At this location, cumulative releases over 10,000 years are calculated for comparison to the multimode release limits table.

"Release mode" means one of four potential ways to be considered in the containment requirements in which radionuclides are transported from the lithosphere to the biosphere, resulting in exposure to humans. The release modes are: land (contaminated solids deposited on the land surface, such as volcanic materials); well (contaminated groundwater pumped to the land surface); river (all fresh surface waters); and ocean.

"Biosphere" means the zone of the Earth extending from (and including) the surface into the surrounding atmosphere.

Section 191.13, Containment requirements, should be revised to read as follows:

191.13 Containment requirements.

The Department may invoke either subsection (a) or (b) of this section.

(a) Disposal systems for radioactive waste shall be designed to provide a reasonable expectation, based upon performance assessments, that the cumulative releases of solid and liquid radionuclides to the accessible environment (for Table 1 in Appendix A), or the cumulative releases of solid and liquid radionuclides, considering all applicable release modes, to the biosphere (for Tables 2 and 3 in Appendix B) for 10,000 years after disposal from all significant natural processes and events that may affect the disposal system shall:

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(1) Have a likelihood of less than one chance in 10 of exceeding the quantities calculated according to Table 1 (Appendix A) or Tables 2 and 3 (Appendix B); and

(2) Have a likelihood of less than one chance in 1,000 of exceeding ten times the quantities calculated according to Table 1 (Appendix A) or Tables 2 and 3 (Appendix B). The Department shall select the release limits method to be used in evaluating compliance.

(b) Disposal systems for radioactive waste shall be designed to provide a reasonable expectation, based upon performance assessments, that the collective (population) effective dose, calculated using the weighting factors in Appendix C, caused by releases of solid and liquid radionuclides to the accessible environment for 10,000 years after disposal from all significant natural processes and events that may affect the disposal system shall:

(1) Have a likelihood of less than one chance in 10 of exceeding 2.5 million person-rem (25,000 person-sieverts); and

(2.) Have a likelihood of less than one chance in 1,000 of exceeding 25 million person-rem (250,000 person-sieverts).

Dose limits are based upon a repository containing the equivalent of 100,000 MTHM of spent nuclear fuel and high-level waste or XX MCi of transuranic waste.

(c) Potential radionuclide releases to the accessible environment that are due to human actions shall be treated separately from releases due to natural events and processes; the treatment of releases shall be qualitative, including discussions of mitigating measures, and shall be based on unspeculative assumptions about future states of human civilizations. That is, the discussions should assume that drilling and mining methods, reasons for intrusion, and societal structures remain the same as they are currently.

(d) {the paragraph designated (b) in the 1985 standard} Performance assessments need not provide complete assurance that the requirements of 191.13(a) or (b) will be met. . .that compliance with 191.13(a) or (b) will be achieved.

The "three-bucket approach" alternative for the containment requirements, as proposed in Sections 191.12(x) and (y) of the draft Federal Register notice (2/3/92), should not be included in the revised standard.

Section 191.15, Individual protection requirements, should be revised to read as follows:

191.15 Individual protection requirements.

a) Disposal systems for radioactive waste shall be designed to provide a reasonable expectation that, for 1,000 years after disposal, undisturbed performance of the disposal system shall not cause the annual committed effective dose received through all potential pathways from the disposal system to any member of the public in the accessible environment to exceed 25 millirems (250 microsevents). The annual committed effective dose for gases released through the atmospheric pathway shall not exceed 10 millirems.

The time period for assessments of individual and groundwater protection should be retained at 1,000 years after disposal (as in Sections 191.15 and 191.16 of the 1985 standard), rather than 10,000 years (as proposed in Sections 191.14 and 191.23 of the Draft Federal Register Notice (2/3/92)).

The revised standard should not include requirements for projection of potential releases, collective doses, or individual doses out to 100,000 years after disposal, as proposed in Sections 191.12(c) and 191.14(b) of the draft Federal Register notice (2/3/92).

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Appendix A should remain the same as in the 1985 standard.

A new Appendix B, similar to Appendix A, should be created as follows:

Appendix B - Alternative Multimode Tables for Subpart B

TABLE 2 - CUMULATIVE RELEASE LIMITS FOR 10,000 YEARS FOR MULTIPLE RELEASE MODES (CURIES)

{See Table 2 at end of chapter}

TABLE 3 - CUMULATIVE RELEASE LIMITS FOR 10,000 YEARS FOR MULTIPLE RELEASE MODES (BEQUEREL)

{See Table 3 at end of chapter}

Application of Tables 2 and 3

Note 1: {same as in Appendix A}

Note 2: {same as in Appendix A}

Note 3: {same as in Appendix A}

Note 4: {same as in Appendix A}

Note 5: {same as in Appendix A}

Note 6: *Use of Site Adjustment Factors.* The Agency assumed, in deriving the release limits for the river and well releases in Tables 2 and 3, that the entire drainage system of all rivers (for river releases) and all aquifers (for well releases) are contaminated by the released radionuclides. Site Adjustment Factors (SAFs) should be used with Tables 2 and 3 to account for specific site locations. The following are examples of how SAFs might be developed for the surface flow system and other geologic and hydrologic components of a geologic disposal system.

Example 1--River Releases: For the river column, the release limits are calculated assuming that the entire drainage of all rivers is contaminated. For an actual site, only the downstream section of the tributary that is fed by groundwater passing through the repository is contaminated. To correct for this, a Site Adjustment Factor for the river release mode (SAF_R) is used as a multiplier to adjust the risk factors. The Reciprocal Site Adjustment Factor ($RSAF_R$), with which the release limits are multiplied, is calculated as follows:

$$RSAF_R = \frac{\sum_{i=1}^n (L_{C(i)} * F_{C(i)}) + \sum_{j=1}^n (L_{U(j)} * F_{U(j)})}{\sum_{i=1}^n (L_{C(i)} * F_{C(i)})}$$

This approximation represents the sums of the products of all tributary lengths and flow

rates divided by the equivalent sums of contaminated tributaries. "L" is the length of the river segments and "F" is the volumetric flow rate of that segment. The subscripts "C" and "U" refer to contaminated and uncontaminated segments, respectively. The release limits in Tables 2 and 3 are then multiplied by this ratio to provide a site-specific release limit for the river release mode.

Example 2--Well Releases: The derivation of the release limits for the well release mode using world average parameters assumes all groundwater from the recharge area to the locations where it enters surface waters is contaminated. For an actual site, wells up-gradient of the repository do not produce contaminated water. In addition, during the 10,000-year regulation period, the contaminated plume may not reach the discharge location, thus some uncontaminated water may also be withdrawn down-gradient from the repository.

A method for approximating the ratio of contaminated to total available water can be applied by dating the water at the repository (A₁), at the point it is expected that the radionuclides will reach in 10,000 years (A₂), and at the location where groundwater discharges to a river (A₃). With these ages, the Site Adjustment Factor for the well release mode (SAF_w) may then be calculated and used as a multiplier to adjust the risk factors. Calculation of the Reciprocal Site Adjustment Factor (RSAF_w) is done by dividing the age of the water at the river by the difference in the ages of the water at the repository and at the farthest point of migration in 10,000 years, or:

$$RSAF_w = \frac{A_3}{A_2 - A_1}$$

However, if it is found that the contaminated plume will reach a river within 10,000 years the formula becomes:

$$RSAF_w = \frac{A_3}{A_3 - A_1}$$

Release limits in Tables 2 and 3 are then multiplied by one of these ratios (the RSAF_{w,s}) to provide a site specific release limit for the well release mode. The use of SAFs and the parameters to be considered in calculating SAFs shall be determined by the Department.

Note 7: Points of Compliance. In calculating cumulative releases over 10,000 years, the points of compliance are as follows:

Release Mode

Point of Compliance

Land

Location where radioactive material is brought directly to the land surface.

Well

Any wellhead outside the controlled area from which groundwater containing radionuclides is withdrawn for purposes such as irrigation or supplying drinking water.

River

Location(s) of existing discharge of groundwater containing radionuclides to a river.

Ocean

Location where a river-water or groundwater containing radionuclides discharges to an ocean.

Note 8: Uses of Release Limits to Determine Compliance with 191.13. Once release limits for a particular disposal system have been determined in accordance with notes 1 through 7, these release limits shall be used to determine compliance with the requirements of 191.13 as follows. In cases where a mixture of radionuclides is projected to be released to the accessible environment, the limiting values shall be determined as follows: For each radionuclide in the mixture, determine the ratio between the cumulative release quantity projected over 10,000 years and the limit for that radionuclide for each applicable release mode as determined from Tables 2 or 3 and Notes 1 through 7. The sum of such ratios for all the radionuclides in the mixture may not exceed one with regard to 191.13(a)(1) and may not exceed ten with regard to 191.13(a)(2).

For example, if all release modes (L,W,R, and O referring to land, well, river, and ocean release modes) are used in the example, if radionuclides a and b are projected to be released in amounts Q_a and Q_b , and if the applicable release limits are RL_a and RL_b , then the cumulative releases over 10,000 years shall be limited so that the following relationship exists:

$$\begin{aligned}
& Q_{L,a}/RL_{L,a} + Q_{L,b}/RL_{L,b} + \dots + Q_{W,a}/RL_{W,a} + Q_{W,b}/RL_{W,b} + \dots + \\
& Q_{R,a}/RL_{R,a} + Q_{R,b}/RL_{R,b} + \dots + Q_{O,a}/RL_{O,a} + Q_{O,b}/RL_{O,b} + \dots + \\
& Q_{O,a}/RL_{O,a} < 1.
\end{aligned}$$

A new Appendix C, Calculation of Annual Committed Effective Dose, should be created. This Appendix could contain the information that was in Appendix B of the Draft Federal Register Notice (2/3/92). However, the information in that Appendix, which is based on ICRP 60, has yet to be fully accepted by the United States. Consideration should be given to returning to the information contained in Appendix A of Working Draft 3 (4/25/91) until ICRP 60 has been accepted.

The existing Appendix B from the 1985 standard should be renamed Appendix D. The following should be inserted between the second and third sentences of the first paragraph:

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Quantitative evaluations for these predictions compare predicted releases with either Table 1 of Appendix A or Tables 2 and 3 of Appendix B. If the multimode release limits in Tables 2 and 3 of Appendix B are used, the presence or absence of the four possible release modes (land, well, river, and ocean) to be considered in the containment requirements must be determined. The fifth release mode, for atmospheric releases, is considered under the individual protection requirements. Site Adjustment Factors for the well and river release modes, to be determined by the Department, may be calculated to account for differences between the actual site-specific availability of water and the original assumption that the entire drainage system is available and contaminated.

The following paragraph in the renamed Appendix D should be revised to read as follows:

Compliance with Section 191.13. The Agency assumes that, whenever practical, the Department . . . compliance with 191.13(a) or (b) into a "complimentary cumulative distribution function" that . . . for each disposal system considered. Section 191.13 contains options for comparing results of performance assessments with release limits and dose limits. The complementary cumulative distribution function may represent both summed release fractions and summed dose fractions. It is appropriate to apply dose standards to specific events or processes for which the release limits are inappropriate. The predicted doses for each event may then be normalized relative to the dose limits set by the Agency in the same manner as predicted releases. The dose fraction then replaces the summed release fraction for that event in the complementary cumulative distribution function. The Agency assumes that . . . this single distribution meets the requirements of 191.13(a) or (b).

The following paragraph should be added to the renamed Appendix D:

Future States. Uncertainties involving things that are unknowable about the future can only be dealt with by making assumptions and recognizing that these may, or may not, correspond to a future reality. The Agency believes that speculation concerning certain future conditions should not be the focus of the compliance determination process. Therefore, it would be appropriate for assessments made under Part 191 to contain the assumption that many conditions remain the same as today's. Conditions in this category include population distributions (i.e., current population distributions should be assumed), level of knowledge and technical capability, human physiology and nutritional needs, the state of medical knowledge, societal structure and behavior, patterns of water use, and pathways through the accessible environment. The Agency would not find it appropriate to include in this category the geologic, hydrologic, and climatic conditions whose future states may be estimated by examining the geologic record. Although the Agency would not find it appropriate to assume that world populations will remain unchanged, it would be inappropriate to assume future world populations that cannot reasonably be sustained by current abilities to produce, distribute, and consume food. For this reason, future world populations in excess of 10 billion people need not be assumed in evaluations under paragraph 191.13.

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The following paragraphs in the renamed Appendix D should be revised to read as follows:

Consideration of Inadvertent Human Intrusion into Geologic Repositories. The most speculative potential disruptions of a mined geologic repository are those associated with inadvertent human intrusion. Some types of intrusion would have virtually no effect on a repository's containment of waste. On the other hand, it is possible through speculation to conceive of intrusions (involving widespread societal loss of knowledge regarding radioactive wastes) that could result in major disruptions that no reasonable repository selection or design precautions could alleviate.

Neither the Agency nor any other regulatory body has identified a reliable, defensible basis for predicting future human behavior and for estimating the probabilities of possible human actions. Therefore, the Agency does not require a quantitative treatment of human actions that affect the repository. Nevertheless, the implementing agency should consider these actions qualitatively in making its determination that there is reasonable expectation of compliance with the standard. These considerations, though fundamentally qualitative, especially in their treatment of probabilities, may refer to calculations that estimate the consequences of human actions. The Agency believes that the most productive consideration of inadvertent intrusion concerns those realistic possibilities that may be usefully mitigated by repository design, site selection, or use of passive controls (although passive institutional controls should not be assumed to completely rule out the possibility of intrusion). In making their qualitative evaluations, the implementing agencies can assume that passive institutional controls or the intruders' own exploratory procedures are adequate for the intruders to soon detect, or be warned of, the incompatibility of the area with their activities.

Frequency and Severity of Inadvertent Human Intrusion into Geologic Repositories by Exploratory Drilling. In the qualitative discussions supplied in compliance with paragraph 191.13(c), the implementing agencies need not assume intrusion scenarios more severe than inadvertent and intermittent intrusion by exploratory drilling for resources. The implementing agency need not assume any drilling for the resources that are provided by the disposal system itself. The implementing agencies should consider qualitatively the effects of each particular disposal system's site, design, and passive institutional controls in mitigating the potential effects of such inadvertent exploratory drilling. Descriptions of the likelihood of such inadvertent and intermittent drilling over 10,000 years need not assume that more than 30 boreholes per square kilometer of repository area will be drilled in that time at geologic repositories in proximity to sedimentary rock formations or that more than 3 boreholes per square kilometer will be drilled in that time at repositories in other geologic formations. Furthermore, when the discussions treat the consequences of inadvertent and intermittent drilling, the implementing agency need not assume that those consequences are more severe than (1) direct release to the land surface. . .the permeability of a carefully sealed borehole.

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Table 2

Cumulative Release Limits for 10,000 years (curies per 100,000 MTHM) for Multiple Release Modes

Release Limit (curies per 100,000 MTHM)				
Nuclide	River	Well	Ocean	Land
C-14	TBD*	TBD	TBD	TBD
Ni-59	2E+07	9E+06	TBD	1E+09
Sr-90	4E	2E+04	4E+07	3E+07
Zr-93	7E	3E+06	3E+07	4E+07
Tc-99	3E+06	1E+06	6E+08	2E+10
Sr-126	1E+04	4E+03	9E+03	7E+05
I-129	1E+04	5E+03	4E+06	3E+05
Cs-135	1E+05	6E+04	2E+07	2E+06
Cs-137	9E+04	8E+04	2E+06	5E+07
Sm-151	1E+08	4E+07	TBD	1E+10
Pb-210	8E+03	4E+03	TBD	7E+06
Ra-226	6E+03	3E+03	TBD	2E+05
Ra-228	4E+04	2E+04	TBD	6E+07
Ac-227	1E+04	6E+03	7E+03	8E+06
Th-229	3E+04	1E+04	6E+03	5E+04
Th-230	2E+03	8E+02	TBD	3E+03
Th-232	3E+03	1E+03	TBD	3E+03
Pa-231	7E+03	3E+03	2E+04	4E+04
U-233	5E+04	2E+04	1E+06	1E+06
U-234	5E+04	2E+04	TBD	2E+06
U-235	5E+04	2E+04	1E+06	1E+06
U-236	5E+04	2E+04	TBD	2E+06
U-238	5E+04	2E+04	TBD	1E+06
Np-237	1E+04	8E+03	7E+04	8E+06
Pu-238	2E+04	1E+04	TBD	3E+06
Pu-239	2E+04	8E+03	2E+04	2E+05
Pu-240	2E+04	8E+03	2E+04	2E+05
Pu-241	5E+05	2E+05	TBD	4E+08
Pu-242	2E+04	8E+03	TBD	2E+05
Am-241	2E+04	8E+03	5E+03	1E+06
Am-243	2E+04	8E+03	5E+03	4E+05
Cm-245	1E+04	4E+03	3E+03	1E+05
Cm-246	2E+04	8E+03	TBD	3E+05

*To be determined

Cumulative Release Limits for 10,000 years (TBq per 100,000 MTHM) for Multiple Release Modes

Release Limit (TBq per 100,000 MTHM)				
Nuclide	River	Well	Ocean	Land
C-14	TBD*	TBD	TBD	TBD
Ni-59	8E+05	3E+05	TBD	5E+07
Sr-90	2E+03	7E+02	2E+06	1E+06
Zr-93	2E+05	1E+05	9E+05	2E+06
Tc-99	1E+05	4E+04	2E+07	7E+03
Sr-126	4E+02	1E+02	3E+02	3E+04
I-129	5E+02	2E+02	1E+05	9E+03
Cs-135	5E+03	2E+03	6E+05	6E+04
Cs-137	3E+03	3E+03	8E+04	2E+06
Sm-151	4E+06	2E+06	TBD	6E+08
Pb-210	3E+02	1E+02	TBD	2E+05
Ra-226	2E+02	1E+02	TBD	7E+03
Ra-228	2E+03	7E+02	TBD	2E+06
Ac-227	6E+02	2E+02	2E+02	3E+05
Th-229	1E+03	4E+02	2E+02	2E+03
Th-230	7E+01	3E+01	TBD	1E+02
Th-232	1E+02	4E+01	TBD	1E+02
Pa-231	3E+02	1E+02	6E+02	2E+03
U-233	2E+03	7E+02	4E+04	5E+04
U-234	2E+03	8E+02	TBD	6E+04
U-235	2E+03	7E+02	4E+04	4E+04
U-236	2E+03	8E+02	TBD	6E+04
U-238	2E+03	7E+02	TBD	5E+04
Np-237	5E+02	3E+02	3E+03	3E+05
Pu-238	9E+02	4E+02	TBD	1E+05
Pu-239	7E+02	3E+02	6E+02	6E+03
Pu-240	8E+02	3E+02	6E+02	7E+03
Pu-241	2E+04	7E+03	TBD	1E+07
Pu-242	8E+02	3E+02	TBD	6E+03
Am-241	7E+02	3E+02	2E+02	4E+04
Am-243	6E+02	3E+02	2E+02	2E+04
Cm-245	4E+02	2E+02	1E+02	5E+03
Cm-246	7E+02	3E+02	TBD	1E+04

* To be determined

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CHAPTER 3

HUMAN INTRUSION

HUMAN INTRUSION

3.1 STATEMENT OF THE PROBLEM

The 1985 standard provides a requirement that human-initiated processes and events be included in the calculations that examine compliance with the numerical, probabilistic containment requirements. This provision creates difficulties that arise because the probabilistic standard forces a demonstration of compliance to estimate the probabilities and the consequences of human-initiated phenomena that may occur during the next 10,000 years. There is no reliable basis for estimating human behavior over so long a period. Consequently, assumptions about the human activities that may occur at a repository site and about their probabilities are difficult to defend, because they lack a firm technical foundation. An analysis of compliance may well be so heavily dominated by such assumptions that it fails to reveal the adequacy, or inadequacy, of the isolation characteristics offered by a repository site. To find a site inadequate solely on the basis of unfounded assumptions about future human activities would defeat a major intention behind the containment requirements. The requirements should not disqualify a site unless the characteristics of the site are inadequate, and speculation about future human activity should therefore not be the focus of the compliance determination process.

On the other hand, the human-initiated events and processes should not be ignored in that process. They clearly should be part of an evaluation of the adequacy of a proposed repository system. The problem, then, is to construct and propose a treatment of such phenomena that guarantees their consideration in determining compliance but does not skew the process toward rejection of adequate sites on the basis of indefensible assumptions.

The following material suggests a way that section 191.13 of the 1985 version of 40 CFR Part 191 might be written to avoid the problems with putting human intrusion into the quantitative, probabilistic comparison with limits. The same material, perhaps with minor changes, may be used if the standard also allows for alternative approaches to the demonstration of compliance.

191.13 Containment requirements.

- a) Disposal systems for spent nuclear fuel or high-level or transuranic radioactive wastes shall be designed to provide a reasonable expectation, based on performance assessments, that the cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal from all significant natural processes and events that may affect the disposal system shall:
 1. Have a likelihood of less than one chance in 10 of exceeding the quantities calculated according to Table 1 (Appendix A); and
 2. Have a likelihood of less than one chance in 1,000 of exceeding ten times the quantities calculated according to Table 1 (Appendix A).
- b) Potential radionuclide releases to the accessible environment that are due to human actions shall be treated separately from releases due to natural events and processes; the treatment of releases shall be qualitative, including discussions of mitigating measures, and shall be based on unspeculative assumptions about future states of human civilizations. That is, the discussions should assume that drilling and mining methods, reasons for intrusion, and societal structures remain the same as they are currently.
- c) {the paragraph designated (b) in the 1985 version, unchanged} Performance assessments need not provide complete assurance that the requirements of 191.13(a) will . . .

If the EPA includes in its next version of the standard some alternatives to the original section 191.13, (e.g., the "four-column" approach or either of the two optional containment requirements suggested in the draft Federal Register notice dated 2/3/92), similar changes should be made. That is, 191.13(a) should be slightly revised (as it is above) to limit it to natural processes and events, and the new subsection 191.13(b) should be inserted, keeping the old subsection 191.13(b) as the new 191.13(c).

The following paragraph is to be added to Appendix B of the 1985 version:

Future States. Uncertainties involving things that are unknowable about the future can only be dealt with by making assumptions and recognizing that these may, or may not, correspond to a future reality. The Agency believes that speculation concerning certain future conditions should not be the focus of the compliance determination process. Therefore, it would be appropriate for assessments made under Part 191 to contain the assumption that many conditions remain the same as today's. Conditions in this category

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include population distributions (i.e., current population distributions should be assumed), level of knowledge and technical capability, human physiology and nutritional needs, the state of medical knowledge, societal structure and behavior, patterns of water use, and pathways through the accessible environment. The Agency would not find it appropriate to include in this category the geologic, hydrologic, and climatic conditions whose future states may be estimated by examining the geologic record. Although the Agency would not find it appropriate to assume that world populations will remain unchanged, it would be inappropriate to assume future world populations that cannot reasonably be sustained by current abilities to produce, distribute, and consume food. For this reason, future world populations in excess of 10 billion people need not be assumed in evaluations under paragraph 191.13.

The above changes in paragraph 191.13 will require a change to the reference to 191.13 that appears in Appendix B of the 1985 version in the paragraph called "*Compliance with Section 191.13.*" Two other references to 191.13 will not need to be changed. The revised paragraph will read as follows:

The Agency assumes that . . . compliance with 191.13(a) into a "complementary cumulative distribution function" that indicates . . . a disposal system can be considered to be in compliance with 191.13 if this single distribution function meets the requirements of 191.13(a).

Some sentences will need to be inserted into the paragraph in Appendix B called "*Consideration of Inadvertent Human Intrusion . . .*" This paragraph will then read as follows:

Consideration of Inadvertent Human Intrusion into Geologic Repositories. The most speculative potential disruptions of a mined geologic repository are those associated with inadvertent human intrusion. Some types of intrusion would have virtually no effect on a repository's containment of waste. On the other hand, it is possible through speculation to conceive of intrusions (involving widespread societal loss of knowledge regarding radioactive wastes) that could result in major disruptions that no reasonable repository selection or design precautions could alleviate.

Neither the Agency nor any other regulatory body has identified a reliable, defensible basis for predicting future human behavior and for estimating the probabilities of possible human actions. Therefore, the Agency does not require a quantitative treatment of human actions that affect the repository. Nevertheless, the implementing agency should consider these actions qualitatively in making its determination that there is reasonable expectation of compliance with the standard. These considerations, though fundamentally qualitative, especially in their treatment of probabilities, may refer to calculations that estimate the consequences of human actions. The Agency believes that the most productive consideration of inadvertent intrusion concerns those realistic possibilities that may be usefully mitigated by repository design, site selection, or use of passive controls (although passive institutional controls should not be assumed to completely rule out the possibility of intrusion). In making their qualitative evaluations, the implementing agencies can assume that passive institutional controls or the intruders' own exploratory procedures are adequate for the intruders to soon detect, or be warned of, the incompatibility of the area with their activities.

The paragraph in Appendix B labeled "*Frequency and Severity of Inadvertent Human Intrusion . . .*," is to be modified as follows (with the original wording continuing from the ellipsis at the end of this suggested wording):

Frequency and Severity of Inadvertent Human Intrusion into Geologic Repositories by Exploratory Drilling. In the qualitative discussions supplied in compliance with paragraph 191.13(b), the implementing agencies need not assume intrusion scenarios more severe than inadvertent and intermittent intrusion by exploratory drilling for resources. The implementing agency need not assume any drilling for the resources that are provided by the disposal system itself. The implementing agencies should consider qualitatively the effects of each particular disposal system's site, design, and passive institutional controls in mitigating the potential effects of such inadvertent exploratory drilling. Descriptions of the likelihood of such inadvertent and intermittent drilling over 10,000 years need not assume that more than 30 boreholes per square kilometer of repository area will be drilled in that time at geologic repositories in proximity to sedimentary rock formations or that more than 3 boreholes per square kilometer will be drilled in that time at repositories in other geologic formations. Furthermore, when the discussions treat the consequences of inadvertent and intermittent drilling, the implementing agency need not assume that those consequences are more severe than: (1) direct release to the land surface . . .

3.3 SUPPLEMENTARY INFORMATION

The following material could be used as supplementary information in explaining why the rule is reasonable when written in the form on the preceding pages. This material could probably appear in the EPA's supplementary information just after its explanations of the probabilistic standard that is promulgated in paragraph 191.13(a).

In developing the probabilistic standard, the Agency recognized that there is a fundamental difference between estimating the probabilities of future natural phenomena and estimating the probabilities of future human activities. Reasonable estimates of natural phenomena can often be based on evidence provided by the geologic record. Most of the natural phenomena that might be expected to affect a repository (e.g., fault movement, erosion, or diapirism) can be studied in records that extend back for millions of years. An extrapolation of that information through the next 10,000 years can be a reasonable basis for estimating the probabilities that those phenomena will occur. Although there will seldom be unanimous agreement among experts about the precise values of those probabilities, their reasonableness can be examined by reference to the geologic record. Believing that probabilities can be derived and defended in this way, the Agency deems appropriate the probabilistic standard required for natural phenomena in paragraph 191.13(a).

On the other hand, there is no similarly reliable basis for estimating what human beings are likely to do in the next few thousand years, or even in the next few hundred years. The records of human activity are not nearly so long as the geologic record, and 10,000-year extrapolations would, for that reason alone, be less reliable than extrapolations from the geologic record. More important, the past few hundred years--the past few decades, in particular--have seen an enormous increase in the rates at which human societies and their associated technical abilities have changed. With such rapid changes in so short a time, extrapolation to 10,000 years would necessarily consist of speculation about whether these rates will continue. Neither the Agency nor other regulatory bodies have identified a reliable basis for such speculation, which the Agency consequently believes should not be the focus of the compliance determination process.

For these reasons, the Agency has not required a quantitative treatment of human actions that may affect a repository. Nevertheless, the Agency believes that an implementing agency should carefully consider the effects of human actions in seeking reasonable expectation of compliance. Paragraph 191.13(b) therefore requires a qualitative discussion of human actions. This requirement avoids the problems of estimating probabilities quantitatively by not requiring compliance with a quantitative, probabilistic limit like that in paragraph 191.13(a) and by not requiring speculation about future conditions. The requirement does not rule out the use of calculations in support of the qualitative discussions; modeling of the consequences of future human actions may, for example, produce useful insights into the future behavior of a repository system. Further information about the Agency's intentions is furnished in Appendix B, which explains what the Agency would consider appropriate treatment of future states of nature and of human civilization.

3.4 TECHNICAL SUPPORT DOCUMENTATION

The following material is supporting information that could be cited as reasons for the DOE suggestions for the above revision. It could be part of a technical support document for the rule.

Many comments on 40 CFR Part 191 have pointed out the difficulties that arise when human activities are included with natural phenomena in the complimentary cumulative distribution function (CCDF) that the Agency recommended in 1985 for examining compliance with paragraph 191.13(a). The difficulties also arise in alternative compliance methods that have been suggested for incorporation into the standard--i.e., the suggestions known as the "four-column" alternative, the collective-dose alternative, and the "three-bucket" alternative. Summarized broadly, these difficulties arise from the basic difficulty of guessing what future human societies will be able to do or will want to do. For example, to include the drilling of exploratory boreholes into a forgotten repository would require estimates of the consequences of the drilling and of the probability of its occurrence. Estimating the consequences would require speculation about how drilling would be done in the future; given the rapid advances in drilling methods in the past hundred years, it would be extremely difficult to guess how drilling will be done thousands of years from now. Estimating the probability of drilling would be even more speculative; given that only 200 years ago deep drilling was a rare occurrence, it is hard to guess how often people will want to drill thousands of years from now.

Because there is no way to rigorously defend estimates of either the consequences or the probabilities of future human actions, the CCDF could easily be dominated by assumptions about these estimates. And there would be little possibility that the estimates could be limited to "reasonable" values, because there appears to be no defensible basis for deciding what will be "reasonable" in future societies.

A specific example of this possibility appears in a detailed preliminary performance assessment recently completed for the potential site at Yucca Mountain, Nevada (Reference 3-1). That study examined the effect of varying the number of boreholes that it assumed would penetrate the repository during the next 10,000 years. At the larger numbers of boreholes, the effects of natural release mechanisms (e.g., groundwater flow) were obscured by the effects of drilling. There was, of course, no basis other than assumption for choosing one number of boreholes over another--i.e., for deciding which CCDF is best representative of the site's future performance. (Although the EPA has provided suggestions that guide assumptions about numbers of boreholes, licensing activities are not bound to follow those suggestions, which appear in the guidelines that accompanied the 1985 version of the standard.) When CCDFs that include guesses about numbers of future boreholes are introduced into licensing activities, the licensing process may find itself focused on speculation about those numbers rather than on substantive issues of repository performance.

In other words, a CCDF dominated by guesses about future human behavior may obscure the more defensible estimates of the ability of a repository system to isolate waste through its natural characteristics and its engineered features. These characteristics and features are barriers on which geologic disposal relies, and it is important that the performance measure embodied in the standard reveal their effectiveness. The CCDF can do so if the obscuring effects of estimates about human actions are removed from it.

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This line of reasoning suggests only that human actions should not be part of the quantitative, probabilistic standard. An implementing agency may wish to consider human activities when it seeks reasonable expectation that a repository system will isolate waste effectively. To meet this desire, a qualitative discussion of human activities can furnish useful information. It may be possible to supplement the discussion with a quantitative study of consequences estimated by modeling present-day human activities and assuming that they occur at the repository. Such a study of consequences would reflect the Agency's belief that an appropriate treatment of future human activities would assume that many societal and technological conditions are the same as today's. Fundamentally qualitative discussions that refer to consequence calculations of this kind can be a valuable addition to material that supports a finding of reasonable expectation but avoids the misleading features of overly quantitative and probabilistic treatments.

Waste disposal programs outside the United States have also recognized difficulties like those explained here. European nations have not come to consensus on an appropriate way to handle human intrusion in their analyses of waste isolation. They do, however, recognize that "such low-probability, high-consequence scenarios would be difficult to treat within the normal regulatory guidelines and might, therefore, need separate consideration . . . These issues will be treated within the NEA Working Group on Assessment of Future Human Actions . . ." (Reference 3-2). Because these nations do not currently plan to use a probabilistic standard like the EPA standard, the difficulties they perceive are somewhat different from those involved with including human intrusion in a CCDF. But they clearly intend to pay special attention to the problems of including human intrusion along with natural disruptions, even in nonprobabilistic assessments.

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REFERENCES

- 3-1. Barnard, R. W., et al. "TSPA 1991: An Initial Total-System Performance Assessment for Yucca Mountain," SAND91-2795, Sandia National Laboratories, Albuquerque, New Mexico.
- 3-2. Nuclear Energy Agency, Organization for Economic Co-Operation and Development, "Radiation Protection and Safety Criteria, Proceedings of an NEA Workshop, Paris, 5-7 November 1990."

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CHAPTER 4

THREE-BUCKET APPROACH

THREE-BUCKET APPROACH

4.1 STATEMENT OF THE PROBLEM

Agencies affected by 40 CFR Part 191 have experimented with the complementary cumulative distribution function (CCDF) that the 1985 rule suggests for demonstrating compliance with the containment requirements. The NRC came forward with an alternative approach in 1991 and offered it up for discussion in informal forums. The approach came to be known as the "three-bucket approach" because it attempts to divide into three categories the phenomena that might affect waste isolation. The EPA has informally circulated a somewhat modified version in the Draft Federal Register Notice (2/3/92). The DOE has begun to examine both statements of the approach, and has noticed that it may present some problems if it is put into practice. Accordingly, the DOE cannot recommend the adoption of this approach until it has conducted further investigations to clarify and perhaps solve the potential problems.

The problem, then, is to state the difficulties that the DOE sees in the "three-bucket approach" and to seek solutions to them through further study.

4.2 RECOMMENDED APPROACH **WORKING PAPER**

The DOE finds that the "three-bucket approach," as it has been stated up to now, is technically incomplete and should not be included in the EPA standard. The DOE intends to investigate the approach, determining whether it can be better defined, whether it is fundamentally sound, whether it can be reasonably implemented, and whether it offers protection of the environment that is consistent with the original standard.

4.3 SUPPLEMENTARY INFORMATION

This material is not "supplementary information" in the sense that it is normally used in the rulemaking process. Instead, it simply explains the DOE reasoning--i.e., why the DOE feels more study is needed before the proposal can be either recommended or rejected. The material in this section may be useful to the EPA if its next proposal for 40 CFR Part 191 is accompanied by supplementary information that explains the EPA position on the "three-bucket approach."

Before the merit of the "three-bucket approach" can be evaluated, a number of questions about it must be answered:

- *How to determine unambiguously the bucket into which each sequence of events and processes falls.* An important feature of the approach is that the phenomena are placed into different categories, or "buckets," that govern the compliance criteria that apply to them. To give just one example of the ambiguity involved in the definitions of these buckets, some interpretations of the approach would place into the first bucket only natural phenomena that fall within the NRC definition of "anticipated." Another interpretation would place into the first bucket all phenomena with a probability greater than 0.1, making no distinction between natural and human-induced phenomena.
- *The meanings of certain terms used in the statements of the approach (e.g., "sequences," "anticipated," "sufficiently credible to warrant consideration," "scenario").* These terms are used in defining the buckets, and there is considerable confusion about their meanings. Any assessment of the merit of the proposal must rest on a firm understanding of what the EPA intends by the terms.
- *The logical consistency of comparing incomplete CCDFs to limits originally established for a complete CCDF.* The approach suggests that only phenomena that meet certain (ambiguously defined) criteria would be examined by inclusion in a CCDF. But this incomplete CCDF would be compared with limits originally derived by the EPA for a more comprehensive set of phenomena. Whether this apparent discrepancy would have any significant effects on the credibility of the standard has not been carefully examined.
- *The uncertainty in knowing how much more restrictive the "three-bucket approach" is, when compared with the original standard.* The approach is intended to be approximately as restrictive as the original, conservative standard. Nevertheless, until some experience in using it has been gained, it is difficult to determine its degree of conservatism.
- *Whether the determinations of probabilities must be more accurate, or less accurate, than those required for showing compliance with the original standard.* The approach is intended to reduce the necessity for deriving accurate probabilities of future phenomena. If, however, the (currently ambiguous) assignment into buckets depends strongly on probabilities, it may become necessary to estimate at least some probabilities more accurately than the original standard requires.

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- *Whether the probability limits for the buckets take parameter variabilities into account.* When any particular sequence of phenomena is modeled, the estimates of consequences usually cover a range that encompasses the natural variations in the properties of natural materials and the uncertainties in the measurements of those properties. Each part of this range of consequences has a different probability associated with it. This range of probabilities may, for some phenomena, extend past the boundary between buckets. What the approach would suggest for handling such a situation is unclear.

Furthermore, although the approach appears on first reading to require only a reformatting of calculations intended for comparison with the 1985 standard, it may not be fully compatible with existing methods for deriving CCDFs. (All of these difficulties are discussed, in somewhat more technical detail, in the accompanying material that could appear in a technical support document.)

Further detailed investigation of the three-bucket approach is needed before the DOE can decide whether it is an improvement over the 1985 containment requirements. Furthermore, the DOE cannot determine whether the approach is implementable until the above questions have been answered. A detailed investigation carried out by the DOE can, in principle, probably suggest resolutions for most of the ambiguities and determine the implementability of the approach. If the investigation shows that the approach is not an improvement or is not implementable, the investigation may suggest a modified "three-bucket approach" that the DOE can recommend to the EPA. The investigation will, however, take several months to perform. The studies that are necessary will involve, at a minimum, a reformatting of the recent total-system performance assessment to make it fit into the three-bucket framework, and they may require that additional total-system analyses be done. In order to study critical parts of the "three-bucket approach", it may also be necessary to modify some of the calculational models so that calculations with them will emphasize those critical parts.

4.4 TECHNICAL SUPPORT DOCUMENTATION

This material is taken almost verbatim from a paper by Bob Klett, "Containment Requirements for Radioactive Waste Disposal," which was presented at the second EPRI workshop on the EPA disposal criteria, February 4-6, 1992.

The three-category, or "three-bucket," approach was suggested by the staff of the NRC as an alternative to the present containment requirements. The main purpose of this proposed change is to eliminate the need to develop precise numerical probability estimates for very unlikely processes and events. Another reason given for using this approach is that it provides a way of separating human intrusion from anticipated or natural events and evaluating them with deterministic requirements. The NRC and the EPA use different wording to describe this approach.

The proposed requirements for the three categories are defined as follows and are illustrated in Figure 4-1 (for comparison, Figure 4-2 shows the requirements in the present containment standard):

- Cumulative normalized releases (as represented in a CCDF) to the accessible environment, of only anticipated processes and events, shall not have a probability of greater than 0.1 of exceeding the release limit defined by Note 6 and Table 1 of Appendix A of the EPA standard. "Anticipated" is defined by the NRC as natural events that are likely to occur during the period of regulation.
- The normalized release from any unanticipated, credible single process, event, or sequence of processes and events (any process, event, or sequence of processes and events that, as defined by the EPA, have probabilities of occurrence less than 0.1 and greater than 0.0001), shall not exceed 10 times the release limit defined by Note 6 and Table 1 of Appendix A of the EPA standard. "Unanticipated" is defined by the NRC as describing natural events that are unlikely to occur during the period of regulation and human intrusion events.
- Noncredible processes and events with probabilities of occurrence in 10,000 years less than 0.0001 are not regulated and would not be included in performance assessments.

The requirements have been stated several ways. In particular, the NRC wording expresses the boundaries between the three categories somewhat differently from the EPA wording. Furthermore, there are at least three interpretations of category membership and how this option would be implemented. In addition, there are ambiguities in all versions that need clarification.

The following is a brief description of the three interpretations and their corresponding methods of implementation.

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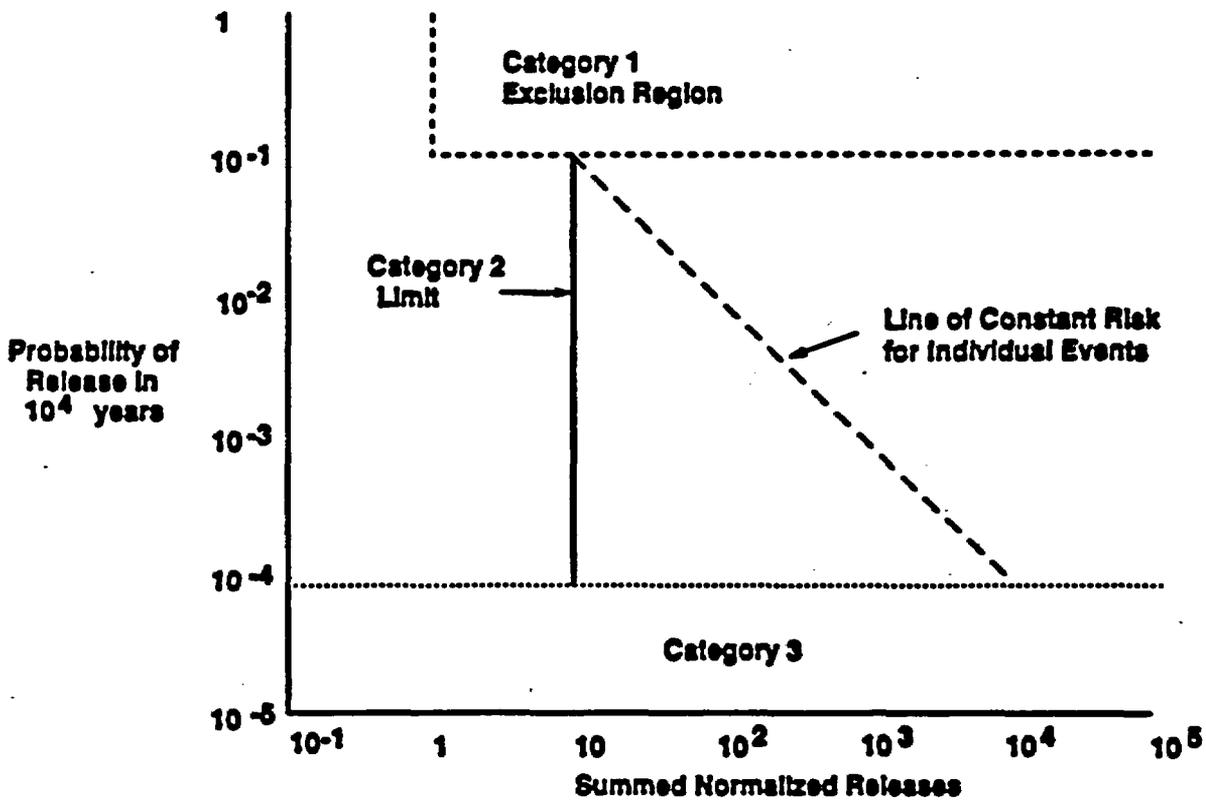


Figure 4-1. Containment Requirements in the Three-Bucket Approach

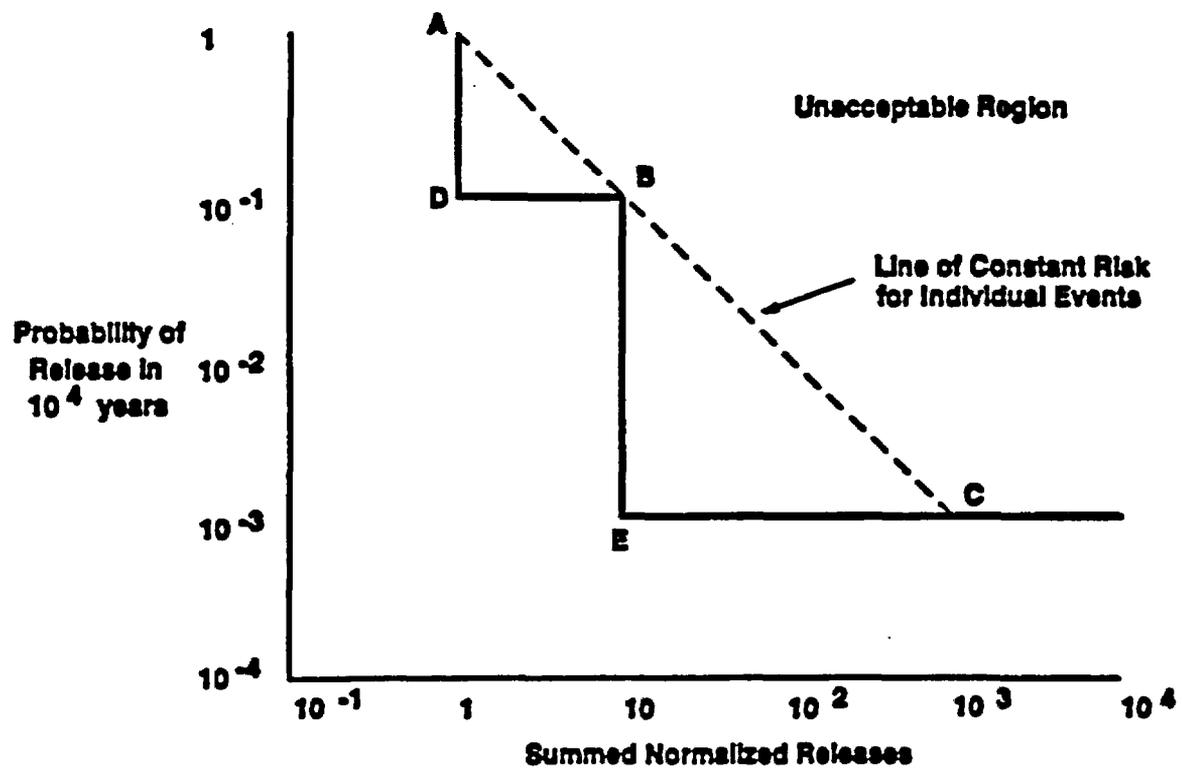


Figure 4-2. Normalized Containment Requirements in 40 CFR Part 191

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1. Category membership in this interpretation is based on the event or process description and a qualitative probability estimate of the event. Category 1 would consist of natural events that are "anticipated" to occur during the period of intended performance. Category 2 would consist of "unanticipated" natural events and human actions. All noncredible events would be in category 3. Human intrusions that have a high probability of occurrence do not seem to be covered by this definition. The implementation procedures for either interpretation 2 or 3 could be used with this definition.
2. Category membership would be based solely on probabilities, and category 2 would control the membership. Any single event or sequence of events with a probability of occurrence between 0.0001 and 0.1 would be in category 2, and individual releases could not exceed 10 times the release limits. Events with probabilities less than 0.0001 would be in category 3 and would not be regulated. In the present standards, all credible events are included in the CCDF that is to be compared with the numerical containment requirements shown in Figure 4-2. In this second interpretation of the three categories, no part of a CCDF consisting of events with probabilities between 0.1 and 1 (those not in categories 2 and 3) could be in the exclusion region shown in Figure 4-1. This would be an incomplete CCDF with the upper probability value less than 1 and conceivably less than the lower level of the exclusion region.
3. Category membership in this third interpretation would be based on probabilities and consequences of the events, and categories 1 and 3 would control the membership. Category 1 would require a CCDF of all events with normalized releases less than 1 to have a maximum probability of at least 0.9. This also would be an incomplete CCDF, but the upper value would have to be at least as high as the lower value of the exclusion region. This interpretation is inconsistent with the wording in the EPA's Working Draft #3 of 40 CFR Part 191. In category 2 the projected releases from individual events with probabilities of occurrence between 0.0001 and 0.1 cannot exceed 10 times the release limits. Some events could be regulated by both categories 1 and 2. Events with probabilities less than 0.0001 would be in category 3 and would not be regulated.

There are some ambiguities and inconsistencies that apply to all three of these interpretations. The probabilities used to define category membership and to generate the category 1 CCDF could be the mean, median, or upper bound of the estimates. The interpretation of "events and sequence of events" could determine their category membership and have a significant effect on compliance. Whenever probabilities of individual events or sequences of events are used, there is the opportunity to subdivide them to decrease probabilities and make compliance easier. Events also could be grouped together to increase probabilities and possibly exclude a safe repository.

This approach has some problems that must be resolved before it could replace the present containment requirements. The system CCDF in category 1 would be incomplete, and the upper level of probability would always be less than 1. Moreover, the upper level of this incomplete system CCDF also would be different for each repository, making the requirement inconsistent. One partial solution would be to normalize the incomplete system CCDF so that it would be complete for anticipated events. The requirement would still be inconsistent and it would not be traceable to the fundamental standard that applies to the entire disposal system, not just to some events. If, to overcome this difficulty, all events were included in the category 1 CCDF to make it complete, the need for precise probability estimates would be the same as the present approach.

The goal of eliminating the need for precise probability estimates for unanticipated processes and events is only partially fulfilled. Probability estimates of unanticipated events in the middle of the category 2 probability range could be off by as much as 1.5 orders of magnitude without affecting the assessment. As the actual probabilities of the events approach either of the category 2 boundaries, however, the accuracy requirements on the probability estimates increase. If the estimates are not very precise in the 0.1 and 0.0001 probability ranges, the event could be placed in the wrong category, resulting in an erroneous evaluation. As an example, an event just above the lower probability limit would have to comply with the same requirements as an event with a probability of 0.1, but an event just below the lower limit would not even be regulated.

Another problem is the nonuniformity of category 2. As can be seen in Figure 4-1, the proposed requirement is 1,000 times as restrictive for events with probabilities of 0.0001 as for events with probabilities of 0.1. This nonuniformity could be eliminated by using the line of constant risk in Figure 4-1 as the category 2 limit. The accuracy requirements for probability estimates would then be uniform for the entire category.

In addition, the "three-bucket approach" may not achieve its potential advantage of separating human intrusion from other phenomena. There is no assurance that human intrusion will be in category 2 if the category definition is based on probabilities. For some repositories, the only credible releases in 10,000 years would be from human intrusion, or human intrusion would be the dominant release mechanism with a probability greater than 0.1. Human intrusion would definitely be in category 1 for these repositories.

To use this approach, compliance evaluation, which is the final step of the analysis, would be carried out differently from the current DOE expectations for the process. The credible events would be divided into two categories, a CCDF of the anticipated events would be generated and compared to the category 1 limits, and the unanticipated events would be compared event-by-event to the category 2 limit. The definition of noncredible individual events for category 3 is the value currently being used in performance assessments. If, however, the definition of "sequences" includes parameter variations, the division of credible events into categories may not be possible until Monte Carlo sampling has determined detailed probabilities. If such a determination is necessary, computer routines for making CCDFs will have to be revised, and the difficulty of implementing the approach would have to be tested before the feasibility of the approach can be said to be fully understood.

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The NRC staff has claimed that the "three-bucket approach" may simplify licensing or permitting of repositories, but the concept and some definitions need clarification, and some modifications are needed to reduce inconsistencies and nonuniformities. It is not clear that categories 1 and 2 can be shown to fulfill the total-system risk requirements of the fundamental criterion.

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CHAPTER 5

MULTIMODE RELEASE LIMITS

MULTIMODE RELEASE LIMITS

5.1 STATEMENT OF THE PROBLEM

In some instances, the release requirements of Table 1 in 40 CFR Part 191 may result in an inappropriate or overly conservative evaluation of repository sites because they do not adequately account for significant features of a site. The 1985 version of 40 CFR Part 191 contained only one release limit table (Table 1) for all release modes. The table was based only on simultaneous releases to all the world's rivers and oceans. The three other basic release modes--atmospheric, land surface, and withdrawal-well, which are the only expected release modes for sites presently under consideration--were not taken into account. Because a single release limit table cannot represent all release modes and release locations, cumulative releases would have been evaluated at the boundary of the repository instead of at locations of release.

5.2 RECOMMENDED APPROACH

A multimode release limit option is proposed in addition to the existing Table 1 limit in Appendix A of the standard. This additional option would include limits for all release modes to be considered in the containment requirements (land, well, river, and ocean). The atmospheric release mode is addressed in the individual protection requirements (as explained in Chapter 9, which discusses Carbon-14), and the human intrusion component is addressed in Chapter 3, which discusses the consideration of human intrusion. In incorporating the proposed new table, a number of corresponding changes to the wording of the rule are needed. These changes are described below.

A number of new terms have been introduced. As used here, these terms are defined as follows:

Point of compliance - the location, for a given release mode, where radionuclides enter the biosphere. At this location, cumulative releases over 10,000 years are calculated for comparison to the multimode release limits table.

Release mode - one of four potential ways to be considered in the containment requirements in which radionuclides are transported from the lithosphere to the biosphere, resulting in exposure to humans. The release modes are: land (contaminated solids deposited on the land surface, such as volcanic materials); well (contaminated groundwater pumped to the land surface); river (all fresh surface waters); and ocean.

Biosphere - the zone of the Earth extending from (and including) the surface into the surrounding atmosphere.

Subsection 191.13(a) needs to be changed to accommodate the option of multimode release limits. The proposed wording is as follows:

- a) Disposal systems for spent nuclear fuel or high-level or transuranic radioactive wastes shall be designed to provide a reasonable expectation, based upon performance assessments, that the cumulative releases of radionuclides to the accessible environment (for Table 1 in Appendix A), or the cumulative releases of radionuclides, considering all applicable release modes, to the biosphere (for Tables 2 and 3 in Appendix B) for 10,000 years after disposal from all significant processes and events that may affect the disposal system shall:
 1. Have a likelihood of less than one chance in 10 of exceeding the quantities calculated according to Table 1 (Appendix A) or Tables 2 and 3 (Appendix B); and
 2. Have a likelihood of less than one chance in 1,000 of exceeding ten times the quantities calculated according to Table 1 (Appendix A) or Tables 2 and 3 (Appendix B).

The Department shall select the release limits method to be used in evaluating compliance.

Appendix A remains the same as in the 1985 version of 40 CFR Part 191.

A new Appendix B would be created. It would be the same as Appendix A except for these changes: replacement of Table 1 with Tables 2 and 3, the addition of two notes, and minor changes to the original Note 6 from Table 1. (The creation of a new Appendix C will be discussed in Chapter 6.)

Tables 2 and 3 provide release limits for the four potential release modes to be considered in the containment requirements expressed in curies and terabequerels, respectively. The proposed tables are included at the end of this section.

New information would have to be added as Note 6 to Tables 2 and 3 of Appendix B. The wording for the new Note 6 would be:

The Agency assumed, in deriving the release limits for the river and well releases in Tables 2 and 3, that the entire drainage system of all rivers (for river releases) and all aquifers (for well releases) are contaminated by the released radionuclides. Site Adjustment Factors (SAFs) may be used with Tables 2 and 3 to account for specific site locations. The following are examples of how SAFs might be developed for the surface flow system and other geologic and hydrologic components of a geologic disposal system.

Example 1--River Releases: For the river column, the release limits are calculated assuming that the entire drainage of all rivers is contaminated. For an actual site, only the downstream section of the tributary that is fed by groundwater passing through the repository is contaminated. To correct for this, a Site Adjustment Factor for the river release mode (SAF_R) is used as a multiplier to adjust the risk factors. The Reciprocal Site Adjustment Factor ($RSAF_R$), with which the release limits are multiplied, is calculated as follows:

$$RSAF_R = \frac{\sum_{i=1}^n (L_{C(i)} * F_{C(i)}) + \sum_{j=1}^n (L_{U(j)} * F_{U(j)})}{\sum_{i=1}^n (L_{C(i)} * F_{C(i)})}$$

This approximation represents the sums of the products of all tributary lengths and flow rates divided by the equivalent sums of contaminated tributaries. "L" is the length of the river segments and "F" is the volumetric flow rate of that segment. The subscripts "C" and "U" refer to contaminated and uncontaminated segments, respectively. The release limits in Tables 2 and 3 are then multiplied by this ratio to provide a site-specific release limit for the river release mode.

Example 2--Well Releases: The derivation of the release limits for the well release mode using world average parameters assumes all groundwater from the recharge area to the locations where it enters surface waters is contaminated. For an actual site, wells up-gradient of the repository do not produce contaminated water. In addition, during the 10,000-year regulation period, the contaminated plume may not reach the discharge location, thus some uncontaminated water may also be withdrawn down-gradient from the repository.

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A method for approximating the ratio of contaminated to total available water can be determined by dating the water at the repository (A_1), at the point it is expected that the radionuclides will reach in 10,000 years (A_2), and at the location where groundwater discharges to a river (A_3). With these ages, the Site Adjustment Factor for the well release mode (SAF_w) may then be calculated and used as a multiplier to adjust the risk factors. Calculation of the Reciprocal Site Adjustment Factor ($RSAF_w$) is done by dividing the age of the water at the river by the difference in the ages of the water at the repository and at the farthest point of migration in 10,000 years, or:

$$RSAF_w = \frac{A_3}{A_2 - A_1}$$

However, if it is found that the contaminated plume will reach a river within 10,000 years, the formula becomes:

$$RSAF_w = \frac{A_3}{A_3 - A_1}$$

Release limits in Tables 2 and 3 are then multiplied by one of these ratios (the $RSAF_w$ s) to provide a site-specific release limit for the well release mode.

The use of SAFs and the parameters to be considered in calculating SAFs shall be determined by the Department.

A second new note, describing the concept of points of compliance for the multimode release limits in the containment requirements will also need to be added to Tables 2 and 3 of the new Appendix B. The note would read as follows:

In calculating cumulative releases over 10,000 years, the points of compliance are as follows:

<u>Release Mode</u>	<u>Point of Compliance</u>
Land	Location where radioactive material is brought directly to the land surface.
Well	Any wellhead outside the controlled area from which groundwater containing radionuclides is withdrawn for purposes such as irrigation or supplying drinking water.
River	Location(s) of existing discharge of groundwater containing radionuclides to a river.
Ocean	Location where a river-water or groundwater containing radionuclides discharges to an ocean.

The existing Note 6 from Appendix A, Table 1 should be revised and used as Note 8 for Tables 2 and 3 of the new Appendix B. Two changes will be necessary.

- The third and fourth sentences should be rephrased as follows:

For each radionuclide in the mixture, determine the ratio between the cumulative release quantity projected over 10,000 years and the limit for that radionuclide for each applicable release mode as determined from Tables 2 or 3 and Notes 1 through 7.

- The last paragraph, the example, should be reworded as follows:

For example, if all release modes (L,W,R, and O referring to land, well, river, and ocean release modes) are used in the example, if radionuclides a and b are projected to be released in amounts Q_a and Q_b , and if the applicable release limits are $RL_{L,a}$ and $RL_{L,b}$, then the cumulative releases over 10,000 years shall be limited so that the following relationship exists:

$$Q_{L,a}/RL_{L,a} + Q_{L,b}/RL_{L,b} + \dots + Q_{W,a}/RL_{W,a} + Q_{W,b}/RL_{W,b} + \dots +$$

$$Q_{R,a}/RL_{R,a} + Q_{R,b}/RL_{R,b} + \dots + Q_{O,a}/RL_{O,a} + Q_{O,b}/RL_{O,b} + \dots +$$

$$Q_{O,a}/RL_{O,a} < 1.$$

The existing Appendix B, from the 1985 standard would be renamed Appendix D. The introductory paragraph of this Appendix discusses evaluating long-term predictions of compliance, focusing on compliance with 191.13. Because of the other proposed changes outlined above, this introductory paragraph should acknowledge two additional steps in 191.13 compliance. The following sentences should be inserted between sentences 2 and 3:

Quantitative evaluations for these predictions compare predicted releases with either Table 1 of Appendix A or Tables 2 and 3 of Appendix B. If the multimode release limits in Tables 2 and 3 of Appendix B are used, the presence or absence of the four possible release modes (land, well, river, and ocean) to be considered in the containment requirements must be determined. The fifth release mode, for atmospheric releases, is considered under the individual protection requirements. Site Adjustment Factors for the well and river release modes, to be determined by the Department, may be calculated to account for differences between the actual site-specific availability of water and the original assumption that the entire drainage system is available and contaminated.

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TABLE 2

Cumulative Release Limits for 10,000 years (curies per 100,000 MTHM) for Multiple Release Modes

Release Limit (curies per 100,000 MTHM)				
Nuclide	River	Well	Ocean	Land
C-14	TBD*	TBD	TBD	TBD
Ni-59	2E+07	9E+06	TBD	1E+09
Sr-90	4E	2E+04	4E+07	3E+07
Zr-93	7E	3E+06	3E+07	4E+07
Tc-99	3E+06	1E+06	6E+08	2E+10
Sr-126	1E+04	4E+03	9E+03	7E+05
I-129	1E+04	5E+03	4E+06	3E+05
Cs-135	1E+05	6E+04	2E+07	2E+06
Cs-137	9E+04	8E+04	2E+06	5E+07
Sm-151	1E+08	4E+07	TBD	1E+10
Pb-210	8E+03	4E+03	TBD	7E+06
Ra-226	6E+03	3E+03	TBD	2E+05
Ra-228	4E+04	2E+04	TBD	6E+07
Ac-227	1E+04	6E+03	7E+03	8E+06
Th-229	3E+04	1E+04	6E+03	5E+04
Th-230	2E+03	8E+02	TBD	3E+03
Th-232	3E+03	1E+03	TBD	3E+03
Pa-231	7E+03	3E+03	2E+04	4E+04
U-233	5E+04	2E+04	1E+06	1E+06
U-234	5E+04	2E+04	TBD	2E+06
U-235	5E+04	2E+04	1E+06	1E+06
U-236	5E+04	2E+04	TBD	2E+06
U-238	5E+04	2E+04	TBD	1E+06
Np-237	1E+04	8E+03	7E+04	8E+06
Pu-238	2E+04	1E+04	TBD	3E+06
Pu-239	2E+04	8E+03	2E+04	2E+05
Pu-240	2E+04	8E+03	2E+04	2E+05
Pu-241	5E+05	2E+05	TBD	4E+08
Pu-242	2E+04	8E+03	TBD	2E+05
Am-241	2E+04	8E+03	5E+03	1E+06
Am-243	2E+04	8E+03	5E+03	4E+05
Cm-245	1E+04	4E+03	3E+03	1E+05
Cm-246	2E+04	8E+03	TBD	3E+05

*To be determined

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TABLE 3

Cumulative Release Limits for 10,000 years (TBq per 100,000 MTHM) for Multiple Release Modes

Release Limit (TBq per 100,000 MTHM)				
Nuclide	River	Well	Ocean	Land
C-14	TBD*	TBD	TBD	TBD
Ni-59	8E+05	3E+05	TBD	5E+07
Sr-90	2E+03	7E+02	2E+06	1E+06
Zr-93	2E+05	1E+05	9E+05	2E+06
Tc-99	1E+05	4E+04	2E+07	7E+08
Sn-126	4E+02	1E+02	3E+02	3E+04
I-129	5E+02	2E+02	1E+05	9E+03
Cs-135	5E+03	2E+03	6E+05	6E+04
Cs-137	3E+03	3E+03	8E+04	2E+06
Sm-151	4E+06	2E+06	TBD	6E+08
Pb-210	3E+02	1E+02	TBD	2E+05
Ra-226	2E+02	1E+02	TBD	7E+03
Ra-228	2E+03	7E+02	TBD	2E+06
Ac-227	6E+02	2E+02	2E+02	3E+05
Th-229	1E+03	4E+02	2E+02	2E+03
Th-230	7E+01	3E+01	TBD	1E+02
Th-232	1E+02	4E+01	TBD	1E+02
Pa-231	3E+02	1E+02	6E+02	2E+03
U-233	2E+03	7E+02	4E+04	5E+04
U-234	2E+03	8E+02	TBD	6E+04
U-235	2E+03	7E+02	4E+04	4E+04
U-236	2E+03	8E+02	TBD	6E+04
U-238	2E+03	7E+02	TBD	5E+04
Np-237	5E+02	3E+02	3E+03	3E+05
Pu-238	9E+02	4E+02	TBD	1E+05
Pu-239	7E+02	3E+02	6E+02	6E+03
Pu-240	8E+02	3E+02	6E+02	7E+03
Pu-241	2E+04	7E+03	TBD	1E+07
Pu-242	8E+02	3E+02	TBD	6E+03
Am-241	7E+02	3E+02	2E+02	4E+04
Am-243	6E+02	3E+02	2E+02	2E+04
Cm-245	4E+02	2E+02	1E+02	5E+03
Cm-246	E+02	3E+02	TBD	1E+04

*To be determined

5.3 SUPPLEMENTARY INFORMATION **WORKING PAPER**

The following material explains why the rule is reasonable when written in the form on the preceding pages. This material could be used by the EPA as supplementary information for the proposed rule.

The 1985 release limits contained in 40 CFR Part 191, Section 191.13, which were stated in terms of the allowable release from a repository containing 1,000 metric tons of heavy metal, were developed by estimating how many curies of each radionuclide would cause 10 premature deaths over 10,000 years if released to the environment. For these calculations, the Agency used very general models of environmental transport, based upon a simultaneous release to all the world's rivers and oceans. The resulting release limits table (Appendix A, Table 1 of the 1985 version), provided a single cumulative release limit per radionuclide that was to be evaluated at the boundary of the controlled area.

Several commenters have suggested that release limits based solely upon a simultaneous release to the world's rivers and oceans, the criteria upon which the Agency based the 1985 version of Section 191.13, may not be appropriate for all releases at all sites. As a result, the Agency has further evaluated the appropriateness of the single generic derived version of the release limits. While the Agency continues to believe that cumulative release limits per radionuclide are an appropriate way in which to regulate the disposal of radioactive waste, several changes have been implemented in order to accommodate any site-specific circumstances which may differ from the assumed circumstances underlying the Table 1 release limits. The Agency further feels that today's proposal gives the Department greater flexibility in complying with the standard, while at the same time it provides at least the same level of protection to human health and the environment as did the 1985 standard.

Given below is a brief description of the relevant changes in the present version from the 1985 version, with a more detailed explanation to follow:

- Table 1 in Appendix A is retained as an option for determining the releases to the accessible environment.
- New multimode release tables (Tables 2 and 3 in Appendix B) for the containment requirements are included as an option for determining releases to the biosphere. Each table consists of four release modes (land, wells, rivers and oceans), each with specific release limits, that can be used to account for site-specific features.
- The multimode release limits (Tables 2 and 3 in Appendix B) are based upon a repository containing 10^5 (100,000) MTHM rather than 10^3 MTHM.
- Compliance with the release limits from the multimode tables is evaluated at the point of release to the biosphere for the particular release mode rather than at the boundary of the controlled area.
- Site Adjustment Factors (SAFs) are provided for use with the multimode release limits. The Department may use SAFs for the river and well release modes. The department would determine the parameters to be used in accounting for specific site locations.

The multimode release limits contained in today's version of Appendix B (Tables 2 and 3) are based upon a 10⁵ (100,000) MTHM repository rather than a 10³ (1,000) MTHM repository. This modification reflects no quantitative change in the level of protection. It simply presents the information in a manner more clearly related to the fundamental criterion (1,000 deaths per 10,000 years per reference repository, whether HLW or TRU waste), and the individual protection dose standards which are based upon a 10⁵ (100,000) MTHM repository. For consistency and scaling efficiency, 10⁵ (100,000) MTHM for HLW and XX MCi for TRU will now be used as the reference repositories for the multimode release method.

Four Column Release Limits Tables

After receiving comment that a single generic derived release limit based upon a simultaneous release to all of the world's rivers and oceans as a radionuclide escapes the controlled area may not be appropriate for all repositories, the Agency has reevaluated the basis of the rule. The Agency feels that more is known now about release modes and pathways than when the 1985 version of the standard was promulgated. Advances in the understanding of geologic disposal systems should be incorporated into the present version of the rule. As a result, the Agency has retained the single generic derived release limit table and added an option of multimode release limits consisting of four column tables addressing land, well, river (including all fresh surface water), and ocean release modes. A fifth release mode, for atmospheric releases, is considered in the individual protection requirements.

The Agency feels that today's version of the multimode release limit tables applies uniformly to all repositories and pathways while allowing all major components of a disposal system to be included in a risk assessment. In setting the multimode release limits for today's rule, the Agency has used the same methodology described in the Background Information Document (BID) for the 1985 version. That is, for each radionuclide, the maximum number of fatalities allowed by the fundamental criterion (1000) was divided by the fatal cancers per curie for each release mode. The summed normalized release limit for each scenario or event would include the release fractions for each radionuclide for each release mode.

The derivations from the 1985 version of the standard have not been updated and extended. The derivation for the land and river release modes in the 1985 version were basically complete. The well release mode limits consist of a minor modification to the river release mode, and the ocean release mode limits have been completely recalculated. For a thorough treatment on exactly how the release limits were derived, the BID should be consulted.

Implementation of Multimode Release Limits

While both the BID and the standard address the implementation of the multimode release limits approach, the Agency feels that it should be addressed here also. It should be stressed that the level of protection provided to human health and the environment, for both present and future populations, has remained the same for today's version of the

standard as that contained in the 1985 version. The only significant change in the containment requirements is the optional method that the Agency is allowing the Department to use in determining compliance with the containment requirements. The Agency believes that in some instances this option may more realistically reflect the actual processes and events that will take place between the repository and the potential release points and therefore may more realistically reflect the potential risks posed by any such repository.

Multimode Well Release Limits Not Applicable within the Controlled Area

The Agency feels that it is necessary to make one point particularly clear with regard to the implementation of the multimode well release limits. That is, these release limits do not apply within the controlled area. This view was upheld by the First Circuit Court (Natural Resources Defense Council v. U.S.E.P.A., 824 F.2d 1258 (1st Cir. 1987)). As the Court stated in upholding the Agency's decision not to apply the groundwater protection standards within the controlled area:

"... the EPA's choice to sacrifice the purity of water at repository sites as part of the control strategy was impliedly sanctioned by Congress when, subsequent to passage of the SDWA [Safe Drinking Water Act], it enacted the Nuclear Waste Policy Act."

Thus, the concept that a certain amount of area directly surrounding the repository is devoted to the disposal of radioactive waste is clearly accepted. Application of the multimode release limits for wells will therefore begin at the boundary of the controlled area.

The multimode release limits method, in addition to expanding the release limits to a four column table, also allows the Department to evaluate potential releases at the points of release to the biosphere for each release mode rather than at the boundary of the controlled area for all potential releases. This approach is consistent with the 1985 approach in that the Agency has modeled the effects of a release of each radionuclide via each of the four release modes for the containment requirements and based the release limits upon this modeling.

In setting the current multimode release limits, the Agency has assessed the impacts upon human health and the environment once a radionuclide escapes through one of the four release modes for the containment requirements. This modeling from the release points to humans ensures uniformity of the biosphere for all applications of multimode release limits in the containment requirements. In contrast, the Agency has decided in providing multimode release limits that it would be more appropriate for the Department to assess the movement of radionuclides from the repository to the points of release. This decision is a result of comments received and further evaluation of potential repository locations.

While the Agency believes that the use of generic models to assess the impacts of radionuclides once they are released into the environment via one of the four release modes is an appropriate method to regulate the release of radionuclides, it is also the Agency's belief that the Department may most appropriately assess the movement of radionuclides from the repository to the points of release. This belief is based upon the

fact that the Department will be in a better position to evaluate the site-specific attenuation factors and their impact upon the movement of radionuclides through the lithosphere to the points of release. Attenuation factors depend on: groundwater velocity, retardation factor, dispersivity, distance of the actual release from the repository in the direction of groundwater flow, duration of regulation, radionuclide half life, time of release from the repository, and rate of release. All components of the disposal system should be evaluated when determining compliance with the multimode release limits unless it can be shown that their effects are negligible.

Site Adjustment Factors

In determining compliance with the multimode river and well release limits, the Agency allows the Department to use site adjustment factors (SAFs). This is necessary because, in deriving the release limits for the river and well release modes, the Agency assumed the entire drainage system of all rivers (for the river release mode) and all aquifers (for the well release mode) would be contaminated by the released radionuclides. Thus, in order to obtain a more realistic depiction of the potential releases from specific sites, the Agency allows SAFs to be used when determining the release limits for actual sites.

As stated earlier, there is no need for adjustment factors in computing compliance with the release limits for the land and ocean release modes. The Department determines the factors to be used in determining SAFs for a specific repository. In applying the multimode release limits to specific sites, the Department should recognize that it will be necessary to allocate radionuclides that reach an aquifer to either the well or river release modes. Surface (river) and groundwater (well) usages vary for different regions in the United States. Thus, the Department will be responsible for determining the appropriate allocations for the specific region in which the site is located.

The effect of multimode release tables on the release CCDF is to change the magnitude of the normalized release (R) for each scenario or event relative to the single release method in the 1985 version of 40 CFR Part 191. The probabilities of the individual scenarios or events that make up the CCDF are unchanged.

The Agency believes that today's rule satisfies comments received concerning the appropriateness of using only a single generic derived release limit applied at the boundary of the controlled area. The option of multimode release limits refines the release limit approach used in the 1985 version of 40 CFR Part 191, Section 191.13. The use of multimode release limits accounts for all release modes to be considered in the containment requirements in assessing the performance of a disposal system. The Department is responsible for determining release modes and release locations for all pathways for each repository. Because the Agency has computed all transport and biological effects from the release location to humans for all four release modes, the biosphere and effects are uniform for all applications of the containment requirements. Multimode release limits are not site specific and can therefore be applied to future repositories.

The following material is supporting information that could be cited as reasons for the suggestions in the proposed revision. It could be part of a technical support document for the rule.

Background

The 1985 version of 40 CFR Part 191 (Reference 5-1) contained a single derived release limit for all release modes that was based on simultaneous release to all the world's rivers and oceans. Cumulative releases would have been evaluated at the boundary of a repository. The EPA based the decision to use this approach on their determinations that releases to surface water through groundwater are usually the most important release mode for mined repositories and that the health effects per curie released are usually the highest for this release mode (Reference 5-2).

In reexamining 40 CFR Part 191, the EPA has received substantial comment addressing release limits based on a single release mode. Characterization of disposal sites currently under consideration indicates that release modes for these proposed repositories are gaseous, land surface, and withdrawal wells. Therefore, it is appropriate to add the option of multimode release limits that, except for gaseous releases, may be used to evaluate these additional release modes in compliance evaluations for the containment requirements. Gaseous releases, although included in this discussion for completeness, are considered in the individual protection requirements of the regulation. The option of multimode release limits satisfies any deficiencies that may have existed in the 1985 version by providing the ability to account for all applicable release modes in assessing the performance of a disposal system. The use of multimode release limits applies the standard at actual release locations (Figure 5-1), so risk attenuation between the boundary and the release locations is considered in the risk assessment. In addition, the methodology for multimode release limits allows corrections for repository locations.

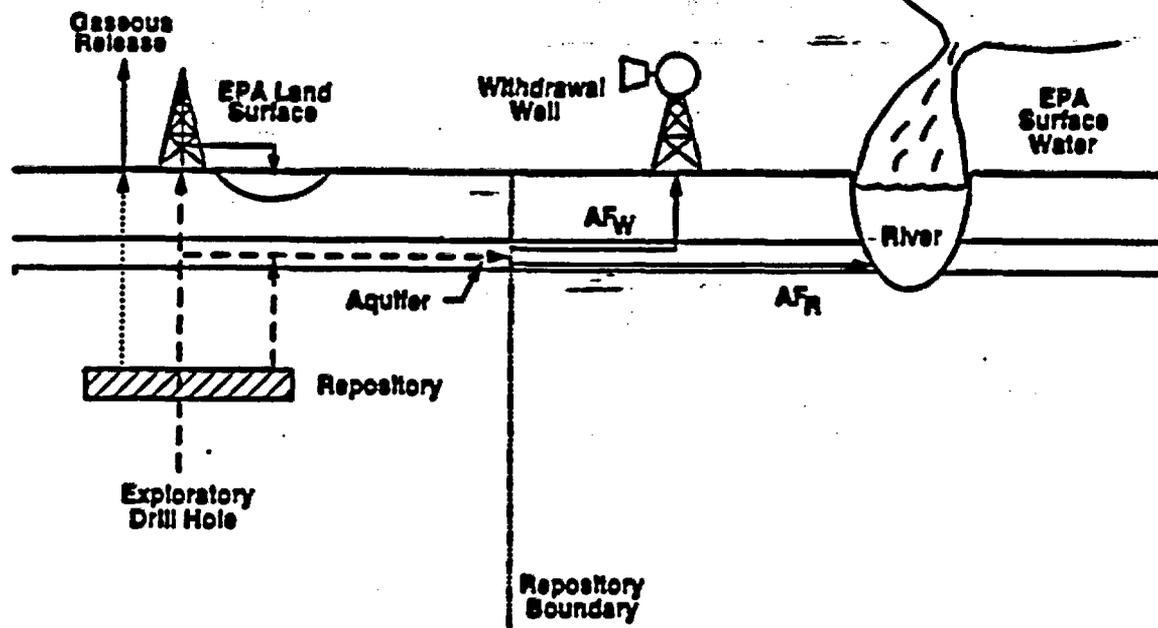


Figure 5-1. Schematic of a Radioactive Waste Disposal System Showing Possible Release Modes and Risk Attenuation Factors Outside the Repository.

(Gaseous releases are considered in the individual protection requirements. In some instances, human intrusion may not be considered in evaluations of the land release mode, as explained in Chapter 3.)

Description of Multimode Generic Release Limits

Tables 2 and 3 are proposed for Appendix B of 40 CFR Part to supply generic release limits that are set at the locations of release to the biosphere for each applicable release mode, which is just one step in the derivation prior to where they were set in the 1985 version of 40 CFR Part 191. The following sections describe multimode release limits, methods used in developing the four-column table of release limits, as well as methods for combining releases from all applicable modes into a single summed normalized release limit, corrections for repository locations and geologic risk attenuation, and suggestions for performance assessments. These multimode release limits contain some generalizations that may not apply to specific repositories, but the generalizations are limited to the processes between the release locations and humans. Multimode standards apply uniformly to all repositories and all release modes considered in the containment requirements. All major components in the disposal system are included in risk assessments.

EPA generic analyses from the release locations to humans ensure uniform modeling of the biosphere for all applications (dashed lines in Figure 5-2). The four-column release table proposed for 40 CFR Part 191 covers all applicable release modes for repositories. The appropriate release mode is selected for each pathway, and all disposal system components are included in the performance assessment. This is similar to the approach used for the 1985 version of 40 CFR Part 191, and most of the derivations of risk factors were completed for that

version of the standard (References 5-2 and 5-3). Differences are that risk factors for well releases have been calculated, and risk factors for ocean releases have been recalculated.* Release limits are still calculated by dividing the fundamental criterion (1,000 deaths per 10,000 years per reference repository) by the risk factor for each radionuclide.

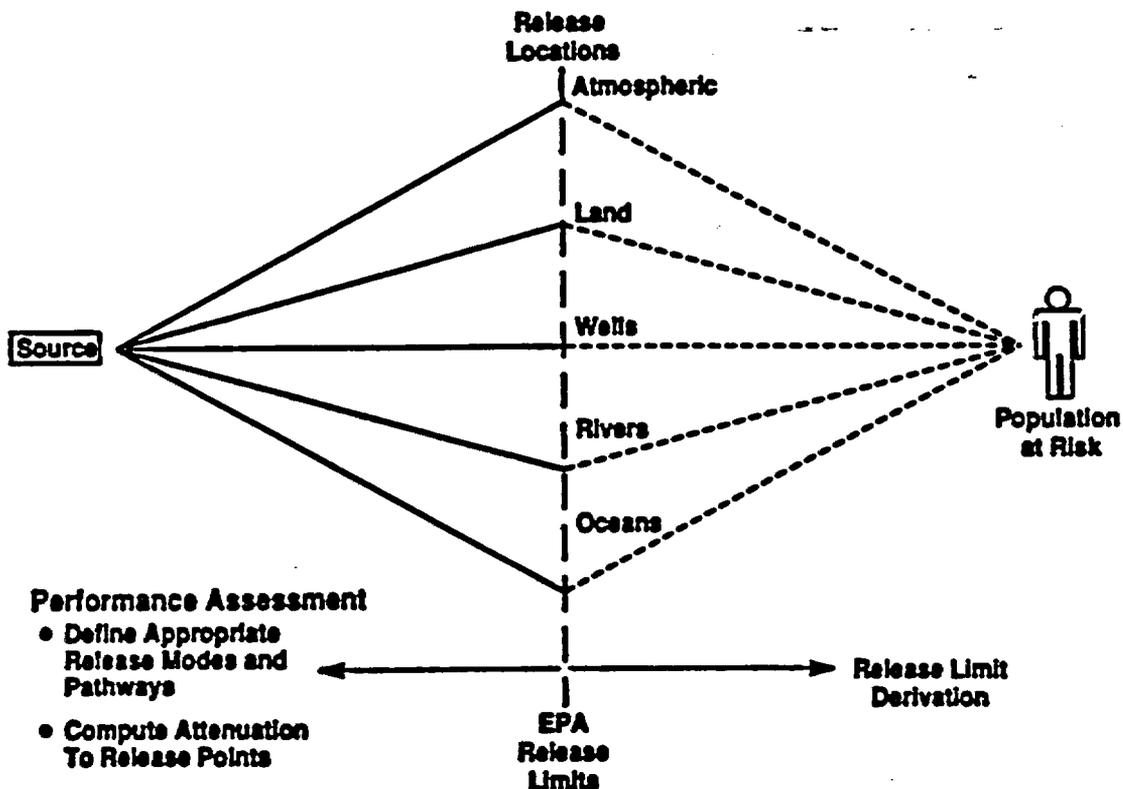


Figure 5-2. Multimode Release Limits in the Risk Assessment Process. (Atmospheric releases are considered in the individual protection requirements.)

Derivation and Implementation of Multimode Release Limits

The following sections summarize the factors considered in the derivation of the four-column tables of release limits in the present version of 40 CFR Part 191. Factors considered in analyses for the river and land release modes are from the Background Information Document (BID) for the 1985 version of 40 CFR Part 191. Factors considered in analyses for the ocean release mode are from a recent study. Data for the well release mode are new and are presented in this chapter.

The derivation of the single generic table for release limits in the 1985 version of 40 CFR Part 191 assumed that all the fresh water that is used comes from the world's rivers. The new multimode release tables separate fresh water into surface water and groundwater. Surface water comes from lakes and rivers, but these sources are combined into a river release mode to be

*This technical support document assumes that analyses will be completed using a program such as MARINRAD (Reference 5-4) and a detailed model with a shelf compartment. Other references in this document to ocean releases make the same assumption. If this study is completed, values obtained from the evaluation should be substituted in Tables 5-3 through 5-6 of this Technical Support Document and in Tables 2 and 3 in Appendix B of 40 CFR Part 191.

consistent with earlier notation. The USGS publishes estimates of water sources and uses at 5-year intervals. Table 5-1 gives the 1985 percentages of water used for irrigation, livestock, and human drinking water that came from groundwater and surface water. Values are given for the United States and for regions with disposal sites currently under consideration. This table (or an updated version of it) is used to allocate water use to the well and river release modes. The values in Table 5-1 represent the percentages of each radionuclide that reach an aquifer by any means that would be available for well withdrawal or discharge to a river. It does not mean that all or any of these radionuclides will reach any points of release before they decay or during the 10,000 years of regulation. The DOE selects the percentages appropriate for each repository region.

Table 5-1. Fresh Water Sources in 1985 (Reference 5-5)

Region	Percentage	
	Groundwater	Surface Water
Rio Grande Region	28	72
Great Basin	19	81
United States	36	64

River Release Mode

World-average parameters were used to compute risk factors included in the 1985 version of the standards (Reference 5-3). This approach is compatible with fundamental criteria for collective risk and can be used with multimode derivations. The pathways to humans for the river release mode include ingestion of drinking water, freshwater fish, food crops, milk, and beef; inhalation of resuspended material; and external exposure to ground contamination and air submersion. "River" includes all sources of fresh surface water. Derivations for the river mode have not been updated with more recent data. Ocean releases, which were included in the 1985 version of the table, have been removed from the river release mode and are now considered separately.

The derivation of the risk factors for the river release mode, using world-average parameters, assumes that the entire drainage system of all rivers is contaminated with the released radionuclides regardless of the repository location (Reference 5-2). Site Adjustment Factors (SAF_R) may be used to correct for actual repository locations and may be selected by the DOE.

As an example, Figure 5-3 shows that, in reality, only the downstream section of the tributary that is fed by groundwater passing the repository is contaminated. The ratio of the actual available contaminated water to the total available water in the drainage system is approximated by dividing the sum of the products of contaminated tributary lengths and flow rates by equivalent sums of all tributaries:

$$SAF_R = \frac{\sum_{i=1}^n (L_{C(i)} * F_{C(i)})}{\sum_{i=1}^n (L_{C(i)} * F_{C(i)}) + \sum_{j=1}^n (L_{U(j)} * F_{U(j)})} \quad (5-1)$$

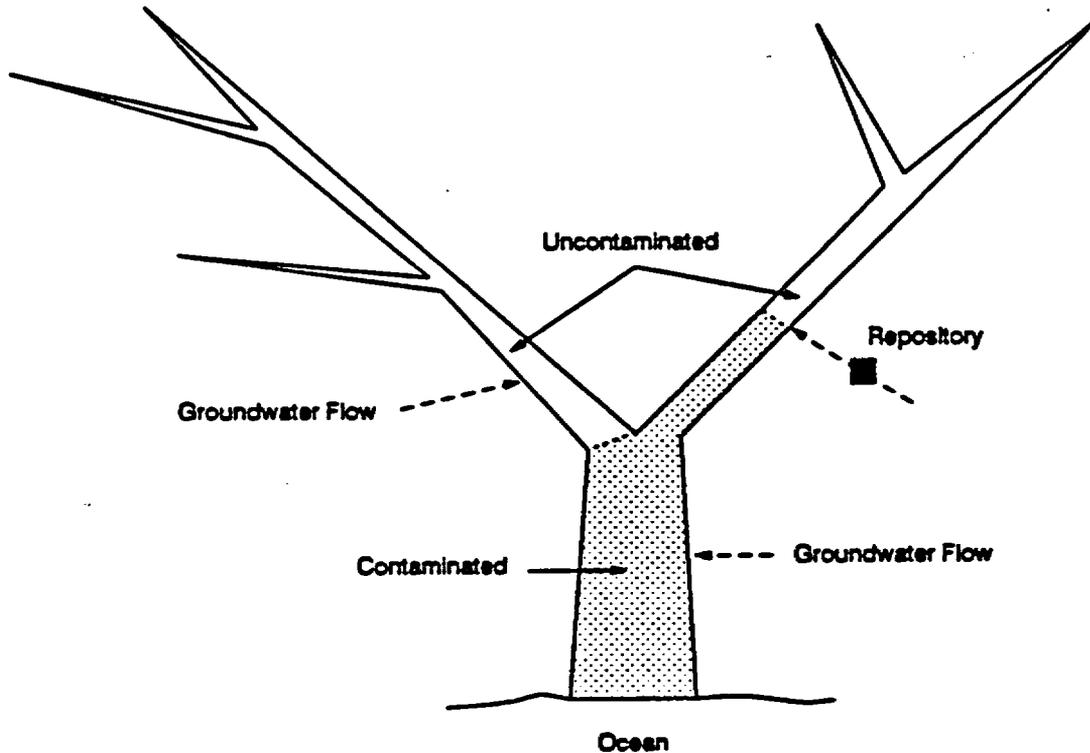


Figure 5-3. Generic River Basin for the River Release Mode

SAF_R is the site adjustment factor used to correct the risk factors for the river release mode. "L" is the length of the river segments and "F" is the volumetric flow rate of that segment. The subscripts "C" and "U" refer to contaminated and uncontaminated segments, respectively. The risk factors for the river release mode are adjusted by multiplying by the SAF_R . If the adjustment is applied to the release limits rather than to the risk factors, the Reciprocal Site Adjustment Factor ($RSAF_R$) is used as the multiplier to adjust the release limits. This definition of water availability is compatible with the derivation in the 1985 version of 40 CFR Part 191.

Attenuation factors (AFs) for radionuclide transport in aquifers depend on flow rates, diffusion, dispersion, retardation, decay rates of the nuclides, the duration of regulation, and the performance of all preceding repository components (Reference 5-6). Determining AFs for the river release mode would extend the present assessments beyond the controlled area.

Pathways for the well release mode are the same as those for the river mode except for fish consumption. The radionuclide concentrations in groundwater used to compute risk factors for the well mode are based on world averages, the same as the river mode, so that the standards are consistent. The total volumetric flow rates for both modes are computed by dividing the volumes of each part of the hydrosphere by their exchange activities. This information is available in a UNESCO report for all the major hydrosphere divisions (Reference 5-7) and is summarized in Table 5-2.

Table 5-2. World Hydrosphere Activities (Reference 5-7)

Part of Hydrosphere	Volume (km ³)	Exchange Activity (yrs)	Volumetric Flow (km ³ /yr)
Rivers	1.2×10^3	.032	3.8×10^4
Lakes	2.3×10^5	10	2.3×10^4
Active Groundwater	4.0×10^6	330	1.2×10^4
Total Groundwater	6.0×10^7	5000	1.2×10^4
World Oceans	1.4×10^9	3000	4.6×10^5

The derivation of the river risk factors in the 1985 version of 40 CFR Part 191 used a volumetric flow rate of 3×10^4 km³/yr. This flow rate is a good average of the lake and river divisions, which comprise surface water sources. The flow rates for groundwater are a factor of 2.5 lower, or the radionuclide concentrations in groundwater are a factor of 2.5 higher. Because the risk factors in the EPA derivations (Reference 5-3) are linear functions of concentration, the risk factors for the two modes scale with concentration. The ratio of release limits for the well release mode to those for the river mode range from 0.400 for Zr-93 to 0.803 for Cs-137. This variation is caused by fish consumption in the river mode.

The derivation of the limits for the well release mode using world average parameters assumes all groundwater from the recharge area to the locations where it enters surface waters is contaminated. Site Adjustment Factors (SAF_w) may be used in the same manner as for the river release mode. As an example, Figure 5-4 shows that, in reality, wells upgradient of the repository do not produce contaminated water. In addition, during the 10,000-year regulatory period, the contaminated plume may not reach the discharge location, and some uncontaminated water also would be withdrawn downgradient from the repository. The ratio of contaminated to total available water can be approximated by dating the water at the repository (A₁), at the point that the radionuclides are expected to reach in 10,000 years (A₂), and at the location where groundwater is discharged to a river (A₃), as shown in Figure 5-4. The site adjustment factor (SAF_w) can then be approximated by dividing the difference in the ages of the water at the farthest point of projected radionuclide migration in 10,000 years (A₂) and at the repository (A₁) by the age of the water at the point of discharge to the river (A₃):

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$$SAF_w = \frac{A_2 - A_1}{A_3} \quad (5-2)$$

However, if the contaminated plume is projected to reach a river within 10,000 years, the SAF_w is approximated by the following formula:

$$SAF_w = \frac{A_3 - A_1}{A_3} \quad (5-3)$$

The risk factors are multiplied by these ratios. If the correction is applied directly to the release limits rather than to the risk factors, the release limits are multiplied by the Reciprocal Site Adjustment Factor ($RSAF_w$).

Computations of attenuation factors are similar to those for the river release mode. Over a 10,000-year period, withdrawal wells could be located anywhere in the contaminated plume outside the controlled area. Therefore, to assume uniform withdrawal in the plume for the entire time is reasonable. The well AFs are then based on a statistical sampling of distances to wells instead of being based on a single distance, as the river mode AFs are.

Ocean Release Mode

Ocean risk factors in References 5-2 and 5-3 were compared with those computed with the MARINRAD (Reference 5-4) computer program and deep ocean and shelf models for the Subseabed Disposal Project (References 5-8 and 5-9). The comparison showed that the ocean risk factors used to derive the release limits in the 1985 version of 40 CFR Part 191 were up to a factor of 100 too low (Reference 5-10). This difference was confirmed by a preliminary study of ocean risk factors that were defined in a letter from R.D. Klett (SNL) to D. Ensminger (TASC) concerning the "Ocean Model for Release Limit Derivation," dated October 22, 1991. The preliminary study was conducted by TASC and explained in a letter from S. Oston (TASC) to R. Williams (EPRI) about "Ocean Pathway Modeling," dated December 10, 1991. [Note: A thorough study of the ocean mode should be conducted with MARINRAD.]

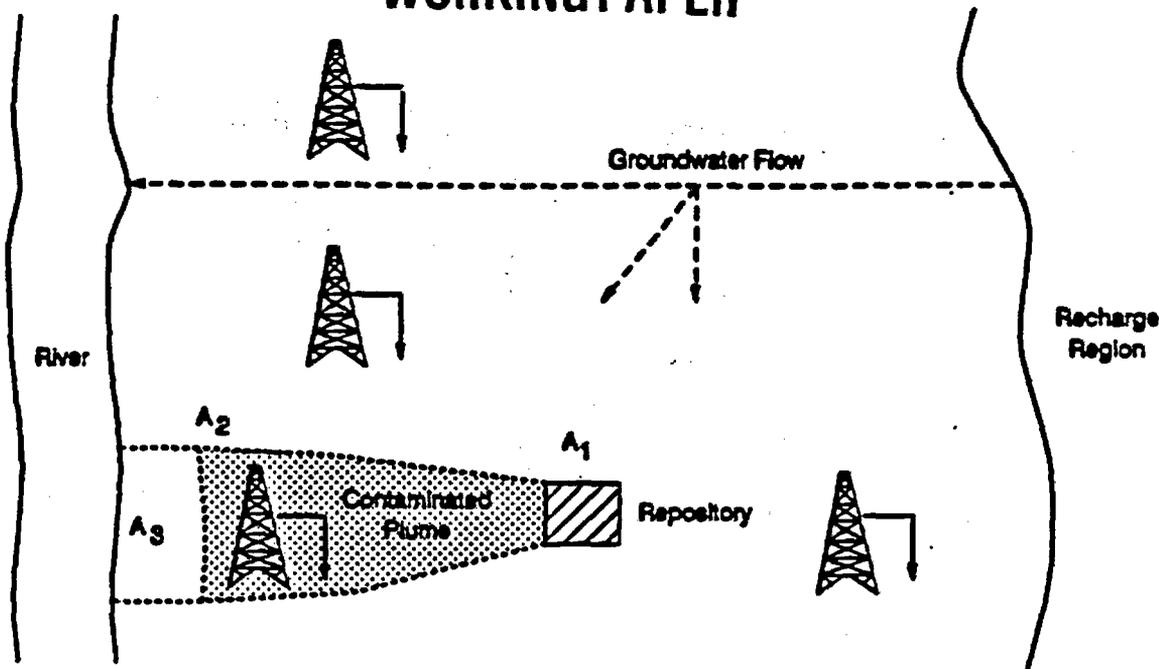


Figure 5-4. Generic Groundwater Diagram for the Well Release Mode

No correction factors for repository location are required for the ocean mode. With the conservative assumptions of no risk attenuation in the rivers and the return of all irrigation water to the rivers, the same geologic AFs are used for the river and ocean release modes for each repository.

Land Release Mode

Changing the method of computing risk factors for the land mode is not necessary, and the risk factors have not been updated with more recent data. No corrections for repository location and no computations of risk attenuation are required for the land release mode.

Atmospheric Release Mode

This release mode is one of the five general modes of release and is included here for completeness. However it is proposed that releases from this mode should be considered in the individual protection requirements. The column for atmospheric releases in the tables for multimode release limits are retained here only for completeness.

Risk Factors

This section presents the derivation results in terms of risk factors, the premature fatal cancers induced over 10,000 years for each curie of the various radionuclides that may be released to the biosphere. These risk factors were used to develop the radionuclide release limits proposed for Tables 2 and 3 of Appendix B of 40 CFR Part 191. Risk factors in cancers per TBq are shown here in Table 5-3, and risk factors in cancers per curie are shown in Table 5-4.

The analyses described in this chapter were used to develop radionuclide release limits for the multimode method that correspond to the level of protection chosen for the containment requirements of the final rule (Section 191.13). The 1985 BID describes the procedure used to determine release limits from the risk factors. The maximum number of fatalities allowed by the fundamental criterion were divided by the fatal cancers per curie for each release mode and each radionuclide. The release limits in SI units are shown here in Table 5-5, and the release limits in curies and associated units are shown in Table 5-6.

Summed Normalized Releases

Note 8 for Tables 2 and 3 proposed for Appendix B of 40 CFR Part 191 indicates how release limits are used in determining compliance with the containment requirements (Section 191.13). In most instances, a mixture of radionuclides is projected to be released to the biosphere. The summed normalized release limit for each scenario or event includes the release fractions for each nuclide for each release mode:

$$Q_{L,x}/RL_{L,x} + Q_{L,y}/RL_{L,y} + \dots + Q_{W,x}/RL_{W,x} + Q_{W,y}/RL_{W,y} + \dots +$$

$$Q_{R,x}/RL_{R,x} + Q_{R,y}/RL_{R,y} + \dots + Q_{O,x}/RL_{O,x} + Q_{O,y}/RL_{O,y} + \dots + \tag{5-4}$$

$$Q_{O,x}/RL_{O,x} < 1. \tag{5-4}$$

Q is the computed 10⁴ year release of a radionuclide for each release mode at the release location, and RL is the release limit for that nuclide and release mode. The subscripts L, W, R, and O refer to the land, well, river, and ocean release modes, respectively, and the subscripts a, b, . . . , n refer to the individual radionuclides listed in the tables. The effect of multimode release tables on the release CCDF is to change the magnitude of the normalized release (R) for each scenario or event relative to the single release method in the 1985 version of 40 CFR Part 191, as illustrated in Figure 5-5. The probabilities of the individual scenarios or events that make up the CCDF are unchanged.

Table 5-3. Fatal Cancers per TBq Released to the Biosphere over 10,000 Years for Multiple Release Modes

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Cancers per TBq					
Nuclide	River ^a	Well ^a	Ocean ^a	Land ^a	Atmosphere
C-14	TBD ^d	TBD	TBD	TBD	1.57E+00 ^e
Ni-59	1.24E-03	3.03E-03	TBD	1.83E-05	NA ^e
Sr-90	6.08E-01	1.51E+00	6.62E-04	1.02E-03	NA
Zr-93	4.08E-03	1.02E-02	1.06E-03	6.10E-04	NA
Tc-99	9.86E-03	2.41E-02	4.29E-05	1.53E-06	NA
Sn-126	2.84E+00	6.95E+00	2.89E+00	3.73E-02	NA
I-129	2.18E+00	5.43E+00	7.32E-03	1.07E-01	6.72E+00 ^e
Cs-135	2.09E-01	4.69E-01	1.73E-03	1.55E-02	NA
Cs-137	2.89E-01	3.60E-01	1.33E-02	5.91E-04	NA
Sm-151	2.53E-04	6.14E-04	TBD	1.81E-06	NA
Pb-210	3.19E+00	7.03E+00	TBD	4.10E-03	NA
Ra-226	4.40E+00	1.05E+01	TBD	1.52E-01	NA
Ra-228	6.51E-01	1.52E+00	TBD	4.24E-04	NA
Ac-227	1.80E+00	4.34E+00	4.13E+00	3.35E-03	NA
Th-229	9.42E-01	2.30E+00	4.64E+00	5.13E-01	NA
Th-230	1.45E+01	3.60E+01	TBD	1.04E+01	NA
Th-232	9.18E+00	2.29E+01	TBD	1.02E+01	NA
Pa-231	4.00E+00	9.87E+00	1.60E+00	6.37E-01	NA
U-233	5.81E-01	1.44E+00	2.50E-02	2.03E-02	NA
U-234	5.29E-01	1.31E+00	TBD	1.77E-02	NA
U-235	5.86E-01	1.45E+00	2.26E-02	2.27E-02	NA
U-236	5.00E-01	1.24E+00	TBD	1.67E-02	NA
U-238	5.56E-01	1.38E+00	TBD	1.86E-02	NA
Np-237	2.15E+00	3.27E+00	3.89E-01	3.27E-03	NA
Pu-238	1.14E+00	2.82E+00	TBD	8.37E-03	NA
Pu-239	1.34E+00	3.32E+00	1.55E+00	1.68E-01	NA
Pu-240	1.31E+00	3.23E+00	1.55E+00	1.41E-01	NA
Pu-241	5.86E-02	1.45E-01	0.00E+00	6.75E-05	NA
Pu-242	1.29E+00	3.20E+00	TBD	1.71E-01	NA
Am-241	1.46E+00	3.28E+00	5.48E+00	2.84E-02	NA
Am-243	1.54E+00	3.49E+00	5.37E+00	6.62E-02	NA
Cm-245	2.73E+00	6.58E+00	8.07E+00	2.18E-01	NA
Cm-246	1.35E+00	3.25E+00	TBD	9.56E-02	NA

Sources:

^aReference 5-2

^bThis report

^cPreliminary incomplete analysis by TASC using MARINRAD

^dTo be determined

^eNot Applicable

^fReference 5-1 using 0.04 cancers per Sv

**Table 5-4. Fatal Cancers per Curie Released to the Biosphere
Over 10,000 years for Multiple Release Modes**

Cancers per curie					
Nuclide	River ^a	Well ^b	Ocean ^c	Land ^d	Atmosphere
C-14	TBD ^e	TBD	TBD	TBD	5.83E-02 ^f
Ni-59	4.61E-05	1.12E-04	TBD	6.79E-07	NA ^g
Sr-90	2.25E-02	5.60E-02	2.45E-05	3.76E-05	NA
Zr-93	1.51E-04	3.77E-04	3.94E-05	2.26E-05	NA
Tc-99	3.65E-04	8.93E-04	1.59E-06	5.65E-08	NA
Sn-126	1.05E-01	2.57E-01	1.07E-01	1.38E-03	NA
I-129	8.07E-02	2.01E-01	2.71E-04	3.96E-03	2.49E-01 ^h
Cs-135	7.73E-03	1.74E-02	6.39E-05	5.75E-04	NA
Cs-137	1.07E-02	1.33E-02	4.92E-04	2.19E-05	NA
Sm-151	9.38E-06	2.27E-05	TBD	6.71E-08	NA
Pb-210	1.18E-01	2.61E-01	TBD	1.52E-04	NA
Ra-226	1.63E-01	3.87E-01	TBD	5.62E-03	NA
Ra-228	2.41E-02	5.62E-02	TBD	1.57E-05	NA
Ac-227	6.67E-02	1.61E-01	1.53E-01	1.24E-04	NA
Th-229	3.49E-02	8.51E-02	1.72E-01	1.90E-02	NA
Th-230	5.38E-01	1.33E+00	TBD	3.86E-01	NA
Th-232	3.40E-01	8.47E-01	TBD	3.76E-01	NA
Pa-231	1.48E-01	3.66E-01	5.94E-02	2.36E-02	NA
U-233	2.15E-02	5.33E-02	9.25E-04	7.51E-04	NA
U-234	1.96E-02	4.86E-02	TBD	6.54E-04	NA
U-235	2.17E-02	5.38E-02	8.36E-04	8.42E-04	NA
U-236	1.85E-02	4.59E-02	TBD	6.18E-04	NA
U-238	2.06E-02	5.11E-02	TBD	6.90E-04	NA
Np-237	7.95E-02	1.21E-01	1.44E-02	1.21E-04	NA
Pu-238	4.23E-02	1.05E-01	TBD	3.10E-04	NA
Pu-239	4.97E-02	1.23E-01	5.73E-02	6.23E-03	NA
Pu-240	4.84E-02	1.20E-01	5.73E-02	5.22E-03	NA
Pu-241	2.17E-03	5.36E-03	TBD	2.50E-06	NA
Pu-242	4.79E-02	1.18E-01	TBD	6.34E-03	NA
Am-241	5.42E-02	1.22E-01	2.03E-01	1.05E-03	NA
Am-243	5.72E-02	1.29E-01	1.99E-01	2.45E-03	NA
Cm-245	1.10E-01	2.44E-01	2.99E-01	8.08E-03	NA
Cm-246	4.99E-02	1.20E-01	TBD	3.54E-03	NA

Sources:

^a Reference 5-2

^b This report

^c Preliminary incomplete analysis by TASC using MARINRAD

^d To be determined

^e Not applicable

^f Reference 5-11 using 0.04 cancers per Sv

Table 5-5. Cumulative Release Limits for 10,000 years (TBq per 100,000 MTHM)
for Multiple Release Modes

(This table should be used only with RSAFs)

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Release Limit (TBq per 100,000 MTHM)					
Nuclide	River ^a	Well ^b	Ocean ^c	Land ^d	Atmosphere
C-14	TBD ^e	TBD	TBD	TBD	6E+02 ^f
Ni-59	8E+05	3E+05	TBD	5E+07	NA ^g
Sr-90	2E+03	7E+02	2E+06	1E+06	NA
Zr-93	2E+05	1E+05	9E+05	2E+06	NA
Tc-99	1E+05	4E+04	2E+07	7E+08	NA
Sn-126	4E+02	1E+02	3E+02	3E+04	NA
I-129	5E+02	2E+02	1E+05	9E+03	1E+02 ^h
Cs-135	5E+03	2E+03	6E+05	6E+04	NA
Cs-137	3E+03	3E+03	8E+04	2E+06	NA
Sr-151	4E+06	2E+06	TBD	6E+08	NA
Pb-210	3E+02	1E+02	TBD	2E+05	NA
Ra-226	2E+02	1E+02	TBD	7E+03	NA
Ra-228	2E+03	7E+02	TBD	2E+06	NA
Ac-227	6E+02	2E+02	2E+02	3E+05	NA
Th-229	1E+03	4E+02	2E+02	2E+03	NA
Th-230	7E+01	3E+01	TBD	1E+02	NA
Th-232	1E+02	4E+01	TBD	1E+02	NA
Pa-231	3E+02	1E+02	6E+02	2E+03	NA
U-233	2E+03	7E+02	4E+04	5E+04	NA
U-234	2E+03	8E+02	TBD	6E+04	NA
U-235	2E+03	7E+02	4E+04	4E+04	NA
U-236	2E+03	8E+02	TBD	6E+04	NA
U-238	2E+03	7E+02	TBD	5E+04	NA
Np-237	5E+02	3E+02	3E+03	3E+05	NA
Pu-238	9E+02	4E+02	TBD	1E+05	NA
Pu-239	7E+02	3E+02	6E+02	6E+03	NA
Pu-240	8E+02	3E+02	6E+02	7E+03	NA
Pu-241	2E+04	7E+03	TBD	1E+07	NA
Pu-242	8E+02	3E+02	TBD	6E+03	NA
Am-241	7E+02	3E+02	2E+02	4E+04	NA
Am-243	6E+02	3E+02	2E+02	2E+04	NA
Cm-245	4E+02	2E+02	1E+02	5E+03	NA
Cm-246	7E+02	3E+02	TBD	1E+04	NA

^aReference 5-2

^eTo be determined

^bThis Report

^fNot applicable

^cPreliminary incomplete analysis by TASC using MARINRAD

^dReference 5-11 using 0.04 cancers per sv

Table 5-6. Cumulative Release Limits for 10,000 years (curies per 100,000 MTHM) for Multiple Release Modes

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(This table should be used only with RSAFs)

Release Limit (curies per 100,000 MTHM)					
Nuclide	River ^a	Well ^b	Ocean ^c	Land ^d	Atmosphere
C-14	TBD ^e	TBD	TBD	TBD	2E+04 ^f
Ni-59	2E+07	9E+06	TBD	1E+09	NA ^g
Sr-90	4E	2E+04	4E+07	3E+07	NA
Zr-93	7E	3E+06	3E+07	4E+07	NA
Tc-99	3E+06	1E+06	6E+08	2E+10	NA
Sr-126	1E+04	4E+03	9E+03	7E+05	NA
I-129	1E+04	5E+03	4E+06	3E+05	4E+03 ^f
Cs-135	1E+05	6E+04	2E+07	2E+06	NA
Cs-137	9E+04	8E+04	2E+06	5E+07	NA
Sm-151	1E+08	4E+07	TBD	1E+10	NA
Pb-210	8E+03	4E+03	TBD	7E+06	NA
Ra-226	6E+03	3E+03	TBD	2E+05	NA
Ra-228	4E+04	2E+04	TBD	6E+07	NA
Ac-227	1E+04	6E+03	7E+03	8E+06	NA
Th-229	3E+04	1E+04	6E+03	5E+04	NA
Th-230	2E+03	8E+02	TBD	3E+03	NA
Th-232	3E+03	1E+03	TBD	3E+03	NA
Pa-231	7E+03	3E+03	2E+04	4E+04	NA
U-233	5E+04	2E+04	1E+06	1E+06	NA
U-234	5E+04	2E+04	TBD	2E+06	NA
U-235	5E+04	2E+04	1E+06	1E+06	NA
U-236	5E+04	2E+04	TBD	2E+06	NA
U-238	5E+04	2E+04	TBD	1E+06	NA
Np-237	1E+04	8E+03	7E+04	8E+06	NA
Pu-238	2E+04	1E+04	TBD	3E+06	NA
Pu-239	2E+04	8E+03	2E+04	2E+05	NA
Pu-240	2E+04	8E+03	2E+04	2E+05	NA
Pu-241	5E+05	2E+05	TBD	4E+08	NA
Pu-242	2E+04	8E+03	TBD	2E+05	NA
Am-241	2E+04	8E+03	5E+03	1E+06	NA
Am-243	2E+04	8E+03	5E+03	4E+05	NA
Cm-245	1E+04	4E+03	3E+03	1E+05	NA
Cm-246	2E+04	8E+03	TBD	3E+05	NA

^aReference 5-2

^eTo be determined

^bThis Report

^fNot applicable

^cPreliminary incomplete analysis by TASC using MARINRAD

^dReference 5-11 using 0.04 cancers per sv

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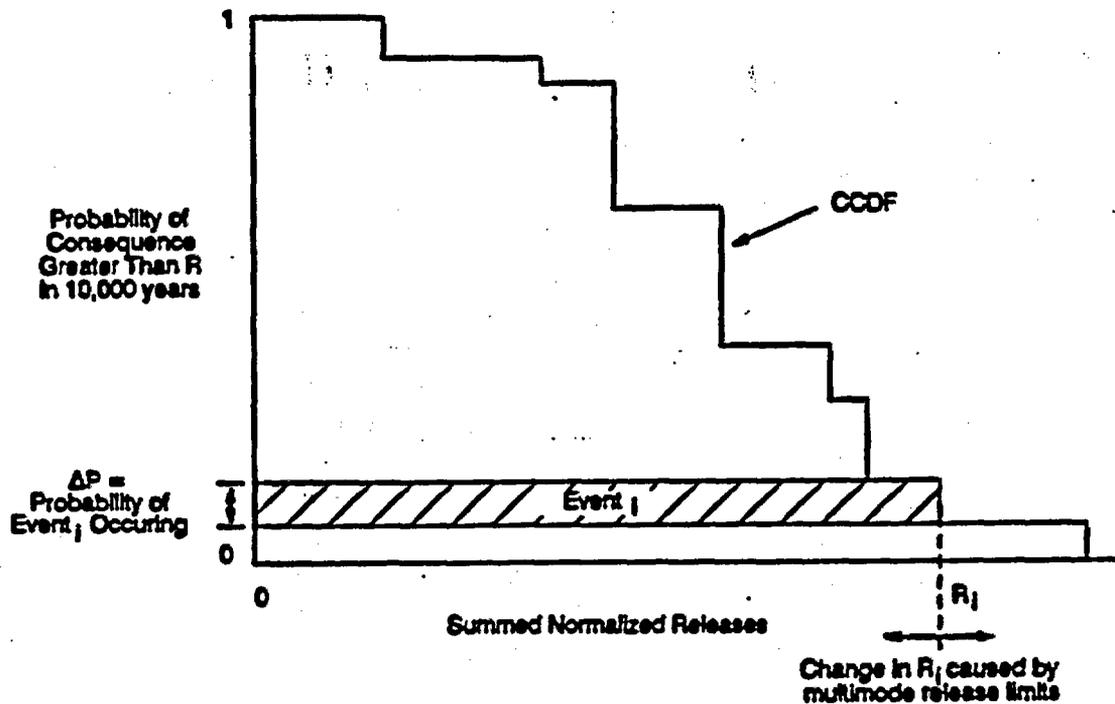


Figure 5-5. Effects of Multimode Release Limits on the Release CCDF

Performance Assessments with Multimode Release Limits

Figure 5-2 illustrates the function of performance assessments (PA) using multimode release limits. Some releases from disruptive geologic events (e.g. volcanos) would be through the upper surface of the controlled volume as shown in Figure 5-1. For these pathways, the PA segment of the risk assessment evaluates releases against land release limits.

For radionuclide transport through an aquifer, the groundwater that is not withdrawn by wells would eventually reach rivers, lakes, and oceans. Computations of releases to wells, rivers, and oceans may require additional attenuation factor analyses (Reference 5-6) by PA, and some site characterization past the controlled volume may be required. Site characterization and analyses only have to extend far enough to show compliance. The remainder of the disposal system could be considered an additional, but unquantified, margin of safety. Because the standards do not specify average fractions of fresh water usage obtained from ground and surface water, regional values are defined by the DOE and incorporated into assessments. The river and well release limits are adjusted by PA to account for the location of each repository relative to the recharge location and closest river or ocean.

The inclusion of multimode release limits as an option in the containment requirements refines the release limit approach used in the 1985 version of 40 CFR Part 191. The use of multimode release limits accounts for the applicable release modes in assessing the performance of a disposal system for the containment requirements. The DOE would be able to select release modes and release locations for all pathways for each repository. PA will include all pre-release disposal system components in the assessments, from the repository to the release locations. Because all transport and biological effects from the release location to humans for all four release modes have been calculated, the biosphere and effects are uniform for all applications. These derivations were conducted with generic models and data, so the multimode release limits still contain some generalizations that may affect risk assessments. Multimode release limits are not site-specific and can therefore be applied to future repositories. This approach is compatible with the 40 CFR Part 191 format. The derivations for the river and land release modes were performed for the 1985 version of 40 CFR Part 191 and are complete. The limits for the ocean release mode should be recalculated, and the derivation for the well release mode is a modification of the limits for the river release mode. The roles of the DOE in PA have been expanded to include release mode selection, corrections to account for repository locations, and possible analyses of attenuation factors outside the controlled area. Site characterization and analyses only have to extend far enough to show compliance.

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REFERENCES

- 5-1. Federal Register, Environmental Protection Agency, 40 CFR Part 191, "Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes; Final Rule," Vol. 50, No. 182, September 19, 1985.
- 5-2. "Background Information Document - Final Rule for High-Level and Transuranic Radioactive Wastes," EPA 520/1-85-023, August 1985.
- 5-3. J. M. Smith, T. W. Fowler, and A. S. Goldin, "Environmental Pathway Models for Estimating Population Health Effects from Disposal of High-Level Radioactive Waste in Geologic Repositories; Final Report," EPA 520/5-85-026, August 1985.
- 5-4. D. A. Ensminger, C. M. Koplik, and J. Y. Nalbandian, "User's Guide to MARINRAD IV: Model for Assessing the Consequences of Release of Radioactive Material into the Oceans," SAND87-7067, September 1987.
- 5-5. W. B. Solley, C. F. Merk, and R. R. Pierce, "Estimated Uses of Water in the United States in 1985," USGS Circular 1004, 1988.
- 5-6. R. D. Klett, "Waste Disposal Performance Assessment Using Attenuation Factors," SAND84-2624, March 1988.
- 5-7. M. I. Lvovitch, "World Water Balance (General Report)," Proceedings of the World Water Balance Symposium, Volume 2, July 1970, Unesco, Paris, 1972.
- 5-8. M. F. Kaplan, in "1985 Subseabed Disposal Project Annual Report: Systems, October 1984 through September 1985," R. D. Klett, Ed., SAND86-0244, May 1986.
- 5-9. G. de Marsilly, et al., "Feasibility of Disposal of High-Level Radioactive Waste into the Seabed: Volume 2, Radiological Assessment," Nuclear Energy Agency, Paris, 1988.
- 5-10. R. D. Klett, "Proposed Extensions of United States Fundamental and Derived Standards for High-Level and Transuranic Radioactive Waste Disposal," SAND91-0211, July 1991.
- 5-11. G. M. Smith and I. F. White, "A Revised Global-Circulation Model for Iodine-129," National Radiological Protection Board", Chilton, Didcot, Oxon, June 1983.
- 5-12. Clean Air Act, 42 U.S.C.A., Section 7401 et seq. (1983 & Supp. 1991).
- 5-13. United States Environmental Protection Agency, "National Emission Standards for Hazardous Air Pollutants," 40 CFR Part 61, Subpart I.

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CHAPTER 6

COLLECTIVE DOSE

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CHAPTER 6

COLLECTIVE DOSE

6.1 STATEMENT OF THE PROBLEM

In some instances the release limits of Table 1 in 40 CFR Part 191 may result in an inappropriate or overly conservative evaluation of repository sites because they do not adequately account for significant features of a site. Release limits are derived standards used only to facilitate regulation. A higher level criterion of dose limits could be used without jeopardizing safety. A dose option similar to that provided in the Draft Federal Register Notice of 40 CFR Part 191 (2/3/92) would allow the Department to show compliance with collective dose limits that are equivalent to the fundamental criterion, i.e., equivalent to 1,000 health effects over 10,000 years per 100,000 metric tons of heavy metal.

6.2 RECOMMENDED APPROACH **WORKING PAPER**

Incorporation of the collective dose option requires only minor wording changes to language developed in EPA's Draft Federal Register Notice (2/3/92). Issues to be considered in using this option are discussed in Chapter 2. Gaseous releases are considered in the individual protection requirements, as discussed in Chapter 9. Human intrusion is discussed in Chapter 3. A standard biosphere, as described in the "Future States" section to be added to Appendix D (Guidance for Implementation of Subpart B), should be specified.

The following material suggests a way that the standard might be rewritten to incorporate the collective dose option. Most of the text for subsection (b) is taken from the Draft Federal Register Notice (2/3/92) but is provided here for clarity. Section 191.13 would be rewritten as follows:

191.13 Containment Requirements

The Department may invoke either subsection (a) or (b) of this section.

(a) Disposal systems for spent fuel

(b) Disposal systems for radioactive waste shall be designed to provide a reasonable expectation, based upon performance assessments, that the collective (population) effective dose, calculated using the weighting factors in Appendix C, caused by releases of radionuclides to the accessible environment for 10,000 years after disposal from all significant processes and events that may affect the disposal system shall:

- (1) Have a likelihood of less than one chance in 10 of exceeding 2.5 million person-rem (25,000 person-sieverts); and
- (2) Have a likelihood of less than one chance in 1,000 of exceeding 25 million person-rem (250,000 person-sieverts).

Dose limits are based upon an HLW/SF repository of 10^5 MTHM and XX MCi for a TRU repository.

Appendix C should contain the information that was in Appendix B of the Draft Federal Register Notice (2/3/92). However, the information in that Appendix has yet to be fully accepted in the United States. Consideration should be given to returning to the information contained in Appendix A of Working Draft 3 (4/25/91) until acceptance of the ICRP 60 methods used in the Draft Federal Register Notice (2/3/92) has been achieved.

Appendix D would contain the information found in Appendix B of the 1985 version of the standard. The following wording should be added to Appendix D, Guidance for Implementation of Subpart B,:

Future States. Uncertainties involving things that are unknowable about the future can only be dealt with by making assumptions and recognizing that these may, or may not, correspond to a future reality. The Agency believes that speculation concerning future conditions should not be the focus of the compliance determination process. Therefore, it

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would be appropriate for assessments made under Part 191 to contain the assumption that many conditions remain the same as today's. Conditions in this category include population distributions (i.e., current population distributions should be assumed), level of knowledge and technical capability, human physiology and nutritional needs, the state of medical knowledge, societal structure and behavior, patterns of water use, and pathways through the accessible environment. The Agency would not find it appropriate to include in this category the geologic, hydrologic, and climatic conditions whose future states may be estimated by examining the geologic record. Although the Agency would not find it appropriate to assume that national or world populations will remain unchanged, it would be inappropriate to assume future world populations that cannot reasonably be sustained by current abilities to produce, distribute, and consume food. For this reason, future world populations in excess of 10 billion people need not be assumed in evaluations under section 191.13.

The following wording should be added between the 2nd and 3rd sentences of the paragraph entitled, "*Compliance with Section 191.13*":

Section 191.13 contains options for comparing results of performance assessments with release limits and dose limits. The complementary cumulative distribution function may represent both summed release fractions and summed dose fractions. It is appropriate to apply dose standards to specific events or processes for which the release limits are inappropriate. The predicted doses for each event may then be normalized relative to the dose limits set by the Agency in the same manner as predicted releases. The dose fraction then replaces the summed release fraction for that event in the complementary cumulative distribution function.

6.3 SUPPLEMENTARY INFORMATION

The following information explains the basis for incorporating a collective dose option in the rule. This material could be used by the EPA as supplementary information for the proposed rule.

The fundamental criterion, which is the basis for the containment requirements in 40 CFR Part 191, is that in disposing of radioactive waste there must be a reasonable expectation that releases from a reference repository will cause no more than 1,000 premature cancer deaths over the entire 10,000-year regulatory period. This criterion was based upon the premise that the overall risks to future generations be comparable to the risks that those generations would have faced from the uranium ore used to create the wastes. The Agency intends that the fundamental criterion shall be met in either of two ways: (1) through the use of derived release limits or (2) through the use of a collective dose standard.

The Agency has provided a collective dose alternative in the present version of the standard as a result of comments received. Some commenters have expressed the view that, in some instances, the use of a dose standard may be more appropriate than the use of generic derived release limits. According to the commenters, generic release limits do not fully account for site-specific attenuation factors that indicate variability in the lithosphere and biosphere surrounding repositories. It is the Agency's belief that derived release limits, either single generic or multimode, are appropriate for application to repositories. However, the Agency does realize that there may exist instances where comparisons to a dose standard more clearly reflects the performance of a repository. In applying the dose alternative, the Department would assess the movement of radionuclides from the repository to contact with humans. Whereas, when applying the release limits the Department assesses the movement of radionuclides from the repository to the accessible environment (for Table 1 in Appendix A) or to a point of compliance or the biosphere (for Tables 2 and 3 in Appendix B), with the Agency generically assessing the impacts beyond this point.

The performance of dose-based risk assessments may require extensive site characterization for repositories that may not have attenuation processes adequately represented by comparison with release limits. To reduce somewhat the scope of such site characterizations, the Agency has added a section in Appendix D of this rule that provides guidance concerning projections of occurrences in the future.

It would be appropriate to apply the dose standards only to specific events or processes for which comparisons to the release limits do not adequately reflect repository performance. Predicted dose for each analyzed event may be normalized relative to the dose limits set by the Agency in the same manner as predicted releases. The dose fraction then replaces the summed release fraction for that event in the CCDF. The probability remains the same, so the only effect is to change the consequence level for that event in the CCDF.

A preliminary performance evaluation may be needed to select the most appropriate standard for a particular repository. Repository evaluations using release limits are less expensive and can be completed in less time because they require less site characterization and a less complex performance assessment. However, the approximate release limits may not adequately represent the attenuating processes of some repositories, and the less approximate dose standards may be used.

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The Agency believes that the collective dose alternative and the release limits alternative are both viable means of providing protection to human health and the environment. In fact, the fundamental criterion, which is expressed in terms of health effects per unit waste over time, remains the same regardless of which alternative is used. The containment requirements are simply a method of showing compliance with the fundamental criterion. Providing both release limits and dose limits does not mean that proposed repositories are expected to comply with both standards. An unsafe repository could not comply with either dose or release limits, so evaluating compliance against both standards is neither expected nor required.

Thus, the Agency is providing the Department with the option of using the alternative it determines is the most appropriate for a given site. The key in determining the appropriateness of one alternative over the other should be based upon the ability of the particular alternative to reflect more clearly the capability of a disposal system to meet the fundamental criterion.

6.4 TECHNICAL SUPPORT DOCUMENTATION

The following material is supporting information that could be cited as justification for the proposed revision. It could be part of a technical support document for the rule.

The 1985 version of 40 CFR Part 191 (Reference 6-1) contained derived release limits as the standard for evaluating protection of future populations for at least 10,000 years from disposal of radioactive wastes. These release limits, which were derived from a dose standard, used predictive assumptions, generalizations, and simplifications in order to provide a generic standard. The EPA believes that, in most instances, exceptionally good protection can be achieved with release limits. However, in reexamining 40 CFR Part 191, the EPA has received substantial comment addressing the use of derived release limits. One aspect that has been commented on in depth is that, for some repositories, the conservative approximate release limits may not adequately account for attenuating processes and that evaluation against a dose standard, which would be more comprehensive, may be required. Dose limits provide a more precise measure of actual risk but may require more extensive site characterizations and performance assessments. In order to allow for possible circumstances that may require a more comprehensive analysis, the Agency has provided dose limits as an alternative to using the release limits in the present rule. Performance assessments now have the option of constructing the CCDF by using all normalized releases, all normalized doses, or a combination of the two. Providing both release limits and dose limits does not mean that proposed repositories are expected to comply with both standards. An unsafe repository could not comply with either dose or release limits, so evaluating compliance against both standards is neither expected nor required.

Description of the Dose Limit Alternative

The information used to develop the dose limit was used in the development of release limits. The implementation of dose and release limits have many similarities.

The dose limits are based on the fundamental criterion of 1,000 premature deaths during the 10,000 year regulatory period for the reference repository. The premature cancer deaths in the fundamental criterion were converted to allowable effective doses using a conversion factor supplied by the ICRP (Reference 6-2) to produce the dose limits. This procedure is explained in the next section.

Consequences using dose limits are normalized for an event or process similar to the way they are normalized using release limits. The normalized dose consequence is the computed dose divided by the dose limit. Performance assessments using dose limit standards produce the same type of normalized CCDF that is produced using release limits. Therefore, consequence CCDFs based on the dose standard and release limits are regulated by the same containment requirements. The probabilities of events or processes in the CCDF are the same with either limit. Only the values of individual normalized consequences (R for summed normalized release and D for normalized dose) are different, as illustrated in Figure 6-1. The CCDF may be constructed using all normalized releases, all normalized doses, or a combination of the two. The latter option is particularly advantageous for repositories that are expensive to characterize and analyze and have only a few events or processes that cannot be represented properly by generic release limits.

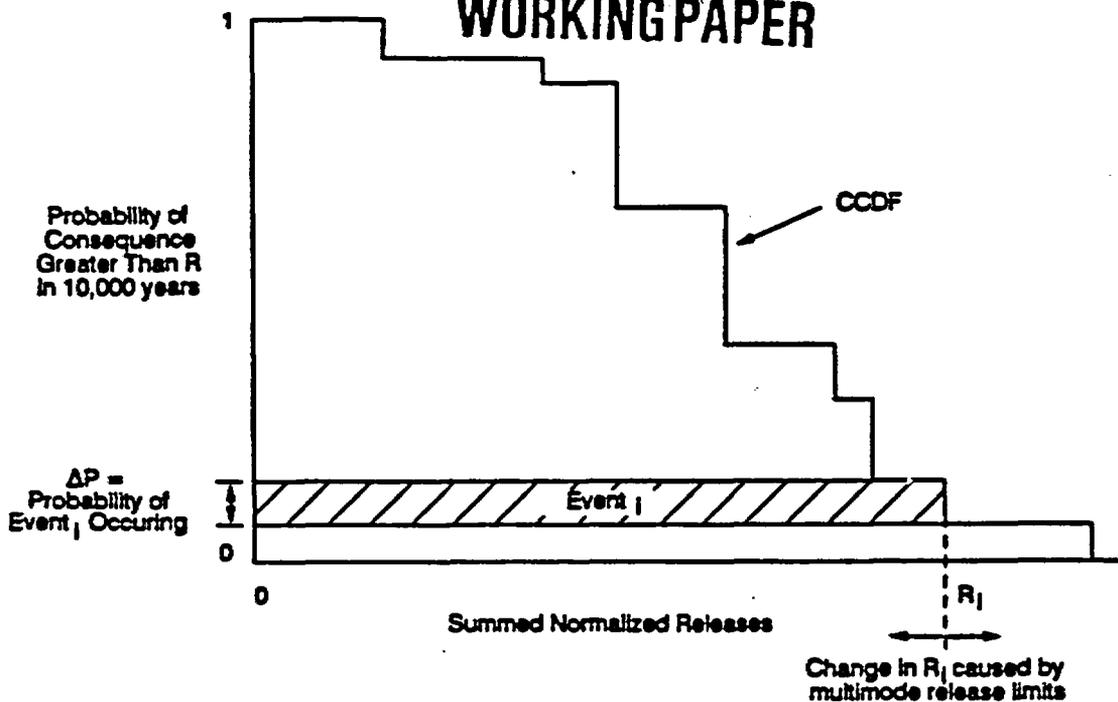


Figure 6-1. CCDF Made Up of Normalized Doses or Normalized Releases

Dose Criteria and Standard Biosphere

The consequences of radiation exposure that were used to develop the dose standard in the Draft Federal Register Notice of 40 CFR Part 191 (2/3/92) (Reference 6-3) are the same as the latest ICRP recommendations (Reference 6-2), which have not yet been accepted in the United States. The nominal probability coefficient for stochastic effects used to set the effective dose limits is 0.04 premature cancer deaths per Sv. Applying this coefficient to the fundamental criterion of 1,000 premature deaths in 10,000 years for the reference HLW repository containing 100,000 MTHM gives an effective dose limit of 25,000 person-sieverts per 100,000 MTHM (0.25 person-sieverts/MTHM). For the reference TRU repository containing XX MCi, the effective dose limit is 25,000 person-sieverts per 20 MCi of radioactive waste (0.00125 person-sieverts/Ci).

Two basic procedures can be used to compute collective effective doses. The procedures in Appendix B of the Draft Federal Register Notice of 40 CFR Part 191 (2/3/92) (Reference 6-3) for computing the effective dose are identical to those in Annex A of ICRP 60 (Reference 6-2). The effective dose (E) is the sum of weighted absorbed doses from all radiation types and energies, in all tissues and organs of the body. It is given by the expression:

$$E = \sum_R w_R \sum_T w_T \cdot D_{T,R} = \sum_T w_T \sum_R w_R \cdot D_{T,R} \quad (6-1)$$

where $D_{T,R}$ is the mean absorbed dose to organ T delivered by radiation R. The radiation is that incident on the body or emitted by a source within the body. Values for the radiation weighting factors (w_R) are given in Table 6-1, and values of the tissue weighing factors (w_T) are given in Table 6-2.

Radiation Type and Energy Range ²	w_R value
Photons, all energies	1
Electrons and muons, all energies	1
Neutrons, energy	5
<10 keV	10
10 keV to 100 keV	20
>100 keV to 2 MeV	10
>2 MeV to 20 MeV	5
>20 MeV	5
Protons, other than recoil protons, >2 MeV	5
Alpha particles, fission fragments, heavy nuclei	20
¹ All values relate to the radiation incident on the body or, for internal sources, emitted from the source. ² The choice of values for other radiation types and energies not in the table, see paragraph A14 in ICRP Publication 60 (Reference 6-2)	

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Table 6-2. Tissue Weighting Factors, w_T ¹

Organ or Tissue	w_T Value
Gonads	0.20
Red bone marrow	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Oesophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surfaces	0.01
Remainder	0.05 ^{2,3}

¹ The values have been developed from a reference population of equal numbers of both sexes and a wide range of ages. In the definition of effective dose, they apply to individuals and populations and to both sexes.

² For purposes of calculation, the remainder is comprised of the following additional tissues and organs: adrenals, brain, upper large intestine, small intestine, kidney, muscle, pancreas, spleen, thymus, and uterus. The list includes organs which are likely to be selectively irradiated. Some organs in the list are known to be susceptible to cancer induction. If other tissues and organs subsequently become identified as having a significant risk of induced cancer, they will be included either with a specific w_T or in this additional list constituting the remainder. The latter may also include other tissues or organs selectively irradiated.

³ In those exceptional cases in which a single one of the remainder tissues or organs receives an equivalent dose in excess of the highest dose in any of the twelve organs for which a weighting factor is specified, a weighting factor of 0.025 should be applied to that tissue or organ and a weighting factor of 0.0225 to the average dose in the rest of the remainder as defined above.

An additional method for calculating doses is provided here because it was considered as an alternative to the approach in Appendix C of the proposed final rule. The NEA used a modification of the ICRP procedures in the dose analyses for the Sub seabed Disposal Program (Reference 6-4). The average effective dose per unit intake of activity for the ingestion and inhalation pathways was computed for each radionuclide. Similar dose conversion factors were computed for external exposure. Tables 6-3 and 6-4 list the dose conversion factors for both systems of units. These tables simplify the dose calculations and assure uniform application. The values used in the averaging of tissue and organ exposure are reasonable approximations considering the accuracy of the dose model and the weighing factors. Tables 6-3 and 6-4 were computed using 1975 to 1985 models and data.

In defining the standard biosphere, demography, and human characteristics, uncertainties involving things that are unknowable about the future can only be dealt with by making assumptions and recognizing that these may, or may not, correspond to a future reality. Speculation concerning future conditions should not be the focus of the compliance determination process. Therefore, it is appropriate for assessments to contain the assumption that many

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Table 6-3. Dose Equivalent Factors for Humans (Curies and Related Units)

Nuclide	Ingestion (Rem/Ci)	Inhalation (Rem/Ci)	Immersion (Rem/Hr-Ci-M**3)	Exposure to Soil (REM/Hr-Ci-**3)
C-14	2.07E+03	2.07E+03	0.00E+00	0.00E+00
Ni-59	2.00E+02	1.33E+03	2.30E-03	0.00E+00
Sr-90	1.44E+05	1.26E+06	5.40E-04	0.00E+00
Zr-93	1.55E+03	3.18E+05	0.00E+00	0.00E+00
Tc-99	1.26E+03	7.40E+03	1.30E-04	0.00E+00
Sr-126	1.89E+04	7.40E+04	1.80E-02	0.00E+00
I-129	2.74E+05	1.74E+05	1.70E-02	4.50E-01
Cs-135	7.03E+03	4.44E+04	6.60E-05	0.00E+00
Cs-137	5.18E+04	3.22E+04	1.00E+00	4.20E+00
Sm-151	3.37E+02	2.81E+04	2.60E-04	4.80E-02
Pb-210	5.18E+06	1.30E+07	3.00E-03	1.30E-02
Ra-226	1.15E+06	7.77E+06	1.80E+00	6.40E+00
Ra-228	1.22E+06	4.44E+06	6.75E+00	2.60E+01
Ac-227	1.41E+07	6.66E+09	1.69E+00	8.21E+00
Th-229	3.70E+06	2.11E+07	5.80E-01	2.20E+00
Th-230	5.55E+05	3.18E+08	1.80E+00	6.50E+00
Th-232	2.74E+06	1.63E+09	4.00E+00	1.56E+01
Pa-231	1.07E+07	1.26E+09	5.00E-01	2.20E+00
U-233	2.66E+05	1.33E+08	5.90E-01	2.30E+00
U-234	2.63E+05	1.33E+08	1.18E-03	7.32E-03
U-235	2.52E+05	1.22E+08	2.96E-01	1.31E+00
U-236	2.48E+05	1.26E+08	2.97E-06	2.06E-04
U-238	2.33E	1.18E+08	7.36E-02	3.52E-01
Np-237	4.07E+06	4.81E+08	3.60E-01	1.40E+00
Pu-238	1.85E+06	4.44E+08	1.50E-04	1.30E-03
Pu-239	2.22E+06	5.18E+08	1.20E-04	7.90E-04
Pu-240	2.22E+06	5.18E+08	1.40E-04	1.30E-03
Pu-241	4.44E+04	1.04E+07	6.10E-05	4.60E-03
Pu-242	2.04E+06	4.81E+08	1.10E-04	1.10E-03
Am-241	2.22E+06	5.18E+08	3.90E-02	1.80E-01
Am-243	2.18E+06	5.18E+08	3.10E-01	1.30E+00
Cm-245	6.66E+04	1.74E+07	3.40E-04	5.50E-03
Cm-246	1.11E+06	2.74E+08	2.60E-04	2.90E-03

conditions remain the same as today's. Conditions included in this category are population distributions (i.e., current population distributions should be assumed), level of knowledge and technical capability, human physiology and nutritional needs, the state of medical knowledge, societal structure and behavior, patterns of water use, and pathways through the accessible environment. However, including in this category the geologic, hydrologic, and climatic conditions whose future states may be estimated by examining the geologic record would not be appropriate. Although assuming that national or world populations will remain unchanged is not appropriate, assuming future world populations that cannot reasonably be sustained by current abilities to produce, distribute, and consume food would likewise be inappropriate. For this reason, future world populations in excess of 10 billion people need not be assumed in evaluations for the containment requirements.

Changes covering varying climatic, geologic, and hydrologic conditions may be assessed with sensitivity studies and stochastic analyses.

Performance Assessment

Dose based risk assessments, for repositories that may not have attenuation processes adequately represented by comparison with release limits, could result in extensive site characterization and analyses. If release limits are inappropriate for evaluation of only a few events or processes that are responsible for the significant releases, these events or processes may be analyzed using dose criteria. The predicted doses for each event are normalized relative to the dose limits set by the EPA in the same manner as predicted releases. The dose fraction then replaces the summed release fraction for that event in the CCDF. The probability remains the same, so the only effect is to change the consequence level for that event in the CCDF.

Summary and Conclusions

It is appropriate to add a collective dose option to 40 CFR Part 191. In addition, a method for selectively substituting dose limits for events or processes that cannot be represented accurately with generic derived release limits is also an appropriate alternative. Substitution of higher level standards in an assessment is always justified. Dose analyses are possible on only selected events and processes, and doses can be normalized to the EPA supplied dose limits. These normalized doses would replace the corresponding normalized releases in the CCDF.

Table 6-4. Dose Equivalent Factors for Humans (TBq and Related Units)

Nuclide	Ingestion (Sv/TBq)	Inhalation (Sv/TBq)	Immersion (Sv/Hr-TBq-M**3)	Exposure to Soil (Sv/Hr-TBq-M**3)
C-14		5.60E+02	0.00E+00	0.00E+00
Ni-59	5.40E+01	3.60E+02	6.21E-04	0.00E+00
Sr-90	3.90E+04	3.40E+05	1.46E-04	0.00E+00
Zr-93	4.20E+02	8.60E+04	0.00E+00	0.00E+00
Tc-99	3.40E+02	2.00E+03	3.51E-05	0.00E+00
Sa-126	5.10E+03	2.00E+04	4.86E-03	2.43E+00
I-129	7.40E+04	4.70E+04	4.59E-03	1.22E-01
Cs-135	1.90E+03	1.20E+04	1.78E-05	0.00E+00
Cs-137	1.40E+04	8.70E+03	2.70E-01	1.13E+00
Sm-151	9.10E+01	7.60E+03	7.02E-05	1.30E-02
Pb-210	1.40E+06	3.50E+06	8.10E-04	3.51E-03
Ra-226	3.10E+05	2.10E+06	4.86E-01	1.73E+00
Ra-228	3.30E+05	1.20E+06	1.82E+00	7.02E+00
Ac-227	3.80E+06	1.80E+09	4.56E-01	2.22E+00
Th-229	1.00E+06	5.70E+06	1.57E-01	5.94E-01
Th-230	1.50E+05	8.60E+07	4.86E-01	1.76E+00
Th-232	7.40E+05	4.40E+08	1.08+00	4.21E+00
Pa-231	2.90E+06	3.40E+08	1.35E-01	5.94E-01
U-233	7.20E+04	3.60E+07	1.59E-01	6.21E-01
U-234	7.10E+04	3.60E+07	3.19E-04	1.98E-03
U-235	6.80E+04	3.30E+07	7.99E-02	3.54E-01
U-236	6.70E+04	3.40E+07	8.02E-07	5.56E-05
U-238	6.30E+04	3.20E+07	1.99E-02	9.50E-02
Np-237	1.10E+06	1.30E+08	9.72E-02	3.78E-01
Pu-238	5.00E+05	1.20E+08	4.05E-05	3.51E-04
Pu-239	6.00E+05	1.40E+08	3.24E-05	2.13E-04
Pu-240	6.00E+05	1.40E+08	3.78E-05	3.51E-04
Pu-241	1.20E+04	2.80E+06	1.65E-05	1.24E-03
Pu-242	5.50E+05	1.30E+08	2.97E-05	2.97E-04
Am-241	6.00E+05	1.40E+08	1.05E-02	4.86E-02
Am-243	5.90E+05	1.40E+08	8.37E-02	3.51E-01
Cm-242	1.80E+04	4.70E+06	9.18E-05	1.49E-03
Cm-244	3.00E+05	7.40E+07	7.02E-05	7.83E-04

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REFERENCES

- 6-1. Federal Register, Environmental Protection Agency, 40 CFR Part 191, "Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes; Final Rule," Vol. 50, No. 182, September 19, 1985.
- 6-2. "ICRP Publication 60 - 1990 Recommendations of the International Commission on Radiological Protection," Annals of the ICRP, Volume 21, Numbers 1-3, 1990.
- 6-3. U. S. Environmental Protection Agency, "Draft Federal Register Notice of 40 CFR Part 191," February 3, 1992.
- 6-4. G. de Marsilly, et al., "Feasibility of Disposal of High-Level Radioactive Waste into the Seabed: Volume 2, Radiological Assessment," Nuclear Energy Agency, Paris, 1988.

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CHAPTER 7

TRU WASTE EQUIVALENCE UNIT

TRU WASTE EQUIVALENCE UNIT

7.1 STATEMENT OF THE PROBLEM

The use of values in the 1985 version of 40 CFR Part 191 that equate TRU waste with HLW and spent nuclear fuel is not technically sound because military TRU waste is not associated with commercial reactor fuel, does not have a unit comparable to a MTHM of fuel, and does not have a comparable risk/benefit relationship. None of the quasi-equivalent units equate the risks of a TRU repository to those of a HLW repository. One option is to develop a fundamental criteria for TRU waste based on acceptable risk to the populace.

[This section of this chapter will be supplied at a later date. The technical analysis is not complete at this time.]

7.3 SUPPLEMENTARY INFORMATION

[This section of this chapter will be supplied at a later date. The technical analysis is not complete at this time.]

7.4 TECHNICAL SUPPORT DOCUMENTATION

[This section of this chapter will be supplied at a later date. The technical analysis is not complete at this time.]

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CHAPTER 8

UNCERTAINTY PROPAGATION

UNCERTAINTY PROPAGATION

8.1 STATEMENT OF THE PROBLEM

In 1985, the U.S. Environmental Protection Agency (EPA) promulgated standards for disposal of spent fuel, high-level and transuranic radioactive wastes in the United States. These standards included an individual protection requirement of maximum individual dose rate that was applicable for 1,000 years and a containment requirement of cumulative radionuclide releases to the accessible environment applicable for 10,000 years. In 1986, the Natural Resources Defense Council and others challenged EPA's decision to limit the individual protection requirement to 1,000 years as arbitrary and capricious. The First Circuit Court of Appeals ruled on this matter and others on July 17, 1987. The court held that the Agency's choice of a 1,000-year individual protection criterion was arbitrary and capricious and remanded that portion of the regulations to the Agency for reconsideration, or a more thorough explanation of the reasons underlying the choice of 1,000 years.

In addition, the Draft Federal Register Notice of 40 CFR Part 191 (2/3/92) includes proposed requirements for calculation of dose and radionuclide release projections for undisturbed conditions up to 100,000 years.

The problem is that there are significant uncertainties associated with calculation of individual doses for 10,000 years, or with projections of doses and radionuclide releases out to 100,00 years. Such calculations would prove to be meaningless and are inappropriate.

This task consists of calculating uncertainty propagation from 1,000 to 10,000 years to select an appropriate time period for individual protection and for groundwater protection requirements, and from 10,000 to 100,000 years to evaluate the usefulness of requiring performance assessment calculations beyond 10,000 years.

8.2 RECOMMENDED APPROACH

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The time period for assessments of individual and groundwater protection should be retained at 1,000 years after disposal (as in sections 191.15 and 191.16 of the 1985 standard), rather than 10,000 years (as proposed in sections 191.14 and 191.23 of the Draft Federal Register Notice of 40 CFR Part 191 (2/3/92)).

In addition, the new standard should not include requirements for projection of potential releases or doses out to 100,000 years after disposal, as proposed in subsections 191.12(c) and 191.14(b) of the Draft Federal Register Notice of 40 CFR Part 191 (2/3/92).

The following material provides an explanation of why the rule could be revised as suggested in the preceding pages. This material could be used by the EPA as supplementary information to accompany the proposed rule.

The containment requirements in 40 CFR Part 191 limit cumulative releases to the accessible environment for 10,000 years after disposal. These requirements were based on a world-wide population risk criterion. The Science Advisory Board (SAB) Subcommittee recommendation at the time the 1985 standard was being promulgated (50 FR 38073, September 19, 1985), included the following statements: "We support the use of a population risk criteria. We believe it is impractical to provide absolute protection to every individual for all postulated events or for very long periods. On the other hand, in our view it is important that, for the first several hundred years, residents of the region immediately outside the accessible environment have very great assurance that they will suffer no, or negligible, ill effects from the repository." Therefore, the Agency felt that this additional assurance (for individual protection requirements) was needed to provide protection for the individual since the primary containment standard was for cumulative releases over 10,000 years, with no limits placed on the rate of such releases.

The individual protection requirements in the final rule issued in 1985 limited annual exposures to individuals from a disposal system during the first 1,000 years after disposal. The Agency examined the effects of different time periods and selected 1,000 years for the individual protection requirement because the Agency's assessments indicated that 1,000 years was long enough to ensure that good engineered barriers would be used.

Demonstrating compliance with individual exposure limits over time frames much longer than 1,000 years appeared to be difficult because of the uncertainties involved. The performance assessments that must be conducted to demonstrate compliance with regulatory requirements include evaluation of parameters and processes that are uncertain. Regardless of how extensive a site characterization program is, these uncertainties will be present. In addition to the initial uncertainty inherent in these parameters and processes, the uncertainty also increases with time. The extent to which these uncertainties change depends, in part, on the extent to which projected site conditions are expected to change. All these uncertainties result in uncertainties in calculation of the performance measures. Demonstrating compliance, therefore, requires an understanding of all the uncertainties, including those inherent in the estimates of future site conditions.

If the present hydrologic conditions at a waste disposal site are expected to persist over time, the uncertainties in calculation of individual dose arise primarily from uncertainties in the description of hydrologic parameters, geochemical parameters, and radionuclide release rates from the repository (canister failure times and leach rates). The uncertainties in calculation of the individual dose rates will increase with time for time periods significantly longer than the radionuclide travel times. These uncertainties will increase significantly over the time period of 1,000 to 10,000 years.

If the present hydrologic conditions at the site are expected to change over time, additional uncertainties are introduced. For example, a change in climate, and thus in infiltration, could affect the hydrologic system at the disposal site. In addition to changing the

parameters discussed in the paragraph above, it could change the hydrologic boundary conditions affecting both the radionuclide release rates from the repository (through changed leach rate) and groundwater flow rates. Since uncertainties in the climate change are larger over longer time periods, the uncertainties would further increase over the time period of 1,000 to 10,000 years.

The Agency believes that a 1,000-year time period is more than adequate to protect individuals from the potential risks associated with geologic disposal. The containment and individual protection requirements are complementary to each other and are not inconsistent with each other. They apply to different site conditions (undisturbed versus disturbed performance). Therefore, there is no need for them to cover similar time periods. The containment requirements in Section 191.13, which cover releases over 10,000 years after disposal, are the primary standard for waste isolation. This standard covers all significant processes and events that may affect the disposal system, thus ensuring that the site has natural characteristics that will adequately protect the environment. The standard allows for inclusion of uncertainties in the behavior of the disposal system over 10,000 years in demonstrating compliance with the containment requirement. The individual protection requirement is different. Because it governs only the undisturbed performance of the disposal system, it is a deterministic standard and does not explicitly account for uncertainties. Therefore, compliance demonstration for the individual protection requirement becomes more difficult when such uncertainties have to be considered.

Consequently, because of these reasons, the Agency has decided to retain the 1,000-year time period for individual protection.

The groundwater protection requirements contained in Section 191.16 of this proposed rule are similar to the individual protection requirements. Their primary purpose is to ensure that engineered barriers perform in such a way as to prevent significant degradation of the groundwater in the vicinity of the disposal facility, and thereby protect the individuals in the area. These requirements only apply to the undisturbed performance of the disposal system and are deterministic in nature, just like the individual protection requirements.

Consequently, the Agency has decided to also retain the 1,000-year time period for groundwater protection.

As discussed above, the regulations being proposed by the Agency for individual and groundwater protection cover a time period of 1,000 years after disposal. The containment requirements cover a time period of 10,000 years. Questions have been raised regarding the extent to which periods past 10,000 years should be evaluated. As indicated in the supplementary information accompanying the 1985 standard, the Agency believed that 10,000 years was an adequate time period for demonstration of compliance with the containment requirements, and 1,000 years for individual and groundwater protection. Nevertheless, in promulgating the new standard after the court remand in 1987, the Agency asked for comments on whether 100,000-year assessments are likely to provide useful information in selecting preferred disposal sites. Comments received from various groups, including the Nuclear Regulatory Commission, the Advisory Committee on Nuclear Waste, and the Department of Energy, indicate that such assessments would not be meaningful as a measure of disposal system performance.

The discussions in the paragraphs above were limited to change in performance of the disposal system for undisturbed conditions over the time period of 1,000 to 10,000 years. If the time period for dose or release projections is increased to 100,000 years, then the uncertainties may become so large as to render the calculations not very meaningful. If disturbances were included, then the uncertainties in calculation of the performance measures would increase further, depending on the uncertainties in the disturbed conditions. This is recognized in the containment requirements by requiring probabilistic treatment. Estimating the effects of disturbances to 100,000 years requires the inclusion of relatively low-probability geologic events in the modeling of repository behavior. Hydrologic and geochemical properties of the site may change significantly as well. Merely extrapolating the present conditions is not a defensible way to extend performance assessment calculations over long periods of time.

The Agency continues to believe that a disposal system capable of meeting the containment requirements for 10,000 years would continue to protect people and the environment well beyond 10,000 years and, therefore, assessments for time periods past 10,000 years should not be required. This is supported by the views of other groups. When the 1985 standard was being promulgated, the SAB Subcommittee reviewed and supported the technical arguments for limiting the containment requirements to a 10,000-year period. In addition, NRC requirements in 10 CFR Part 60 already contain siting criteria and performance objectives that reduce the potential for significant release after the 10,000-year period has elapsed.

Consequently, the Agency has decided to not require projections of releases or doses out to 100,000 years after disposal.

8.4 TECHNICAL SUPPORT DOCUMENTATION

Technical analyses in support of the discussion on propagation of uncertainty over time are continuing and are expected to be completed by August 1992. A system-level performance assessment model, which permits calculation of uncertainty propagation through the system, is being used. Time-variant parameter distributions will permit calculation of uncertainty propagation with time. This work will attempt to quantify uncertainty propagation for generic site conditions from 1,000 to 10,000 years for undisturbed conditions to investigate the impact of changing the individual and groundwater protection requirements over this time period. In addition to the undisturbed conditions, effects of all significant events and processes will also be evaluated to determine uncertainty propagation for time periods to 100,000 years.

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CHAPTER 9

CARBON-14

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CHAPTER 9

CARBON-14

9.1 STATEMENT OF THE PROBLEM

The purpose of 40 CFR Part 191 is to protect public health and safety. The 1985 rule was developed on the basis of the assumption that the repository would be located in a geologic formation that lies below the water table. It was therefore assumed that the principal mechanism of pollutant migration would be via dissolution of radionuclides in groundwater and transport by aqueous means.

We now find the nation examining the suitability of unsaturated sites, specifically Yucca Mountain, a site that is located above the water table. At this site, and other unsaturated sites, it is appropriate to examine gaseous release and transport of pollutants in order to determine site adequacy. When the provisions of the 1985 standard are applied to Yucca Mountain, specifically the limits for Carbon-14, we can release in 10,000 years no more than 7,000 curies of Carbon-14 in the form of carbon dioxide. Meanwhile, calculations indicate that the repository may release about 8,000 curies of Carbon-14 dioxide, an amount that exceeds the standard by 10 to 20 percent.

For the first 1,000 to 2,000 years after the repository is closed, it is expected that the host rock will contain the Carbon-14 dioxide. For containment for longer periods of time, we must rely on a durable waste package, one utilizing a multiple-layer design. Such an approach could be very costly. Estimates indicate the cost would increase by \$3.2 billion.

The basis of the 1985 standard was that, in a site below the water table, the limit for Carbon-14 was technically achievable. It was not a standard based on a release level that would prevent a danger to public health. If we examine the danger to public health of the release of 8,000 curies of Carbon-14 dioxide during an 8,000-year period, this release would not pose a significant threat to public health. Industry and natural sources release many times this amount of Carbon-14 dioxide each year. The question therefore becomes: is it appropriate to spend an additional \$3 billion on waste packages when this will not provide an improvement in public health?

A situation exists in which the 1985 rule has an unintended result. It appears that a potential repository at Yucca Mountain can release its inventory of Carbon-14 dioxide without endangering public health, yet it appears the site may not be able to satisfy a standard that has as its ultimate purpose the protection of public health. Thus, an alternative approach is needed. The EPA should regulate Carbon-14 dioxide under a more equitable standard, similar to those in the clean air regulations, or not regulate it at all.

9.2 RECOMMENDED APPROACH

The following material suggests an alternative method of regulating gaseous releases from the repository. The containment requirements, expressed as curies/1,000 MTHM, would apply only to solid and liquid releases to the land, a well, a river, and the ocean (see Chapter 5). The individual protection requirements, expressed as millirems/year, would continue to apply to all releases through all pathways. However, exposures from radioactive gases cannot exceed 10 millirems/year.

The following is a possible revision of subsection 191.13(a) of the 1985 standard:

191.13 Containment requirements.

(a) Disposal systems for spent nuclear fuel or high-level or transuranic radioactive wastes shall be designed to provide a reasonable expectation, based upon performance assessments, that the cumulative releases of solid and liquid radionuclides to the accessible environment for 10,000 years after disposal from all significant processes and events that may affect the disposal system shall:

(1) Have a likelihood of less than one chance in 10 of exceeding the quantities calculated according to Table 1 (Appendix A); and

(2) Have a likelihood of less than one chance in 1,000 of exceeding ten times the quantities calculated according to Table 1 (Appendix A).

The following is a possible revision of Section 191.15 of the 1985 standard:

191.15 Individual protection requirements.

(a) Disposal systems for radioactive wastes shall be designed to provide a reasonable expectation that, for 1,000 years after disposal, undisturbed performance of the disposal system shall not cause the annual committed effective dose received through all potential pathways from the disposal system to any member of the public in the accessible environment to exceed 25 millirems (250 microsevents). The annual committed effective dose for gases released through the atmospheric pathway shall not exceed 10 millirems.

The following material explains the basis for the revisions suggested in the preceding pages. This material could be used by the EPA as part of the supplementary information for the proposed rule.

Besides the remand from the First District Court of Appeals, much has transpired since the Agency issued its standards in September, 1985, that has led us to reconsider our containment and individual protection requirements. Congress amended the Nuclear Waste Policy Act (Act); the Agency proposed and issued new clean air regulations (40 CFR Part 61); and the U.S. Department of Energy (DOE) has begun to characterize an unsaturated site. After considering these developments, we propose to change the requirements. The containment requirements would apply only to solid and liquid releases to the land, a well, a river, and the ocean. The individual protection requirements would continue to apply to all releases from an undisturbed repository through all pathways, but now exposures from radioactive gases cannot exceed 10 mrem/year. Without these changes, the standards would not be generic, they would not be consistent with the clean air regulations, and the standards could force the DOE to needlessly spend billions of dollars.

The Act directed the Agency to issue generally applicable standards, and the amended Act directed the DOE to characterize only Yucca Mountain, an unsaturated site. We issued our standards after the Act was passed but before the Act was amended. At that time, saturated sites were the leading contenders for a repository. Consequently, our containment requirements were not intended to control gases that would be released through fractures in unsaturated rock.

Information developed by the DOE and others indicates that, when applied to gases, namely Carbon-14 dioxide, the containment requirements become overly stringent - millions of times more stringent than the clean air regulations. The stringency would not affect a saturated repository, but would discourage the development of any unsaturated repository. Thus, to keep our standards generic and consistent with other regulations, the Agency proposes these changes.

The Agency proposes to regulate solid and liquid releases under the containment requirement and regulate gases in a manner that is consistent with our National Emissions Standards for Hazardous Air Pollutants (NESHAP) (40 CFR Part 61). In developing NESHAP, we found that a maximum individual dose of 10 millirems per year (mrem/yr) provides an ample margin of safety. We now propose this same dose limit for a repository. The dose would appear in our individual protection requirements along with the current 25 mrem/yr limit that an individual could receive through all pathways.

Even though these changes could potentially allow approximately 8,000 curies of Carbon-14 dioxide (the repository's entire inventory) to be released over a 10 thousand year period, such a release does not pose a significant threat to public safety. If the 8,000 curies were released in just one year, an individual would be exposed to less than 0.5 mrem. During the same year, this individual would receive 300 mrem from natural background radiation and 1.3 mrem from the Carbon-14 within his own body.

Without the above revisions, DOE would be forced to design and fabricate an overly expensive waste package that completely contains the 8,000 curies of Carbon-14 dioxide. Complete containment does not make sense when Carbon-14 dioxide is routinely released throughout the world. A typical nuclear power plant releases, without any restriction, about 24 curies of Carbon-14 each year; a typical reprocessing plant, about 860 curies; and a coal-fired power plant releases much more. But under the 1985 standard, a repository filled with 70,000 MTHM can average no more than 0.7 curies/year. If just 3 waste packages fail in 1 year, about 1 curie of Carbon-14 dioxide will be released. A more durable waste package may contain the Carbon-14 dioxide, but the benefits do not justify the cost.

The more durable Carbon-14 package could cost \$213,000 each or \$5.3 billion for the 25,000 packages that will be needed. The DOE is considering several designs, such as thick-walled packages and multi-layered packages with either metallic or ceramic inserts. The fabrication of these more conservative packages will need development, particularly those made of ceramic materials. The DOE believes that ceramics are feasible but development will be difficult. For example, a hot isostatic press must be designed and constructed to remotely fuse the ceramic around the spent fuel assemblies. With an additional \$100 million for research and development, the Carbon-14 packages total \$5.4 billion.

The DOE's present reference waste package could cost \$88,000 each or \$2.2 billion for 25,000. Fabricated from a corrosion-resistant alloy, these packages may provide substantially complete containment for 1,000 years, but the DOE cannot guarantee that they will contain the radioactive gases for 10,000 years.

The difference between these two types of waste packages, \$3.2 billion, constitutes the cost of meeting the current (1985) limits for Carbon-14 dioxide. Stated another way, the DOE must spend \$400 million to contain 1 curie of Carbon-14 dioxide, while the world's industries release thousands of curies each year. The Agency finds that the negligible benefits to public safety do not justify the high cost. We therefore propose to exclude gases from our containment requirements and regulate them under the more equitable individual dose limits of 10 mrem/yr.

The following material is supporting information that could be cited in support of the above revisions. It could be part of a technical support document for the rule.

Many technical analyses and evaluations regarding Carbon-14 have been done by the DOE, its contractors, national laboratories, and others. These have included analyses of the source term, transport mechanisms, health effects, uncertainties, as well as evaluation of the regulatory implications concerning releases of Carbon-14. Appendix A of this document contains a paper written by Dr. U-Sun Park, of Science Applications International Corporation, that discusses these various aspects. This paper was prepared in support of the workshop on 40 CFR Part 191 sponsored by the Electric Power Research Institute (EPRI) in February 1992. Much of the information presented in this chapter was based on that paper.

In addition to the technical analyses and evaluations discussed above, evaluations have also been done to determine the relative costs associated with containment of Carbon-14 dioxide. The following information provides this cost perspective.

Containment of Carbon-14 dioxide, or any other radioactive gas, requires a multi-barrier waste package concept with, at least, one of the barriers utilizing a material that has very low corrosion characteristics. The Department of Energy (DOE) is currently considering robust waste packages to increase design margins, but DOE is not specifically addressing Carbon-14 containment. This evaluation attempts to quantify the additional costs of developing and manufacturing such a containment without a determination of its technical feasibility, which can come only after considerable research and development.

Using a statistical model to calculate the cumulative failure distribution for high-level radioactive waste containers, Bullet (Reference 9-1) shows that multiple-barrier systems have potential to delay the failure of waste packages depending on the choice of each barrier material. A multi-barrier approach was assumed for the Carbon-14 containment cost evaluation, with one barrier utilizing a ceramic material known to have very low corrosion rates. Other barriers would be similar to the reference design described in the Site Characterization Plan (SCP) allowing the cost evaluation to focus on added costs to contain Carbon-14 within a ceramic barrier.

The selection of ceramics infers a requirement for considerable research and development (R&D) to develop the data, processes, and equipment necessary to produce this material and predict its performance. The consensus of the Engineered Barrier System Concepts Workshop (Reference 9-2) regarding use of ceramics was that their feasibility was undetermined because of the current lack of appropriate data on these materials. An R&D program for ceramics costing \$10-15 million per year out to license application in the year 2001, totaling \$80-100 million, is necessary to generate the performance data and develop the manufacturing processes (see Table 9-1). These costs would be in addition to the currently estimated costs of developing the reference waste package. Currently, no facility in the U.S. can fabricate a ceramic large enough to hold the spent fuel. Moreover, the DOE would have to build a facility to remotely encapsulate the spent fuel within the ceramic.

**Table 9-1. Ceramic Research and Development Costs
Leading to License Application, \$1,000**

ACTIVITY	FY 93	FY 94	FY 95	FY 96	FY 97	FY 98	FY 99	FY 00	FY 01	TOTAL
Design	500	1000	1000	1000	1000	1000	1000	1000	1000	8500
Process Development	200	500	1500	2000	2000	2000	2000	2000	2000	14200
Fabrication Equipment Development	50	100	500	2000	2000	2000	2000	2000	2000	12650
Nondestructive Exam (NDE)	50	100	200	200	200	200	200	200	200	1550
Material Characterization & Test	200	1000	2000	4000	4000	4000	4000	4000	4000	27200
Prototype Fabrication & Test	50	100	500	1000	2000	2000	2000	5000	5000	17650
TOTAL	1050	2800	5700	10200	11200	11200	11200	14200	14200	81750

For this cost evaluation, it was assumed that the Carbon-14 package would contain the same amount of waste as the reference design, so that direct comparisons can be made. This design contains three PWR and four BWR spent-fuel assemblies. Approximately 25,000 waste packages would be required to accommodate the first repository inventory. Larger concepts are currently being evaluated that could reduce the number of packages, but this effort has not proceeded far enough to provide a basis for comparison.

The Carbon-14 package, defined for this evaluation, is based on an external metallic barrier and an inner second barrier of alumina or titania ceramic to contain Carbon-14. Inside the ceramic, a steel handling canister would hold the spent fuel. Alloy 825 is assumed for the outer container because cost data are available for it (Reference 9-3). The diameter of this external container must be increased over the reference design to accommodate the ceramic barrier. The ceramic barrier would be approximately 3 inches thick, and the steel canister would be 0.39 inch thick.

Cost estimates for the ceramic barrier in the size needed are not readily available, because these sizes are larger than what is currently manufactured. However, it is the opinion of ceramic researchers and manufacturers that a ceramic container of the size needed would have costs comparable to the corrosion-resistant high-nickel alloy container being considered for the metallic barrier. The cost of 25,000 ceramic packages plus R&D totals \$5.4 billion. The cost of 25,000 reference packages plus R&D totals \$2.2 billion. The difference, \$3.2 billion, constitutes the cost of containing Carbon-14 dioxide (see Table 9-2).

Table 9-2. Carbon-14 Containment Costs, \$

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CONCEPT	PACKAGE QUANTITY	BARRIER NUMBER	BARRIER MATERIAL	UNIT COST	ASSEMBLY COST	TOTAL COST
SCP	25000	1	ALLOY 825	83000	5000	88000
C-14 Package	25000	1	ALLOY 825	95000	2000	97000
		2	CERAMIC	75000	5000	80000
		3	STEEL	31000	5000	36000
		TOTAL C-14		201000	12000	213000
Added Costs Over SCP Per Package				118000	7000	125000
Added Cost for Research and Development						1.E+08
Total Added Cost to Program						3.2E+09

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REFERENCES

- 9-1. Bullet, Daniel B., "Engineered Barrier System Failure Modeling: A Statistical Approach", from the Proceedings of the Third International High Level Radioactive Waste Management Conference, April 12-16, 1992.
- 9-2. Yucca Mountain Site Characterization Project Extended Summary Report on Engineered Barrier System Concepts Workshop, June 18-20, 1991.
- 9-3. Russell, E. W., et al, "Cost Estimate of High-Level Radioactive Waste Containers for the Yucca Mountain Site Characterization Project" UCID-21863, August 1991.

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APPENDIX A

REGULATORY OVERVIEW AND RECOMMENDATIONS

ON A REPOSITORY'S RELEASE OF CARBON-14

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REGULATORY OVERVIEW AND RECOMMENDATIONS ON A REPOSITORY'S
RELEASE OF CARBON-14

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SUMMARY

The release of gaseous carbon-14 (C-14) dioxide from a potential Yucca Mountain repository to the accessible environment, with the current design of waste packages, could exceed the release limits set by the U.S. Environmental Protection Agency (EPA) and U.S. Nuclear Regulatory Commission (NRC). The amount released depends on the sources of C-14, mechanisms to free C-14 from the sources, and transport mechanisms to the accessible environment, each of which is in turn affected by many parameters in the natural geologic environment. This paper examines the current information on the amount, the sources, and the transport of carbon-14. From this information, the paper assembles a coherent conceptual model for C-14 release and transport. It is shown that the uncertainties in our knowledge and data are so large that we must conclude there is a significantly high probability of exceeding both the NRC and EPA release limits, and consequently violating both NRC and EPA regulations. The uncertainties are in both the source term (engineered) and transport (natural), of which the former may be more dominant. The source term, however, is also so strongly influenced by the natural system, primarily the hydrology of the site, that even after site characterization the residual uncertainties may still be unacceptably high. This may force the U.S. Department of Energy (DOE) to look for an expensive solution to the source term (costing billions of dollars and years of delay).

Analyses done by the DOE contractors and others have been reviewed, including the regulatory implications of the preliminary results. It has already been demonstrated that the additional expenditures that would be required to contain C-14 would not measurably benefit the public health and safety. Several regulatory alternatives have been discussed. The gaseous release of radionuclides could be regulated by the Clean Air Act (CAA) requirements, either through EPA's National Emission Standards for Hazardous Air Pollutants (NESHAP) or by a rulemaking in consultation with the NRC. It is recommended that the currently existing NESHAP Subpart I be used, which exempts the facilities regulated by 40 CFR Part 191.

In terms of the gaseous emission standard, there are several options available whose pros and cons are discussed in detail. Among them, the following option seems to be most reasonable in terms of providing a technical basis for the numerical criteria and regulatory consistency with the CAA requirements.

"The gaseous release of radionuclides shall not exceed the amounts that would cause any member of the public to receive an effective dose equivalent of 5 mrem/yr, except that any combined releases that would cause an effective dose equivalent of 0.1 mrem/yr or less need not be regulated."

Although the implementation was considered in recommending the alternatives, other political considerations may have to be factored into the final formulation of the emission standard applicable to the gaseous releases. There is no one solution that will solve all the problems and satisfy all the parties involved. In addition, the problem is a global one and may require a global solution.

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I. INTRODUCTION

The release of carbon-14 (C-14) from potential high-level nuclear waste repositories in the U.S. is regulated by the NRC's 10 CFR Part 60. This regulation implements environmental standards specified in the EPA's 40 CFR Part 191. When these regulations were promulgated, major candidate sites for repositories were in saturated zones in different geologic formations. Although an unsaturated zone in tuff was also considered before 40 CFR Part 191 was finalized in 1985, no specific consideration for the release of gaseous radionuclides was made. The only gaseous radionuclide that could be released in any significant amount from a potential repository in the unsaturated zone at Yucca Mountain, Nevada, is C-14 in the form of carbon dioxide (Ref. 1).

Recent performance assessment studies conducted by the DOE (Ref. 2) and the Electric Power Research Institute (EPRI) (Ref. 3) show that Yucca Mountain's compliance or non-compliance with the regulations is largely dominated by the uncertainties associated with the release of C-14. Among the radionuclides regulated by the EPA and NRC, C-14 is the only radionuclide that is a part of our essential environment, is in our daily diet, is present everywhere on earth and in the atmosphere (even in the human body); is abundant in nature (global inventory of 230 million curies: 7.5 million curies in land biosphere and humus, and 3.8 million curies in the atmosphere) (Ref. 4, 5), and gives a very small exposure to any individual from a very large inventory. The expected release rate from a potential repository at Yucca Mountain (less than a few curies per year) is so small that it would hardly affect the radiation dose that any individual on Earth would receive naturally during his or her lifetime. Yet this release could violate the EPA and NRC regulations unless very costly design alternatives are adopted or a significant amount of additional site characterization work is done with great cost and significant project delays. A more robust design of the waste package will undoubtedly enhance the confidence that the regulations are met for other, more soluble radionuclides. However, the requirements on C-14 are more severe than on other radionuclides, as evidenced in the DOE's Performance Assessment Calculation Exercise (PACE). The inappropriateness of regulating such a low release as that expected from a geologic repository has been expressed by many scientists (Ref. 6, 7).

This paper reviews what DOE Yucca Mountain Project (YMP) researchers know about C-14; i.e., measurements made and analyses performed to date by YMP scientists and others. It also discusses regulatory aspects of C-14 releases through both liquid and gaseous pathways, lays out possible alternative regulatory standards for C-14, and recommends a technical position on C-14 for the DOE to consider. Attempts were made to use references extensively in order to avoid unnecessary duplication of information readily available in the literature.

II. REVIEW OF ANALYSES

Since the current regulations governing the geologic repositories are expressed in terms of cumulative release, individual doses and release rate, the main questions to be addressed are how much C-14 has been emplaced (inventory), how much and how fast it can be freed from the various confinements (source term), how fast it can travel toward the accessible

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environment (transport), and what it will do to the individual in the population (radiological exposure). These questions are examined individually with our current knowledge and understanding, based on actual measurements or analyses with ranges of assumptions where these are available or on pure speculation where they are not. An effort was made to identify the sources of information so one can trace the original source of information and make a reasonable guess on the associated uncertainties.

A. Inventory

Carbon-14 is produced as an activation product during reactor operation by neutron reactions with nitrogen-14 (N-14) impurities in the fuel, cladding, hardware and coolant, and with oxygen-17 (O-17) in the oxide fuel and coolant. Production of C-14 by ternary fission can be safely ignored (Ref. 8). The amount produced is directly proportional to the neutron flux and the duration of irradiation provided the latter is much shorter than one-tenth of the half-life of activated product, which is the case for C-14. In other words, the amount of C-14 in the spent fuel depends on the amount of power generated from the fuel. For this reason, most literature values of C-14 production in the reactor are expressed in terms of curies per gigawatt-year of electricity produced. Since not all fuel elements are exposed to the same level of neutron flux and nitrogen impurity content varies, the amount of C-14 in each fuel element can vary substantially. Calculations based on average burnup and expected level of nitrogen impurities and O-17, therefore, can provide as reasonable an estimate of the total C-14 inventory in the spent fuel as those based on the few available laboratory measurements of samples.

The most comprehensive calculations for U.S. fuel were done by Davis at Oak Ridge National Laboratory (ORNL) (Ref. 9), and have subsequently been updated by others (Ref. 10, 11). The values in the studies have been used as a base in the Yucca Mountain Site Characterization Plan (SCP) and other regulatory analyses (Ref. 6), shown in Table 1.

TABLE 1

Estimated C-14 Content of Spent LWR Fuel (Ci/MTHM)

	<u>Burnup</u> <u>(MWd/MTHM)</u>	<u>UO₂</u>	<u>Zircaloy</u>	<u>Fuel Assembly</u> <u>Hardware</u>	<u>Total</u>
BWR	27,500	0.54	0.76	0.23	1.5
PWR	33,000	0.60	0.35	0.60	1.55

The estimated C-14 content in the UO₂ fuel matrix agrees with actual measurements made by the Materials Characterization Center at Pacific Northwest Laboratories. Van Konynenburg documented available measured data on C-14 content in the spent fuel (4 Pressurized Water Reactor and 1 Boiling

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Water Reactor fuel assemblies) (Ref. 12). Using the actual measured concentrations of C-14 and more recent data on nitrogen impurities, he revised the estimate of C-14 content in spent Light Water Reactor fuel (Ref. 7) as shown in Table 2.

TABLE 2

Revised Estimate of C-14 Content in Spent LWR Fuel (Ci/MTHM)

	<u>Burnup (MWd/MTHM)</u>	<u>UO₂</u>	<u>Zircaloy</u>	<u>Fuel Assembly Hardware</u>	<u>Total</u>
BWR	27,500	0.54	0.38	0.10	1.02
PWR	33,000	0.60	0.18	0.22	1.00

He then adjusted these numbers for higher average burnups of 29,500 and 37,500 MWd/MTHM for BWR and PWR, respectively, and a total inventory of 70,000 metric tons of initial uranium equivalent, which consisted of 22,500 MTHM of BWR, and 40,500 MTHM of PWR fuel elements, and 7,000 MTHM equivalent of defense waste, to get an average of 1.12 Ci/MTHM in the spent fuel and a repository total of 71,000 curies of C-14.

A more global review of C-14 production from nuclear industries, including seven different types of power reactors and fuel reprocessing, was done by Bush et al. for the Commission of the European Communities (Ref. 13). Their numbers were also based on actual measurements and calculations, including those from the U.S. Since the purpose of their review was to address the total C-14 production from the nuclear industry that will eventually have to be managed, they also included estimates of C-14 in the reactor hardware, which will become low or intermediate level wastes after decommissioning. Table 3 summarizes the values for BWR and PWR. Since the C-14 production is expressed as Ci/GWe-yr in the report, the numbers have been converted to Ci/MTHM using nominal values of 40.2 and 33.5 MTHM/GWe-yr for BWRs and PWRs, respectively.

TABLE 3

Total Production of C-14 from nuclear power generation (Ci/MTHM)

	<u>UO₂</u>	<u>Zircaloy and Fuel Hardware</u>	<u>Reactor Off-Gas</u>	<u>Reactor Hardware</u>	<u>Total</u>
BWR	0.5	0.5	0.25	1.11	2.36
PWR	0.6	0.6	0.15	0.75	2.10

The C-14 inventory in the uranium fuel matrix, cladding, and hardware compares well with those given by Van Konynenburg (Ref. 7). The latter are used as a reference inventory for the following burnup adjustment.

The Table 1 release limits for containment requirements in 40 CFR Part 191 apply to the wastes containing 1,000 MTHM exposed to a burnup between 25,000 and 40,000 MWd/MTHM (Ref. 14). If the burnup is higher, a credit is given. In other words, more release per MTHM is allowed for fuels with higher burnup (where more energy is produced) only if the burnup is higher than 40,000 MWd/MTHM; likewise, a penalty (less release per MTHM) is imposed on those with a burnup less than 25,000 MWd/MTHM. The table does not make any distinction between the BWR and the PWR, and the burnup credit is calculated in reference to a standard burnup of 30,000 MWd/MTHM. Any fuel with a burnup higher than the nominal values of 27,500 (BWR) and 33,000 (PWR) MWd/MTHM but below 40,000 MWd/MTHM will have a higher C-14 inventory than those in Table 2, but will not be allowed with a commensurate increase in the release limit. This would penalize fuels with a higher burnup than the nominal one in terms of allowable fractional release of C-14 if we used the inventory of C-14 in fuels with a nominal burnup as a reference. It is true that any fuel with a burnup below the nominal values but higher than 25,000 MWd/MTHM will benefit in terms of allowable fractional release of C-14 inventory. However, the general trend is toward higher burnups for both the BWRs and PWRs. In addition, the actual measurements for the PWR fuels with high burnups show a substantially higher C-14 content than those in Table 2 (Ref. 7). For those fuels, even after the burnup credit the use of the values in Table 2 will not be conservative. For the purpose of regulatory compliance analysis in this review, the values in Table 2 have been adjusted upward toward higher burnups as shown in Table 4.

TABLE 4

Adjusted C-14 Content in Spent Fuel (Ci/MTHM)

	Burnup (MWd/MTHM)	UO ₂	Zircaloy	Fuel Assembly Hardware	Total
BWR	35,000	0.69	0.48	0.13	1.30
PWR	40,000	0.73	0.22	0.26	1.21
Weighted Average		0.72	0.31	0.21	1.24

The 70,000 MTHM to be emplaced in the first repository will consist of 22,500 MTHM of BWR and 40,500 MTHM of PWR spent fuel, and 7,000 MTHM equivalent of high-level defense waste. The average C-14 content for both the BWRs and PWRs is shown in Table 4. The high-level defense waste is the liquid waste generated in fuel reprocessing that has subsequently been solidified in a glass matrix. Because of an almost complete removal of C-14 during the fuel reprocessing and the subsequent vitrification process, these contain hardly

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any C-14. The total repository C-14 content will then be 78,000 curies, almost entirely from spent fuel.

At present, it is not clear how the burnup credit is going to be applied to the defense waste. If the burnup credit is given on each radionuclide, the defense waste may not be allowed to release any C-14, since all C-14 in the fuel has already been released to the atmosphere during the processing, or at best it could be treated as a waste with the lowest burnup (i.e., 5,000 MWd/MTHM) allowed in 40 CFR Part 191 and get one-sixth (5,000/30,000) of release credit. In other words, the Table 1 limit for the 7,000 MTHM equivalent defense waste will be either zero or 117 (700/6) curies. Note 4 in Appendix A (Table for Subpart B) of 40 CFR Part 191, however, strongly indicates that no credit may be taken for C-14 for the defense waste, since the release during reprocessing of the fuel already exceeds the release limit of the spent fuel had it not been reprocessed. The release limit for the nominal spent fuel (25,000 to 40,000 MWd/MTHM burnup) for 63,000 MTHM is 6,300 curies. The total release limit for the entire repository would then be 6,300 curies, which represents approximately eight percent of the total inventory.

B. Source Term

C-14 in the spent fuel is distributed in the UO₂ matrix, Zircaloy cladding, and other fuel hardware. A small but significant amount has also been found on or near the surface of the cladding (Ref. 15, 16). Compared to the uncertainty in the inventory of C-14 discussed in the previous section, there is a tremendous uncertainty about the amount of C-14 that will become mobile and be released out of the waste package and Engineered Barrier System (EBS); i.e., the source term for transport to the accessible environment. In fact, this uncertainty may become the main source of difficulty in determining the compliance or non-compliance of the repository system with the regulations. The source term depends on many factors, including the container failure rate, fuel cladding failure rate, fuel oxidation rate, and fuel dissolution rate, all of which in turn depend on conditions in the repository environment such as temperature, amount of water, and water chemistry. Detailed discussion of these subjects is beyond the scope of this paper; only a brief analysis of relevant studies on C-14 is provided below.

1. Waste Container Failure

The container failure rate, as well as the cumulative container failures in 10,000 years, must be known to assess compliance with both the NRC and EPA regulations. At present, our knowledge of both is preliminary. The container material has not yet been selected and the design of waste packages for the spent fuel and defense waste is only at the conceptual stage. The problem, however, is more fundamental than that. There is no established method of predicting, with any certainty, the performance of any man-made material tens of thousands of years into the future. Efforts are being made to develop methods to project the life of containers that far into the future.

It has been shown that, for the release of radionuclides by the aqueous pathway, extending container life beyond 300 years and up to 1,000 years does not improve the total system performance (Ref. 17). 10 CFR Part 60

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requires only 300 to 1,000 years of substantially complete containment. The SCP reference strategy for meeting the NRC regulation for the gradual release of radionuclides after the containment period does not rely on the integrity of the containers. Therefore, unless the containers are designed for a longer lifetime to contain gaseous nuclides, the probability of failure of a large fraction of the current reference design containers in 10,000 years is assumed to be high if water comes in contact with the containers, primarily because of a large uncertainties in our knowledge.

The container failure rate depends greatly on the environmental conditions. It is believed that the current candidate repository horizon has remained unsaturated for more than one million years (Ref. 18). Even during the hot period immediately after waste emplacement, when there could be much refluxing of moisture around the waste packages, the DOE's near field performance assessment show that the rock around the waste packages would not become saturated. In addition, there is no known mechanism by which the water in the pores can cross the air gap between the containers and the host rock other than through diffusion across contact areas that might develop or by fracture flows. Depending on the climate, the containers may or may not fail completely during the next 10,000 years. Uncertainties in predicting the climate and repository environment may be so great that the DOE must assume that all containers will fail in 10,000 years. Even with an expensive, more durable container, it would be difficult to guarantee its integrity with any "reasonable assurance."

2. Release from the Waste Container

When a container fails, the spent UO_2 fuel is normally still protected by the Zircaloy fuel cladding, but C-14 on the surface of Zircaloy cladding is not protected and can be released in the form of carbon dioxide. This C-14 is termed the "rapid release fraction of C-14" in the SCP. One measurement of C-14 released from the cladding surface by this mechanism was obtained from an intact PWR spent fuel assembly with 204 rods in it (Ref. 15). The fuel assembly was stored in a test canister filled with air and radiated about 10^4 Rad/hr. The canister was heated to 275°C and slowly cooled. A gas sample taken at 118°C during the heating period indicated very little release of C-14. A second gas sample was taken 38 days later at 275°C and contained 1.5 mCi of C-14. It was not reported how long the fuel had been at 275°C before the sample was taken. A third gas sample taken a month later at 270°C indicated an additional release of 0.3 mCi of C-14. It also indicated that one fuel rod out of 204 had breached, as evidenced by the presence of the fission product gas Kr-85. It is, however, believed that the additional C-14 also originated from the external surface of the fuel assembly, based upon later analyses of fuel rod fill gas from other assemblies (Ref. 12). The total release of 1.8 mCi is 0.26 percent of the estimated total inventory of 690 mCi in the sample. Since the estimated total inventory was based on high values of nitrogen content in the fuel and Zircaloy, the actual fractional release may have been somewhat higher than 0.26 percent. Samples taken four months later contained little C-14.

Additional laboratory tests were conducted to determine the magnitude of the rapid release fraction of C-14 and its distribution in the Zircaloy. The results showed that the concentration of C-14 in the 10-micron thick oxide layer is up to five times higher than that in the bulk cladding

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(Ref. 19). Release tests were performed with a small piece of Zircaloy sample heated in both air and argon atmospheres at different temperatures. The results indicated that most of the C-14 was released in the form of carbon dioxide from the oxide layer. A release as high as about three percent of total inventory in eight hours was observed at 350°C in air. After eight hours at 350°C, the release appeared to be relatively complete. Considering the variations in the C-14 inventory among different fuel assemblies, H. Shaw of Lawrence Livermore National Laboratories (LLNL) believes that as much as five percent of the inventory could be rapidly oxidized and released (Ref. 20).

It was also observed that a much smaller, but still significant, amount of C-14 was released in an argon environment. It was speculated that some C-14 might have been present in an oxidized form or could be oxidized even in the absence of air before the container was breached (Ref. 21). The implication of this speculation is significant. Since the rate of oxidation of C-14 strongly depends on temperature, the size of the fast release fraction of C-14 could decrease significantly as the waste package cools. However, if the C-14 was oxidized before the container breached, then the amount of rapid release would not depend much on when the breach occurred. This speculation still must be confirmed. The argon gas used in the experiment contained approximately 10 to 50 ppm (vol) of oxygen, an amount far in excess of what would be required to oxidize all the carbon in the sample used (Ref. 21). The presence of other, preferred oxygen-getters such as zirconium may not have completely blocked the oxidation of C-14. Further tests with ultra-pure argon gas were planned but not carried out due to a reduction in funding. [Note: R. Van Konynenburg, LLNL, informed me that a more recent German experiment conducted in an ultra-pure argon environment indicated that an external supply of oxygen would be needed to oxidize the C-14.]

In a different experiment in a saline environment at 200°C, German researchers found that about 50 percent and 95 percent, respectively, of the C-14 inventory in cladding samples of PWR and BWR fuel could be released by corrosion (Ref. 22). This suggests that in addition to the rapid release fraction of C-14 from the oxide layer of Zircaloy cladding, C-14 can also be released as carbon dioxide after the cladding corrodes. The corrosion rate of Zircaloy cladding under conditions at Yucca Mountain is not known. An initial evaluation of samples from two-, six- and twelve-month electrochemical corrosion experiments indicated no Zircaloy-4 corrosion at a detection sensitivity of 1 to 2 microns of corrosion per year (Ref. 23). Further study also indicates that for the storage conditions investigated, the outer zirconium oxide layer is in a state of compression, thus making it unlikely that stress corrosion cracking of the exterior surface will occur (Ref. 24). However, the uncertainty in the long-term corrosion rate of cladding remains. It is assumed, therefore, that once the container is breached, the cladding will also likely breach within a 10,000-year time frame. For this reason, the SCP states that credit will be taken for the cladding as a barrier only if analyses could support it. Even if the cladding does not breach, corrosion processes could release some C-14. In the absence of any data on the corrosion rate of the cladding, Park and Pflum speculated that the combined release in 10,000 years from the rapid release fraction and cladding corrosion could reach ten percent of the total inventory (Ref. 6).

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A different type of analysis measured gaseous C-14 through penetrations that corroded through the canisters (Ref. 25, 26, 27). The flow of gases in and out of the container through the penetrations was modeled as a function of time after emplacement, size of the penetration, time of the breach, and internal packaging pressure. The results show that small penetrations will limit the rate of escape of gas from the container. These analyses are useful in analyzing the release of C-14 during the substantially complete containment period. However, they all show that 10,000 years is enough time for the oxygen to diffuse into the container and oxidize C-14 in the Zircaloy oxide layer, and for the C-14 dioxide to escape from the container. In addition, the uncertainties involved in these analyses are too great for the results to be directly useful. It is not presently possible to predict how many and what size penetrations would be created by metal corrosion, and when they would occur. Studies in this area are still very preliminary and the uncertainties involved in the predictions, even if they were possible, would be very large. For the C-14 analysis, therefore, we assume C-14 can move freely through the penetrations once the container is breached.

3. Release from the Fuel Matrix

After the container and cladding are breached, the UO_2 fuel matrix will be altered and dissolved when contacted by the water. Data on the long-term matrix alteration rate are not available. Although a value of 5.3×10^{-6} /yr was used in the Fiscal Year 1990 PACE exercise (Ref. 28), the uncertainty is very large. A value as high as 10^{-3} /yr was used in source term calculations for the tuff repository (Ref. 29). Any contact with water would be limited by the small amount of water flux at the repository horizon, even if a pluvial climate developed in the future, and it is highly likely that the site will remain unsaturated for the next 10,000 years. The earlier study at 25°C indicated a saturated dissolution rate of less than 10^{-5} /yr (Ref. 30). More recent studies indicated, however, that the rate could be two orders of magnitude higher at higher temperatures (Ref. 31). At the flux assumed in the SCP (20 liter/yr/waste package), the entire spent fuel inventory could be dissolved in 10,000 years if the container and cladding breached. This, of course, is a very unlikely scenario, especially in view of the fact that the SCP assumed a flux rate 80 times higher than the 0.5 mm/yr considered a reasonable and conservative upper bound for a Yucca Mountain repository (Ref. 32). It should be noted that the nominal flux used in the FY 90 PACE exercise is 0.01 mm/yr. Nonetheless, in the presence of high water flux, a substantial portion of spent fuel and hence C-14 could be dissolved and transported in water. Due to an extremely low diffusion coefficient in unsaturated rubble around the waste package (Ref. 33) and low flux, the liquid would travel very slowly and would be exposed to gas flow moving upward. The heat from the emplaced wastes in an unsaturated site could induce a large-scale air and gas convective movement (Ref. 34).

The C-14 in the water will reach thermodynamic equilibrium between gaseous CO_2 and aqueous HCO_3^- . Once the C-14 transfers to the gaseous phase it will go through the same process as the gaseous C-14 released from the Zircaloy surface. It should be noted that the conditions above and below the repository level are almost identical in terms of the CO_2 environment, so the CO_2 will partition between the liquid and gas regardless of the origin. The C-14 in the gaseous phase will move upward much faster than the liquid will travel downward. The net result is that most of the C-14 in the water, after

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some time delays due to retardation, could end up being released in gaseous form to the environment. Therefore, the net source term for the gaseous transport of C-14 would be the sum of the rapid release fraction from the Zircaloy surface and a significant fraction of the C-14 dissolved in water. While the former is a one-time release from the breached container, the latter is a continuous and cumulative release from all breached containers as long as the fuel continues to dissolve. The cumulative release of C-14 from spent fuel dissolution could provide a much larger source term than the rapid release fraction, depending on the amount dissolved and the degree of thermodynamic equilibrium (partitioning between the gas and liquid).

Carbon-14 may exist in various chemical forms in spent fuel and hardware. Release of C-14 from reactor off-gas was observed to be in the form of carbon dioxide, carbon monoxide, and hydrocarbons including methane (Ref. 12). The C-14 in the Zircaloy surface is oxidized first, before it is released. The actual release measured from the test fuel assembly was in the carbon dioxide form with no measurable amount of carbon monoxide, except for one sample that contained an insignificant amount (Ref. 15). During the dissolution of chopped spent LWR fuel rods with air sparging at ambient temperature (in nuclear fuel reprocessing plants), almost all C-14 is released into the dissolver off-gas in the form of carbon dioxide. Therefore, it appears that the gaseous release of C-14 from the tuff repository would most likely be in a carbon dioxide form.

C. Transport of C-14

The transport of gaseous C-14 from the repository to the environment would be controlled primarily by the flow of gas through fractures and rock pores. The gas interacts with the water trapped in rock pores or on the fracture surface. C-14 in the gas will exchange with the C-12 in the pore gas, which is in equilibrium with the bicarbonate ions in the pore water, which in turn may be in equilibrium with calcite in the rock. The net result is an effective retardation of C-14 movement through the rock. The degree of retardation depends on the degree of deviation from a thermodynamic equilibrium between the gas and liquid in the pores.

1. Gas Flow Through the Mountain

Gas moves through the deep unsaturated zone at appreciable velocities (Ref. 18). This is a convective movement caused by the density difference in gases with depth due to the geothermal temperature gradient, as well as by diurnal and seasonal changes in barometric pressure (Ref. 35, 36). Substantial air flow has been observed in several wells drilled in the vicinity of Yucca Mountain and a section of open hole above the water table. In one well, the observed flow rates are so great they can only be explained as fracture flow phenomena (Ref. 37). Nearly 40 percent of the actual flow from one observation well is generated by wind effects. The flow log also indicates that the midpoint for flow entering the well is at a depth of 20 meters (Ref. 37). Although the observed gas flow velocity -- ranging from negative to +7 m/s at the top of the well -- has been modeled, gas flow throughout the mountain is not known well, especially at the repository depth.

If high-level waste is placed in an unsaturated repository, the heat generated by the waste will provide a driving force that moves large volumes of gas. Tsang and Preuss estimated the velocity of heat-driven gas flow from a hypothetical repository and natural geothermal temperature gradient (Ref. 38). Their results show that gas phase convection could take place with appreciable velocity, of the order of 22 m/yr. This average velocity has been used by others to calculate the rate of C-14 transport through Yucca Mountain (to be discussed later). More detailed simulation of gas flow velocities as a function of depth shows a range from 4.5 to 1174 m/yr at 100 years after waste emplacement, with the highest velocity at the repository level. Other studies of the potential repository at Yucca Mountain indicate that the temperature disturbance resulting from emplacing the waste will be significant even after 10,000 years (Ref. 39, 40). In a recent study, Tsang simulated the temperature and gas velocity field up to 10,000 years after waste emplacement using the layered stratigraphy at Yucca Mountain and the reference heat load of 57 kW/acre at the time of emplacement (Ref. 41). The results still show a wide range of velocities through the different strata, from a fraction of a meter per year in Paintbrush tuff (gas flow only through matrix pores with porosity of 0.4 was assumed) to over 200 m/yr at the repository level. The average velocity near the top of Tiva Canyon still approaches 40 m/yr at 100 years, 20 m/yr at 1,000 years, but then decreases to a few m/yr at 5,000 years. Due to a buoyancy effect, the locus of the fastest velocity moves toward the top of the Topopah Spring tuff.

Water vapor movement produced by the heat pipe near the waste package could affect the migration of gaseous radionuclides. Zhou et al., however, show that for the equivalent waste sphere the heat pipe exists from eight days to 40 years after emplacement (Ref. 42). In addition, they also conclude that the heat pipe extends from the waste surface to about three meters from the center of the equivalent waste sphere. For a large-scale gas movement for 10,000 years, therefore, we can safely ignore the heat pipe effect.

2. Retardation

The movement of gaseous C-14 can be retarded by complex chemical interactions with the pore water and the solid rock. Ross describes a general chemical model for C-14 retardation at Yucca Mountain and estimates the bounds of the retardation factor to be 2 to 2,000 (Ref. 43). In a more recent study, he calculated the retardation factors for three different stratigraphic layers as a function of temperature, obtaining a range of 30 to 70 with an approximate median at 50 (Ref. 44). Ross used the PHREEQE computer code to obtain the equilibrium distribution coefficient. Others used data from the literature, expressed as a function of pH and temperature, to account for the retardation of gaseous C-14 movement in their transport equations (Ref. 45, 46). Although they did not calculate retardation factors explicitly, their numbers are of the same order of magnitude but higher than those calculated by Ross. While Knapp used the equilibrium distribution coefficients at pH 8 as a function of temperature, Light et al. used a fixed value at pH 7 and 50°C to get an equilibrium distribution coefficient of 3 (Ref. 47).

Many implicit assumptions have been made in calculating the retardation factor, of which the most important is that of a thermodynamic equilibrium between the gas and liquid. On the time scale involved in the repository C-14 travel, Ross justifies the validity of such an assumption. Yang

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analyzed pore fluid and pore gas to determine the extent of the water-rock interaction and gas travel time at Yucca Mountain using an isotope ratio of carbon, oxygen, and tritium (Ref. 48). His preliminary finding suggests a lack of thermodynamic equilibrium between the gas and liquid but the results are not conclusive. Although the gas and pore liquid were obtained generally from the same geologic strata, the actual gas sample was collected from the UZ-1 hole while the pore water was extracted from UZ-4 cores. The data still strongly suggest the possibility of a very low retardation, especially if the liquid is confined to small pores (high suction pressure) and the gas flows through the path of least resistance (fractures and large pores) with minimal contact with pore liquid.

All this suggests that the degree of retardation may also strongly depend on the degree of saturation. With a pluvial scenario, more liquid flux to the repository (still unsaturated) may accelerate the corrosion of containers, thus increasing the source term for C-14. A possibly lower temperature resulting from more cooling may also reduce the rate of oxidation, but in the long run the total release may not be affected much. On the other hand, a higher saturation may enhance liquid-gas contact, hence increasing the retardation. No quantitative data are available on the relative contribution of these two counteracting effects from increased flux. However, it can be seen that the source term and transport strongly depend on the expected hydrology.

3. Far Field Transport

A nominal travel time of gaseous C-14 from the repository to the accessible environment can be obtained from the gas flow velocity through the mountain and the retardation coefficient of C-14. As mentioned earlier, the unretarded gas travel time through the mountain is relatively short -- from tens to hundreds of years -- which means the retarded travel time could be from less than 1,000 years to over 10,000 years. Since the half-life of C-14 is 5,730 years, the effect of retardation can become significant with a long travel time. Although this view of gas travel time is very simplistic, it clearly indicates that the travel time is neither very short nor very long and more accurate estimates are needed.

Ross first modeled the C-14 transport at Yucca Mountain (Ref. 43). His preliminary calculations based on the governing equation and order of magnitude estimates indicated that a substantial portion of C-14 could reach the surface in less than 10,000 years. Knapp solved an analytic equation for gas phase transport of a C-14 kinematic wave, incorporating advection, isotope exchange between CO_2 in a flowing gas phase and HCO_3^- in a static aqueous phase, and radioactive decay (Ref. 45). His calculations indicate that the C-14 wave takes about 5,900 years to reach the surface. This implies that about half of the C-14 released from the repository during the first 4,000 years will reach the surface during the regulatory time frame of 10,000 years. His calculation is based on an estimated gas Darcy velocity of 1 m/yr and no diffusion, with dispersion and temporal and spatial variations in rock and fluid properties taken into consideration.

Lerman also estimated the travel time of gas through an unsaturated rock zone based on the expanding gas volume and the density gradient caused by the heat generated in the repository and diffusional flux (Ref. 49). He estimated an

average gas velocity of 2 m/yr, using a gas permeability three orders of magnitude lower than the values reported by Montazer et al. (Ref. 32). Although his analysis made the point that some gaseous radionuclides might reach the surface in a relatively short time, his model grossly lacked the complexities needed; e.g., no geochemical retardation was modeled.

Light et al. also solved the governing equation using an equivalent porous-medium approach and calculated the gas concentration at the ground surface as a function of time and gas flow velocity in the mountain (Ref. 46). They used the Darcy velocity of gas calculated by Tsang and Preuss (Ref. 38) as a reference, and calculated the gas travel time for 0.1, 1.0, and 10 times the reference Darcy velocity. A fixed equilibrium distribution coefficient of 3 at pH 7 and 50°C was used to calculate the retardation. The results show C-14 travel times to the surface to be in hundreds to thousands of years for the assumed parameter values.

The most rigorous and comprehensive modeling was done by Ross et al. (Ref. 44). A two-dimensional, steady state numerical model of rock-gas flow driven by temperature and humidity differences, called TGIF (Thermal Gradient Induced Flow), was developed to determine flow paths by particle tracking and to calculate C-14 travel time. The model takes into consideration the different geologic strata with different permeabilities, tilting of the bed, Yucca Mountain topography, and geochemical equilibrium between the gas and liquid. The model treats the fractured tuff as a homogeneous medium. C-14 travel times were calculated for three different repository temperatures two levels of permeability contrast between the Paintbrush nonwelded tuff and the Tiva Canyon and Topopah Spring welded units at four east-west cross sections. Fixed repository temperatures were used instead of the actual time dependent heat generation rate of the waste. The temperature profiles generated using a waste heat load of 57 kW/acre by Tsang indicate the repository temperature could be higher than the values used by Ross, especially during earlier times, even up to several thousand years (Ref. 41). The C-14 travel times calculated were shown in histograms. As expected, the unretarded travel times range from tens to hundreds of years, and the retarded travel times are generally in thousands of years. His calculations also show that at lower temperatures and higher permeability contrasts, many or most of the retarded travel times exceed the C-14 half-life of 5,730 years and the regulatory time frame of 10,000 years. On the other hand, with a low permeability contrast and a repository temperature of 330°K, almost all C-14 escapes to the atmosphere in less than 2,000 years.

Overall, these calculations show that the expected C-14 travel time is generally several thousands of years or less, including retardation. These calculations assume the maximum retardation possible using thermodynamic equilibrium, but do not take into account the effects from wind and barometric pumping. Analysts used a retardation factor of about 50, which is a very high retardation for gas movement. In many other geologic media, the retardation results from physical or chemical sorption of C-14 on the media itself. There is little information on the sorption of C-14 on various kinds of rocks. There are some indications, however, of the magnitude of retardation that sorption provides. Bush et al. used a value of 8 for retardation in a clay medium, which is highly sorptive (Ref. 13). The high retardation at Yucca Mountain is due to the geochemical interaction of C-14 dioxide with HCO_3^- in the pore water, which is in equilibrium with an

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abundant amount of calcite in the rock. Other geologic media may not have as high a retardation factor as Yucca Mountain; therefore, it appears that the relatively short C-14 travel times may not be unique to Yucca Mountain, but may apply to most generic unsaturated sites in the U.S. Ross also states that the general conditions used in his simulation would apply to most other unsaturated sites (Ref. 44).

D. Health Effects of C-14

Carbon is one of the most abundant elements on earth and in the biosphere. It constitutes over 22 percent of the human body by weight (Ref. 8) and is abundant in our daily diet. Natural carbon contains about 1.4×10^{-12} g C-14/g C. A reference human being weighing 70 kg contains 0.1 microcurie of C-14, from which he receives 1.3 mrem/yr of radiation exposure (Ref. 8, 50). The global inventory is estimated to be 230 million curies, which are distributed as follows: 90 percent in deep ocean more than 100 m from the surface; 8 percent in surface waters, sediment and biosphere; and two percent in the atmosphere (Ref. 51). In addition to the large inventory of C-14 already existing in the natural system from cosmic ray production, additional C-14 is continuously produced in the atmosphere by the interaction of cosmic ray neutrons with nitrogen. The amount in the atmosphere is estimated to be 3.8 million curies, and the annual natural production of 28,000 curies in the atmosphere (Ref. 52) balances the loss by radioactive decay.

C-14 released from a repository in gaseous form would enter the atmosphere and mix completely in about four years to become part of the global inventory. C-14 in the human body also comes to an equilibrium with the atmospheric C-14 after a lag time of 1.4 years (Ref. 53). Once it is released, C-14 becomes a part of the global inventory and any increase in concentration in the atmosphere could affect the entire world population, provided the assumption of a linear no-threshold relationship between the health effect and radiation exposure holds. It should be noted that this assumption is not well established at a low level of radiation.

The C-14 in the atmosphere exchanges with carbon in the ocean surface waters, which in turn exchanges with carbon in other reservoirs such as deep ocean, land biosphere, and humus; most of the radioactive decay occurs in the ocean, where it stays longest during the global circulation cycle. As a result, the effective half-life of C-14 in the biosphere is much shorter than its natural half-life of 5,730 years.

The potential health effects of C-14 from both the natural and man-made sources have been studied extensively (Ref. 50). Infinite time (effectively about eight half-lives or 46,000 years) population dose commitment of C-14 has been calculated by many studies (Ref. 13, 50). The numbers range from 370 to 620 man-rem/Ci (divide the number by 100 to get person-Sievert/Ci) based on a projected steady world population of 10 to 12 billion. In a more recent study, McCartney et al. reported a value of 460 man-rem/Ci for the 100,000-year dose commitment based on a steady world population of 10 billion (Ref. 54). The biological effect per unit population dose also varies depending on the pathway model and other assumptions used. Reported values range from 100 to 200 cancers for 1×10^6 man-rem (Ref. 8, 50). The EPA used a value of 146 cancers per 1×10^6 man-rem exposure in their analysis, although they also indicated the value probably was lower by a factor of 1.5

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based on newer data (Ref. 55). [Note: They are using 400 cancers per 1×10^6 man-rem now, according to Mr. Galpin at the 11/91 EPRI Workshop]. We use a number of 200 cancers per 1×10^6 man-rem, which is consistent with the value recommended by the ICRP. The number of genetic effects from C-14 exposure is estimated to be about one-tenth to two-third of the total cancers (Ref. 50, 55). Using these numbers, the limit of 6,300 Curies to comply with the EPA regulation from the 70,000 MTHM repository equates to a total cancer death of 580 over 10,000 years. It is to be compared with 370,000 cancers from natural C-14 and 37 million from total natural background radiation over the same time period.

The health effect of a release of C-14 from a potential repository at Yucca Mountain has been calculated by Daer under two different scenarios (Ref. 56). Under the first bounding scenario, a release of 1,000 curies in one year from the ground surface was assumed. It was also assumed that the entire projected surface area of the repository was covered by an invisible confinement 2 meters high, and the C-14 inside stayed within this volume for the entire year. People lived inside the confinement eating contaminated food grown inside and drinking contaminated water. Under this ultra-conservative, almost implausible scenario, the maximum exposure was calculated to be about 2 mrem/yr. Obviously C-14 would not be trapped locally, the annual release would be almost three orders of magnitude lower, and there would not be much vegetation near the Yucca Mountain area. Ingestion dose dominated over submersion and inhalation doses, as expected.

The second analysis was only for internal and external doses from air containing C-14, and was based on a uniform release of 1,000 curies from the ground surface of the repository in one year and currently prevailing climate conditions, such as wind velocity, direction, dispersion of the plume, etc., at Yucca Mountain. Under this still conservative scenario, the exposure to the maximally exposed individual was calculated to be 0.05 mrem/yr. Under the allowable release limit of an average of 0.63 Ci/yr (6,300 Ci per 10,000 years), the corresponding exposure would be 3×10^{-5} mrem/yr. The second analysis did not include the dose from ingestion. In areas with much vegetation, the ingestion dose from the food chain dominates over the dose from inhalation and immersion by about two orders of magnitude. At Yucca Mountain, however, the ingestion dose is expected to be only one order of magnitude larger than the inhalation dose, primarily due to the low potential for vegetation (Ref. 57). If we include the dose from ingestion in the second scenario, the total dose from C-14 from the potential Yucca Mountain repository would be 3×10^{-4} mrem/yr, which is about one one-millionth of what an average individual receives from natural background and one ten-thousandth of what an individual receives from natural C-14 from the atmosphere.

In a more recent study, done as a part of the FY 91 PACE by Pacific Northwest Laboratory and Sandia National Laboratories, the potential dose from the repository C-14 was calculated (Ref. 57). The ground surface source term of C-14 for the dose calculation was estimated probabilistically for different container failure times, two different gas flow modes; i.e., matrix and fracture flow, an average wind speed of 3.3 m/sec with no vertical or horizontal dispersion, and different matrix gas permeabilities. The overall scenario, including the source term from the EBS, was very conservative. Under this scenario, the calculated dose to a hypothetical, maximally exposed individual living on the surface of Yucca Mountain ranged from 2.3×10^{-17} to

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1.2×10^{-1} mrem/yr. No attempt was made to calculate an average or median value in this preliminary study. The numerical values calculated deterministically by Gary Daer fall within the range of this study.

For the purpose of the regulatory analysis in the next section, we will use 3×10^{-4} mrem/yr as the basis.

E. Uncertainties

Among the factors influencing the release of C-14 to the accessible environment, the inventory estimates have the least uncertainty, though they are still significant. Considering the accuracy of the ORIGEN code used in the calculation of isotope generation in the reactors, the amount of nitrogen impurities in the fuel, cladding, hardware, variability among fuels, the fact that two-thirds of the spent fuel to be emplaced in the repository doesn't even exist today, and the trend toward ever higher fuel burnups, the uncertainties in the inventory are probably at least -50 to +100 percent.

The largest uncertainty, however, is in the source term, which in part stems from the uncertainty in the post-closure near field environment. Container failure rate is largely unknown and uncertainties will remain even after the material and design are fixed. If the near field environment remains unsaturated and relatively dry, the container failure rate would be very small and a large fraction of the waste containers will survive for 10,000 years. If the climate changes to a pluvial condition, fracture flows dominate at the repository level, and a large amount of water comes into contact with the waste containers, then, conservatively, with the current design of the waste package it should be assumed that most of the containers would fail during the first 10,000 years. The uncertainties in the container failure rates would be at least one order of magnitude and could be higher, depending on the degree of site characterization and material testing. The uncertainties in container failure rate could be reduced by employing more robust, long-life waste package design, but presently there is no regulatory need for a long-life (10,000 years or longer) waste package to meet the EPA performance requirements other than that for C-14. Compliance with the NRC's subsystem performance requirements on waste packages and EBS may necessitate a long-life waste package because of the need to contain gaseous radionuclides and several other readily soluble radionuclides. Among these, the requirement for C-14 would still be the most imposing.

Data on the C-14 release from the surface of fuel assemblies; i.e., the rapid release fraction, are extremely limited, so more experimental measurements are needed. The value assumed for the rapid release fraction in the SCP; i.e., one percent, appears low in view of more recent laboratory experimental results. Two to ten percent may be a reasonable range, although there is a possibility that it may even exceed ten percent. Again, it should be mentioned that these figures are based on a limited number of observations and are speculative at best.

Release of C-14 from the fuel matrix would be strongly influenced by the alteration rate of the fuel. Current assessment indicates a possible range of at least two to three orders of magnitude. There is an additional uncertainty in the fraction of C-14 released in liquid form initially that might eventually be released to the accessible environment in a gaseous form.

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Depending on the scenarios for the near and far field environment, the fraction could vary from almost 0 to 100 percent.

Most calculations on the C-14 travel time at Yucca Mountain indicate that it may be relatively short compared to the 10,000-year regulatory timeframe and the half-life of C-14. The natural barriers at Yucca Mountain may not be able to delay the movement of C-14 past the regulatory time limit or until it decays by a significant amount, even with the retardation due to geochemical interactions. It would be reasonable to assume that all C-14 released from the waste packages within the 10,000-year timeframe would reach the accessible environment quickly, without much radioactive decay. Aside from the uncertainties in the retardation factor, from one to an average of 50, the travel time is strongly influenced by rock permeabilities that vary in different strata. C-14 could reach the surface in a few years to tens of thousands of years, although a few thousand years seems the most likely.

The long-time population dose commitment of C-14 is generally well established. Models for the global carbon circulation cycle have long been in existence, from the simple three-reservoir models of earlier days to recent, more sophisticated multi-reservoir models. Most of the models currently in use are variations of the six-reservoir model by Bacastow and Keeling (Ref. 58). Results from different models generally agree well because the deep ocean acts as the primary reservoir, holding more than 90 percent of global C-14 and dominating the circulation cycle.

The overall combined uncertainties are so large, including those for the disturbed scenarios, that from almost 0 up to 50 percent of the total inventory in the repository (up to 40,000 curies) could be released in the gaseous form over the 10,000-year period. Of course, this is a very high estimate, and most likely the probability distribution of release would be highly skewed toward lower values. The big question is what would be the probability of the release exceeding eight percent of the total inventory. Due to the uncertainties discussed above, it would be reasonable to assume a ten percent probability that the gaseous release would exceed eight percent of the C-14 inventory.

F. Need for Additional Analyses

The results of most analyses are uncertain because of lack of data, especially long-term data that may or may not be fully obtainable. Some uncertainties could be reduced by site characterization data and laboratory and field experimental measurements, but there will always be residual uncertainties from both the known and unknown unknowns. Since the transport of C-14 is relatively fast, what is needed most is more data on the source term, not only for Yucca Mountain but for other unsaturated sites as well. Analyses that could reduce the uncertainty band in the source term should be emphasized.

It might be worthwhile to solicit expert opinions in each of the categories discussed above to narrow the range of uncertainties, then to run a simple model to obtain a probability distribution of C-14 gaseous release by employing time-distributed container failure, range of retardation and travel time, etc. The results, however, would still be speculative at best since we are limited more by the lack of real data than by reliable means of analysis.

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Additional data needs have already been discussed in the Yucca Mountain SCP and briefly in the sections above, and will not be repeated here.

The analyses in the previous sections deal only with undisturbed performance of the geologic repository. Based on our preliminary knowledge of volcanism scenarios, it was assumed in this study that any gaseous release of radionuclides under disturbed conditions of the repository would be insignificant. This, however, should be investigated further.

III. REGULATORY IMPLICATIONS AND POSSIBLE ALTERNATIVES

A. Regulatory Implications

The NRC's subsystem performance requirements in 10 CFR Part 60 require that the containment of radionuclides in the waste packages be substantially complete for 300 to 1,000 years, and that after containment the annual release rate of any radionuclide from the EBS not exceed one part in one hundred thousand of the inventory of that nuclide at 1,000 years after emplacement with an exclusion limit for radionuclides with an extremely small release potential. The regulatory term "substantially complete containment" has not yet been defined quantitatively. The NRC made it clear in its Site Characterization Analyses that the term should be interpreted to mean that the release during the containment period be much less than that allowed during the post-containment period (Ref. 59). Design goals were established in the SCP with a goal of achieving a C-14 release rate of less than 10^{-6} /yr of the 1,000 year inventory, which would correspond to 7.8×10^{-2} Ci/yr. Even if we assume the rapid release fraction to be two percent of the inventory in the container, failure of two or fewer containers per year would exceed the SCP goals and the 10 CFR Part 60 requirements even if we ignore the C-14 released through the aqueous phase. If we take a more conservative number of ten percent for the rapid release fraction, then it takes only a fraction of one waste container to violate the requirement in a given year. The 10 CFR Part 60 requirements could also be violated if 2 to 20 waste containers breach in a given year. If we include the cumulative release from all failed containers that will cross the EBS boundary in either a gaseous or liquid form, the number of containers that can breach annually would be even less. This level of containment may be possible if an expensive waste package design with multiple barriers is employed. Nevertheless, it would be almost impossible to guarantee such a low level of failure on an annual basis as the NRC regulations require.

The EPA regulation, 40 CFR Part 191, does not specify any requirement on the performance of subsystems. It is an overall environmental standard, and as such it only limits cumulative release to the accessible environment. The limit for C-14 is 100 curies per 1,000 MTHM over 10,000 years with better than 90 percent probability that the level would not be exceeded, provided no other radionuclides are released at the same time. If other radionuclides are released concurrently, the release limit must be prorated (i.e., reduced) by a formula given by the EPA. The release limits were conceived to limit the number of fatal cancers to 1,000 over 10,000 years from a repository containing 100,000 MTHM. As shown in the previous section, the final number used for C-14 is equivalent to 570 fatal cancers over 10,000 years from a repository containing 70,000 MTHM, of which 63,000 MTHM are spent fuel. The level of risk; i.e., 1,000 cancers over 10,000 years, was considered easily

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achievable at the time based on performance assessment of generic sites, and was also considered to be comparable to the risk from the unmined uranium ore (Ref. 55, 60).

The EPA limits total release of C-14 to 6,300 curies in 10,000 years and the NRC limits the release to about 0.63 Ci/yr. If only eight percent of the C-14 inventory at emplacement escapes to the accessible environment, we could violate the EPA and NRC regulations. The current lack of data and high uncertainties also reduce the confidence that we can meet the regulations.

It has also been shown in the preliminary performance assessment of the Yucca Mountain repository that the complementary cumulative distribution function (CCDF) of the release is largely dominated by the release of C-14 (Ref. 2, 3). Although the results show that the CCDF curve is still within the bound of the EPA limit it is very close to violating it, even without taking into account all the uncertainties discussed in the previous section.

A few alternative waste package strategies have been proposed in the SCP that could be very expensive and still might not be able to provide reasonable assurance that the release would be within the EPA and NRC limits. Some of the proposed technologies have not yet been fully developed or demonstrated. They are discussed below in conjunction with regulatory alternatives.

B. Discussion of Regulatory Alternatives

The EPA conclusion that its release limits were easily achievable was based on assessments of several hypothetical repositories (Ref. 61). Unsaturated repositories and gaseous radionuclides were not considered in determining whether the release limits could be met. The hypothetical repositories were also simpler than the real sites the DOE has studied, making the validity of the EPA's conclusions questionable.

An apparent basis for the EPA limits is hidden in their comparison of repository risks to the risk from unmined uranium ore:

"Accordingly, the Agency has promulgated environmental standards that would restrict projected releases from high-level waste disposal system -- for 10,000 years after disposal -- to levels that should keep the risks to future generations less than the risks they would have been exposed to from the unmined ore if these wastes had not been created." (Ref: 55)

The level of risk from unmined uranium ore was calculated for a few real and one hypothetical uranium mine (Ref. 62). Using a hypothetical uranium mine as a basis is unreasonable in view of the fact that most of the uranium mines from which the first 70,000 MTHM fuel would be produced could be identified (both domestic and foreign), and the risks from unmined uranium ore body could also be obtained from environmental documents. The probability limits EPA assigned to the release; i.e., 0.1 and 0.001, also have no basis, since the probability of releasing the calculated amount from a real mine is almost 1.0, because those assessments are based on actual measurements. These facts have been pointed out in testimony to the Advisory Committee on Nuclear Waste

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(ACNW) by U. Park (Ref. 63). A subsequent ACNW evaluation confirmed that the EPA release limit was at least one order of magnitude more stringent than the limit that would produce the same risk from res. unmined uranium ores in terms of release probability, and three orders of magnitude in terms of the associated health effects due to radionuclide releases (Ref. 64). In explaining why the EPA did not choose higher (less protective) release limits, they state:

"... The differences in costs for different levels (of protection) are much smaller than the overall uncertainties in waste management costs. For example, consider the increased costs of complying with the release limits we have proposed, rather than release limits 10 times less stringent. The potential increase ranges from zero to 50 million (1981) dollars per year.... As discussed above, setting the release limits at the level we chose -- as opposed to a level 10 times less or 10 times more stringent -- appears to cause only very minor effects on the costs of high-level waste disposal. This is why we did not choose higher (less protective) release limits." (Ref. 65)

The EPA was mistaken. Costs are very sensitive to the level of protection, especially when the requirements push the design of waste packages to the limits of practical engineering and science. If costs were properly considered, the release limit could be justified at 10 times higher than what was finally set by the EPA and the public health and safety would still be fully protected.

Given this general background on the EPA regulation, the following approaches to develop an alternative standard for allowable release of C-14 would seem to merit consideration:

- o Keep the current regulation and
 - use longer-life containers
 - release the C-14 before emplacement
 - use fuel reprocessing
- o Relax the current release limit for all radionuclides by a factor of ten.
- o Give special consideration to C-14 because of its unique nature and because it produces an individual dose that falls well below regulatory concern (dose truncation).
- o The same as above, except base the truncation on the affected population (geographic truncation).
- o Change the basis of the standard from population dose to individual dose.
- o Regulate repository gases under the National Emission Standards for Hazardous Air Pollutants Act (NESHAP) (40 CFR Part 61).

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- o State that the release limits in Table I of Subpart B, Appendix A do not apply to gaseous release of radionuclides and hold the regulation of gaseous releases in reserve.

These options are discussed individually below in terms of their advantages and disadvantages from a scientific point of view and, to the extent possible, from their political implications.

1. Keep the Current Regulation

The current regulation was promulgated based on three basic premises: (1) it is easy to meet the limits; (2) the risk is comparable to the risk from unmined uranium ore, which is acceptable to the public; and (3) more stringent regulation does not incur any significant additional cost. However, what may have been a reasonable assessment based on the state of knowledge 10 to 15 years ago is no longer valid. The regulation is outdated and should be changed.

There appears to be a high probability that it will not be possible to satisfy the EPA and NRC regulations because of overwhelming uncertainties in the source term. The preliminary performance assessment clearly showed that the main reason for potential violation of the regulations is the gaseous release of C-14. This has been foreseen by YMP scientists for a long time, and the DOE has proposed several alternative approaches in the SCP in case the reference waste package cannot meet the requirements due to uncertainties in the site conditions (Ref. 18). The alternatives were presented primarily to address the NRC's 10 CFR 60.113 requirements. They include the use of alternative container design and materials, use of 10 CFR 60.113 (b) (variation in containment period and post-containment release rate), release of C-14 from the surface of fuel assemblies prior to emplacement, taking more credit for cladding if this could be supported by more testing, and inclusion of part of the host rock in the EBS. Among these, only two could address the C-14 problem for both the EPA and NRC requirements: a long-life waste package using alternative material, and the pretreatment of fuel assemblies to release the rapid release fraction of C-14. These are discussed in more detail below.

a. Use of long-life waste packages

The current reference design for the waste packages is a thin-walled, single wall metallic container that capitalizes on the unsaturated nature of the site. In the absence of any significant water movement at the repository level, this design would be adequate to protect the public health and safety. Under any scenario that would allow the breach of waste containers in any significant quantity during 10,000 years, the reference design and the current candidate materials may not be adequate or may be adequate but cannot be so proven. Since the rapid release fraction of C-14 is on the outside surface of the fuel cladding, the waste container wall must be gas tight for 10,000 years. Most metals have only a short performance history and are susceptible to various failure mechanisms. Ceramics such as alumina were considered in combination with metal inner or outer layers. The additional cost over that of the reference design is estimated to be in the billions of dollars for 35,000 waste packages. In addition,

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the technology exists only in small-scale applications. Significant technology development would be needed involving an additional cost and schedule delay. The DOE is studying other long-life waste package designs that rely on multiple barriers to increase reliability, but no firm designs have evolved yet. The high cost of developing and fabricating long-life waste packages compared to the negligible gain in public health and safety has already been pointed out (Ref. 6,7).

b. Pretreatment of the fuel assemblies

The existing regulations do not regulate the release of C-14 from nuclear power reactors and other nuclear fuel cycle facilities. The operating PWRs and BWRs release gaseous C-14 at the rate shown in Table 3. Each reactor releases 5 to 10 curies every year. If the C-14 on the surface layer of Zircaloy cladding is released prior to emplacement, it would not violate any regulation. The rate of release from this operation would be much higher than the release of C-14 from the repository, since at least two percent of the total inventory (1,500 curies) would be released in less than 50 years. Assuming that the linear dose-response model is valid, the resulting health effects would be much higher than the effects produced by the expected release from the repository, although both would still be very low.

To release C-14, the fuel must be heated to about 275°C for an undetermined length of time. Under laboratory conditions with a purge gas flow, the release was almost complete after 8 hours. However, the only actual test done with an intact fuel assembly indicates up to two months might be needed. The cost of performing this operation, even if it was technically feasible, would be extremely high. The annual spent fuel receiving rate is twice as high as the rate at a full-scale, 50 GWe/yr fuel reprocessing plant, and the fuel would then have to be stored for up to two months at 275°C. The fuel assemblies would have to be cooled before transport to the repository. The cost of such a facility, operated remotely, would be prohibitively high when the off-gas treatment and other handling facilities are included.

In addition, the effect of heating the fuel in a dry condition is not known. One out of the 204 fuel rods failed during the test. Other technical problems include finding a method of heating the fuel assemblies uniformly without overheating to prevent cladding failure, and the treatment of radioactive off-gases Kr-85 and I-129 from breached fuel rods. Both Kr-85 and I-129 are regulated under current regulations. The C-14 gas from heating would have to be vented to the atmosphere, since it would be diluted so much with air it could not be recovered economically.

It should be noted that releasing the C-14 at a higher rate just to circumvent the repository regulations may not be acceptable to the public regardless of the low health effects.

c. Fuel reprocessing

Fuel reprocessing is not a real solution to the C-14 problem, since the decision to reprocess will involve many considerations and C-14

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may not be an important one. Although the release of C-14 from a fuel reprocessing plant (FRP) is not regulated at present, primarily because there is no FRP in the U.S. except for the defense facilities, the off-gas stream is concentrated enough to warrant its collection from a cost/benefit point of view (Ref. 66).

Technologies are available to collect the C-14 (diluted with C-12 to increase the efficiency the fixation process). The problem is what to do with the waste containing C-14. Most fixation processes capture the C-14 in a carbonate matrix. The release rate of C-14 from such waste forms packaged in a less stringent container buried in a shallow or deep geologic disposal may be significantly higher than the release rate from a repository. [See Radiation Physics & Chemistry, Vol. 37, No. 2, pp. 363-365, (1991) on radiolytic decomposition of $\text{Ca}^{14}\text{CO}_3$.]

2. Relax the Stringency by a Factor of 10

The stringency of the current regulation does not have its basis on a firm need to protect the public health and safety. The ACNW showed that the EPA used a factor of 10 conservatism in the probability and three orders of magnitude in the associated health effects (Ref. 64). In 1984 the EPA's Science Advisory Board (SAB) recommended that EPA relax the risk objective for all nuclides by an order of magnitude (Ref. 67).

There is plenty of justification to relax the regulation by a factor of 10 based on a realistic estimate of risks from unmined uranium ores, difficulty for any generic site to meet the current regulation under real repository conditions (all unsaturated sites may be penalized), and the high cost of meeting the regulation with little benefit to the public health and safety. On the other hand, it might be perceived by the public that the public health and safety would be compromised, if the regulation were relaxed.

3. Dose Truncation

It has already been shown that the expected radiation exposure from C-14 by the repository release is very small, even to the maximally exposed individual; i.e., on the order of 3×10^{-4} mrem/yr. Although the no-threshold linear dose assumption is well accepted by the scientific community, its applicability to low levels of radiation dose has been questioned continuously. The current acceptance of the no-threshold assumption at low doses is not because of demonstrated validity but because it is believed that it will not make much difference, since most sources of such low doses are not regulated. Most other EPA regulations allow a lifetime risk factor of 10^{-4} to 10^{-6} , and the EPA's NESHAP allows an exposure of 10 mrem/yr, which corresponds to an individual risk of 3.3×10^{-4} . The NCRP also recommends the exclusion of any exposure of 1 mrem/yr (3.3×10^{-5} individual risk) or less from the assessments (Ref. 68).

The 3×10^{-4} mrem/yr radiation exposure from the repository would be 3 to 4 orders of magnitude lower than the level for below regulatory concern (1 mrem/yr). This level of exposure is equivalent to an additional exposure to cosmic rays caused by reduced shielding when one wears a pair of shoes with heels of an inch higher than normal. Evidence does not suggest a higher rate of cancers at higher altitudes, even at several thousand feet higher than sea

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level. Women are not reluctant to wear high heels because of higher exposures to radiation, nor are people reluctant to live in the "Mile High City" of Denver, Colorado. The public should readily accept this level of imaginary risk.

Some people may be concerned over the possibility that most of the radionuclides in Table 1 may be excluded under this rule since, depending on the scenario, the expected exposure of the public to many radionuclides may be very small. It should be noted, however, that the low exposure from gaseous C-14 is generic; i.e., it is almost independent of scenarios. The low exposure is the result of the abundant presence of non-radioactive carbon everywhere on earth, especially in the biosphere. The number of potential health effects from the release of one curie of C-14 used in developing the EPA regulation is based on applying the inherently low dose to over 1.4 trillion people over their lifetime (70 years). No other radionuclide was applied to such a large critical population base, so a stronger case can be made for dose truncation for C-14 than for other radionuclides.

4. Geographic Truncation

Carbon-14 in the global inventory affects the total world population, which is the basis of the EPA regulation. The EPA model is valid when the release is large, such as that expected from a commercial nuclear fuel reprocessing plant; i.e., 860 Ci/yr from a 50 GWe/yr plant, if no treatment is done, as it is not required under the current regulation. When the release level is low, it would be within the natural level of variation among different regions. (The C-14 concentrations in the Pacific and the Atlantic oceans are different, and the difference is used to measure the communication between them under the North Pole.) At that low level, the potential effect would be localized. Eventually, the C-14 would become a part of the global inventory, but its residence time in the ocean is so long that its global impact on other regions of the world would for all practical purposes be nil. The health effect should therefore be calculated based on regional population, such as that of the U.S. or North America.

This logic is not meant to ignore the health impact outside the region. Rather, it is based on the premise that at an extremely low level of release, at a "noise" level, the actual impact would be limited to the regional population. It should not be confused with dose truncation, since the population dose, no matter how small, would still be calculated based on the regional population. This would have the same effect as relaxing the release limit for C-14 (but not for other radionuclides), by an order of magnitude.

5. Change to an Individual Dose Basis

This was strongly advocated by the Waste Isolation Systems Panel (WISP) of the National Research Council (Ref. 69). The current EPA philosophy is based on protecting both the population and the individual, not one or the other. Although most European countries have adopted individual dose as the basis for regulation, it was done for reasons more applicable to them, such as a high population density in the region, which makes for less difference between population and individual protection.

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If a standard based on individual dose is adopted, gaseous C-14 will no longer be of concern. If, however, C-14 is released in liquid form through fracture flows, such a standard would penalize sites with no means of diluting the radionuclides, as was shown in the WISP report (Ref. 69).

It should also be noted that the geologic repository system relies on favorable geologic conditions, which may include a lack or slow movement of the media that would carry the radionuclides and a significant retardation of movement of radionuclides by sorption and precipitation. Since for most sites (except probably those in the salt media) there are groundwater flows that could carry the radionuclides, the retardation by sorption would play an important role in limiting the release. The sorption process, however, concentrates the radionuclides in the media by a similar process to that used in chromatographic separation and concentration. The irony is that the better the site is, the longer it delays the release, but the more it concentrates the radionuclides and the higher the dose to the maximally exposed individual becomes when the concentrated peak finally reaches the accessible environment unless the retardation is so large that the radionuclides decay by a significant amount. For most sites the peak dose would appear after the 10,000-year regulatory time frame, and for some sites the peak dose may not appear for over 100,000 years. Concerns about the delayed appearance of the peak dose have been expressed (Ref. 69). Since the only alternatives to a high peak dose, aside from a perfect site with no carrier media, are no retardation (earlier release) and dilution (more population exposure), the truncation of the regulatory timeframe before the appearance of a delayed peak dose would be a justifiable and better alternative.

Because this is an alternative with far more impact on all other radionuclides than on C-14, its consideration is outside the scope of this paper.

6. Apply Clean Air Act

Neither the EPA's 40 CFR Part 191 nor the NRC's 10 CFR Part 60 were intended to regulate radioactive gases released from the repository after closure. When the initial analysis was done for the EPA standards, gaseous releases were not considered credible by the NRC nor the DOE (Ref. 70). It now appears that only the Clean Air Act (CAA) provides a general framework for the regulation of gaseous release of radionuclides from the repository after closure. In 1979, the EPA listed radionuclides as hazardous air pollutants under Section 112 of the CAA (Ref. 71). As a result, the EPA was required by Section 112(b)(1)(B) of the CAA to establish the National Emission Standards for Hazardous Air Pollutants (NESHAP). Following their earlier attempts not to regulate NRC-licensed facilities (including the high level radioactive waste facilities), the EPA in 1991 published Subpart I of the NESHAP for radionuclide emissions from facilities licensed by the NRC, but exempted facilities regulated under 40 CFR Part 191, which include the high level radioactive waste repository (Ref. 72). The EPA estimated the individual risk from the HLW disposal facilities to be very small, 7×10^{-8} , much less than the 1×10^{-4} benchmark, and determined no NESHAP was needed (Ref. 72). In this determination, however, the EPA did not consider the gaseous release after permanent closure of the repository (Ref. 73). In essence, the NESHAP never addressed the gaseous release of radionuclides from the repository

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after closure. Regulatory implications of this omission of post-closure gaseous release of radionuclides is discussed below in conjunction with the 1990 amendments to the CAA. It should be noted that the CAA has not exempted the gaseous releases from the HLW repository from the CAA requirements. It provided the EPA two options: (1) promulgate emission standards (NESHAP) for the HLW repository, or (2) exempt it from the NESHAP by rulemaking after consultation with the NRC, provided the program established by the NRC provides ample margin of safety. Since the CAA does not delegate the regulation of gaseous release of radionuclides to 40 CFR Part 191, any regulation of gaseous release from the repository added to 40 CFR Part 191 would have to be made consistent with the CAA. This is in keeping with the court ruling that remanded the 40 CFR Part 191, Subpart B because of the inconsistency of the groundwater protection requirement with the Safe Drinking Water Act.

Section 112(d) (9) of the CAA, addressing the emission standards for NESHAP, states:

"No standard for radionuclide emissions from any category or subcategory of facilities licensed by the Nuclear Regulatory Commission (or an Agreement State) is required to be promulgated under this section if the Administrator determines, by rule, and after consultation with the NRC, that the regulatory program established by the NRC pursuant to the Atomic Energy Act for such category or subcategory provides an ample margin of safety to protect the public health." (Ref. 74)

Since the EPA (Administrator) has not determined by rule that the regulatory program established by the NRC provides an ample margin of safety to protect the public health, and since the NRC regulation 10 CFR Part 60 did not consider gaseous release of radionuclides in the analysis during promulgation, the CAA still requires the gaseous release to be regulated under the NESHAP until the Administrator makes the determination mentioned above in regard to the regulatory program established by the NRC. In fact, Section 112(f) (2) (B) further states:

"Nothing in subparagraph (A) or in any other provision in this section shall be construed as affecting, or applying to the Administrator's interpretation of this section, as in effect before the date of enactment of the Clean Air Act Amendments of 1990 and set forth in the Federal Register of September 14, 1989 (54 Federal Register 38044)."

The (EPA) Administrator's interpretation of the gaseous release of radionuclides has been reflected in 40 CFR Part 61 (NESHAP), including the background analyses and records of promulgation. Within this regulatory framework, the EPA has a few options to regulate gaseous release of radionuclides under the CAA.

- a. Repromulgate the NESHAP to include the HLW repository. Since the current NESHAP, Subpart I, exempted the HLW repository with no consideration of gaseous release of radionuclides after closure of

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the repository, it did not fully implement the mandate of the CAA. Under this choice, the EPA would promulgate an emission standard in the NESHAP, Subpart I, that would apply to the repository after closure and the standard would be consistent with the standards in other subparts of the NESHAP.

- b. Regulate repository gases under the current NESHAP. However, since the current NESHAP, Subpart I, exempts the facilities regulated by 40 CFR Part 191, and delegates the responsibility to 40 CFR Part 191, the EPA would have to add a new performance standard to 40 CFR Part 191 that would apply to gaseous release of radionuclides. This new performance standard for gaseous nuclides could be any of the alternatives already discussed or the standard in (6)a. above.
- c. Consult with the NRC and amend the NRC regulation 10 CFR Part 60 to include performance standards for gaseous release of radionuclides for the post-closure period. Then no NESHAP would be required. The NRC could also consider the alternatives already discussed.

Under the first option, the standard would be consistent with those in other subparts of NESHAP. In establishing the policy for setting NESHAP, the EPA determined that emissions resulting in a lifetime maximum individual risk (MIR) no greater than approximately 1×10^{-4} are presumptively acceptable (Ref. 72). The subparts of NESHAP involving radionuclide emissions are all based on an MIR equal to or greater than 1×10^{-4} . Subparts B, H, and I limit the emissions to a level that would cause 10 mrem/yr effective dose equivalent (ede) exposure, which is equivalent to an MIR of 3.3×10^{-4} ; Subpart K limits the release of Po-210 from elemental phosphorus plants to 2 Ci/yr, which is also equivalent to an MIR of 3.3×10^{-4} ; and the Subparts Q, R, T, and W limit the release of Rn-222 to 20 pCi/m²-sec, which is equivalent to an MIR of 1×10^{-3} (Ref. 72). Therefore, a consistent standard for gaseous release of radionuclides from the repository could be set in the NESHAP at 10 mrem/yr (MIR= 3.3×10^{-4}) or 3 mrem/yr (MIR= 1×10^{-4}). It should be noted that 3 mrem/yr is based on the EPA's own dose conversion factors (Ref. 72). If we use the dose conversion factor of 200 cancers for 1×10^6 man-rem, discussed in section II-D, then the 10 mrem/yr exposure would correspond to an MIR of 1.4×10^{-4} and a MIR of 1×10^{-4} would represent about 7 mrem/yr. The discrepancy between the two numbers representing different dose conversion factors, can be resolved by averaging the two numbers -- namely use 5 mrem/yr for a MIR of 1×10^{-4} .

No additional explanation is necessary for the second and third options, except to say that the same degree of individual protection would be incorporated in 40 CFR Part 191 under the second option.

If the EPA does not defer to NRC regulations and exempt the HLW repository from the NESHAP regulation per Section 112(d)(9), the EPA may be subject to Section 112(f) requirements. Although there is no advantage to any party involved, it would be detrimental for the DOE to proceed with no clear regulatory criteria for gaseous releases. If the EPA decides to use Section 112(f), it may be forced to comply with the Section 112(f) by default if they do not take any of the actions discussed above; i.e., the three options. It is interesting to note that Section 112(f) indirectly provides a minimum MIR cutoff level at 1×10^{-6} for lifetime, above which the EPA is mandated to

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promulgate standards if the pollutants are classified as known, probable, or possible carcinogens. This risk level corresponds to an annual exposure of 0.03 mrem, using the EPA's own dose conversion factors. If we use the dose conversion factor discussed in Section II.D, the same risk level would correspond to an annual exposure of 0.07 mrem, or approximately 0.1 mrem, since these are not exact numbers.

The 1×10^{-6} risk cutoff is consistent with other regulatory precedents. Analyses of regulatory decisions based on risk showed that every chemical that presents an individual risk of 4×10^{-3} was regulated (Ref. 75). Except for one case, no action was taken to reduce the risk below 1×10^{-6} . Similar cutoffs for lifetime risk for individuals, typically 1×10^{-6} for large populations like that of the U.S. and 1.5×10^{-3} for smaller populations, were noted by others (Ref. 76). [Note: The information in this paragraph was provided by Robert Wilems, RAE.]

7. Hold the Regulation of Gaseous Release of Radionuclides in Reserve

As discussed in the previous section, the EPA will have to comply with the requirements in the CAA either through the NESHAP or by exempting the HLW repository from the NESHAP process by complying with the requirements in Section 112(d)(9). In either case, the EPA has the option of not making any decisions or taking any actions immediately. This would temporarily relieve the EPA from the gaseous C-14 problem without affecting the court-mandated repromulgation of 40 CFR Part 191, Subpart B. This alternative could also be treated as a fourth option under the CAA, which was discussed in the previous section. It has been separated because it does not provide any solution, but avoids the problem by deferring any action on it.

This alternative, however, should be considered as a last resort. It is clear that the implementation of the current (court-vacated) regulation to gaseous radionuclides is impractical, although not impossible, as was discussed earlier. To have the EPA state that the current Table 1, Subpart B does not apply to gaseous radionuclides and that regulations governing their release will be held in reserve would provide the EPA grounds for future actions. While not providing the DOE any advantage over the current regulation, and the uncertainties about future regulation would be so great that the DOE would be forced to assume the worst case scenario, resulting in unnecessary expenditures and schedule delays.

IV. DISCUSSION AND RECOMMENDATIONS

A. Regulation of Gaseous Release of Radionuclides

The regulation of gaseous release of radionuclides certainly falls under the CAA, and it leaves the EPA with only two choices: Alternatives 6 and 7 in the previous section. Alternatives 1 through 5 are possible options only through Alternatives 6a through 6c.

Among these possible alternatives, the most logical choice would be 6c, which has its basis in the 1990 amendments to the CAA. It would provide the EPA and NRC the highest flexibility, although it does not provide them any technical basis to develop quantitative criteria unless they borrow the same basis used in Alternatives 6a and 6b. Both 6a and 6b employ the NESHAP as a

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vehicle to regulate the gaseous release of radionuclides, the difference being that 6b takes the EPA out of using NESHAP through the existing interpretation of NESHAP, Subpart I, which is allowed in the CAA. In terms of quantitative criteria, both 6a and 6b would have to rely on the same type of risk assessment used in the NESHAP as discussed in 6a. Alternative 6b would have Alternatives 1 through 5 available to the EPA. For this reason, it is strongly recommended Alternative 6b be adopted.

Under 6b, the EPA has six options altogether, namely Alternatives 1 through 5 and adoption of the same numerical values used in 6a, since both 6a and 6b employ the NESHAP process. Adoption of the same risk criteria as NESHAP (Alternative 6a) through the 6b process would be my first recommendation, followed by the Alternatives 4, 3, 2, and 1a, in that order.

The preferred option can be stated as follows:

Per the 1990 Amendments to the CAA, the EPA determines to uphold the current NESHAP (40 CFR Part 61, Subpart I) and regulate the gaseous release of radionuclides by adding a new standard to 40 CFR Part 191, which would apply to the gaseous releases only. The new standard shall be consistent with the requirements in the CAA and the risk assessment methodology used in other subparts of the NESHAP; i.e., the release of gaseous radionuclides shall not exceed those amounts that would cause any member of the public to receive an effective dose equivalent to 5 mrem/yr, except that any combined release that would cause no greater than 0.1 mrem/yr effective dose equivalent need not be regulated. In addition, since the CAA/NESHAP already insures public health with an ample margin of safety, the release of gaseous radionuclides need not be included in the probabilistic calculation of releases required in 40 CFR 191.13.

B. Exempt C-14 Release from Regulation

As mentioned earlier, C-14 has unique characteristics. As long as there are sources of neutrons in the presence of nitrogen, the production of C-14, whether in a reactor or in the atmosphere, will continue. Once it is produced it can only decay away, but never disappears. Therefore, the best management of C-14 from a public health point of view would be the one that would minimize the exposure of the public (decay in isolation) and slow the release to reduce the individual dose to a noise level, at which there is no evidence of discernible health effect. The geologic repository provides such a solution.

As the use of nuclear energy increases, the generation of C-14 will also increase, even with the efforts to minimize the C-14 production per unit energy produced. In addition, there are other technical reasons why the production of C-14 per unit energy produced may even increase substantially in order to gain other benefits (Ref. 13). In one estimate, the annual C-14 release to the atmosphere from envisaged global nuclear power production could even approach the same level as the natural production of C-14 in the atmosphere (28,000 Ci/yr), twice as much accumulating in solid wastes. At present, the release of C-14 from nuclear power plants and fuel reprocessing

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plants is not regulated anywhere in the world. Even if some control measure is adopted to capture it in solid waste forms, the resulting waste forms do not provide the same degree of isolation as the spent fuel emplaced in the geologic repository. It should be noted that the release would be significant in terms of curie amount but, not in terms of health effect.

Restricting a repository's release of C-14 to less than 1 Ci/yr, which is less than the annual release from a single operating reactor, is almost meaningless compared to the global release of C-14 into the atmosphere. This is a global problem, if it is a problem, and requires a global solution. Spending billions of dollars to keep the repository release below 1 curie per year while others are pouring thousands of curies into the atmosphere simply does not make any sense. It would be prudent for the EPA to exempt the gaseous release of C-14 from 40 CFR Part 191.

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If there are errors or omissions, they are all mine.

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REFERENCES

1. Park, U., "Gaseous and Semi-volatile Radionuclides," presentation to the Nuclear Waste Technical Review Board in Denver (June 25, 1991).
2. Park, U., personal communication with L. Rickertsen, Rogers and Associates Engineers (October 1991).
3. Park, U., personal communication with Electric Power Research Institute (September, 1991).
4. Hayes, D. W. and MacMurdo, K. W. "Carbon-14 Production by the Nuclear Industry," Health Physics, 32, pp. 215-219 (1977).
5. Plesset, M. S. and Latter, A. L., "Transient Effects in the Distribution of Carbon-14 in Nature," Proceedings of N.A.S., Vol. 46, pp. 232-241 (1960).
6. Park, U. S. and Pflum, C. G., "Requirements for Controlling a Repository Releases of Carbon-14 Dioxide; The High Costs and Negligible Benefits," Proceedings of the 1990 International High Level Waste Management Conference, Las Vegas, NV, p. 1158 (1990).
7. Van Konynenburg, R. A., "Gaseous Release of Carbon-14: Why the High Level Waste Regulations Should be Changed," Proceedings of the 1991 International High Level Waste Management Conference, Las Vegas, NV, pp. 313-319 (1991).
8. Fowler, T. W., Clark, R. L., Gruhke, J. M., and Russel, J. L., "Public Health Considerations of Carbon-14 Discharges from the Light-Water-Cooled Nuclear Power Reactor Industry," U.S. EPA Technical Note ORP/TAD-76-3 (1976)
9. Davis, Jr., W., "Carbon-14 Production in Nuclear Reactors," ORNL/NUREG/TM-12, Oak Ridge National Laboratory (1977).
10. Croff, A. G., and Alexander, C. W., "Decay Characteristics of Once-Through LWR and LMFBR Spent Fuels, High-Level Wastes, and Fuel-Assembly Structural Materials Wastes," ORNL/TM-7431, Oak Ridge National Laboratory (1980).
11. Roddy, J. W., Clairborne, H. C., Ashline, R. C., Johnson, P. J., and Rhyne, B. T., "Physical and Decay Characteristics of Commercial LWR Spent Fuel," ORNL/TM-9591/V1&R1, Oak Ridge National Laboratory (1986).
12. Van Konynenburg, R. A., "Review and Position Paper on Carbon-14 RELEASE from the Proposed High-Level Nuclear Waste Repository at Yucca Mountain, Nevada," draft report submitted to DOE/YMPO (1989).

WORKING PAPER

13. Bush, R. P., Smith, G. M., and White, I. F., "Carbon-14 Waste Management," Commission of the European Communities, EUR 8749 EN (1984).
14. U.S. Environmental Protection Agency, "Environmental Standards for the Management and Disposal of Spent Fuel, High-Level and Transuranic Radioactive Wastes, Final Rule," 40 CFR Part 191, Federal Register, Vol. 50, pp. 38006-38089 (1985).
15. Van Konynenburg, R. A., Smith, C. F., Culham, H. W., and Otto, Jr., C. H., "Behavior of Carbon-14 in Waste Packages for Spent Fuel in a Repository in Tuff," Lawrence Livermore National Laboratory, UCRL-90855, Rev. 1 (1984).
16. Van Konynenburg, R. A., Smith, C. F., Culham, H. W., and Smith, H. D., "Carbon-14 in Waste Packages for Spent Fuel in a Tuff Repository," UCRL-94708 (1986).
17. U.S. Nuclear Regulatory Commission, "Staff Analysis of Public Comments on Proposed Rule 10 CFR Part 60, Disposal of High-Level Radioactive Wastes in Geologic Repositories," NUREG-0804, U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Washington, D.C. (1983).
18. U.S. Department of Energy, Site Characterization Plan - Yucca Mountain Site, Nevada Research and Development Area, Nevada, DOE/RW-0199, Washington, D.C. (1988).
19. Smith, H. D., and Baldwin, D. L., "An Investigation of Thermal Release of C-14 from PWR Spent Fuel Cladding," paper presented at Focus '89 - Nuclear Waste Isolation in the Unsaturated Zone, Las Vegas, NV, (September 18-21, 1989).
20. Park, U., personal communication with H. Shaw, Lawrence Livermore National Laboratory (1989).
21. Memo from H. Shaw, LLNL, to U. Park, SAIC, "C-14 Data from Initial Scoping Experiments," LLYMP8906149, Lawrence Livermore National Laboratory (1989).
22. Bleier, A. D., Beuerle, M., Ellinger, M., and Bohlen, D., "Investigation into the Chemical Status of C-14 After Leaching of Cladding Material from Spent PWR and BWR Fuel Rods in a Salt Solution," BMFT KWA 3503/6, Siemens A.G. Unternehmensbereich KWU, Erlangen, Germany (1987).
23. Smith, H. D. and Oversby, V. M., "Spent Fuel Cladding Corrosion Under Tuff Repository Conditions - Initial Observations," UCID-20499, Lawrence Livermore National Laboratory (1985).
24. Santanam, L., Shaw H., and Chin, B., "Modeling of Zircaloy Cladding Degradation Under Repository Conditions," UCRL-100211, Lawrence Livermore National Laboratory (1989).

WORKING PAPER

25. Pescatore, C., "C-14 Release from Failed Spent Fuel Containers," Proceedings of the American Nuclear Society Topical Meeting, Las Vegas, NV, High Level Radioactive Waste Management, pp. 426-429 (1990).
26. Pescatore, C., and Sullivan, T. M., "Potential C-14 Dioxide Releases from Spent Fuel Containers at Yucca Mountain," Proceedings of the American Nuclear Society Topical Meeting, Las Vegas, NV, High Level Radioactive Waste Management, pp. 1066-1073 (1991).
27. Zwahlen, E. C., Lee, W. W., Pigford, T. H., and Chambre, P. L., "A Gas Phase Source Term for Yucca Mountain," U.C. Berkeley/Lawrence Berkeley Laboratory, UCB-NE-4167 (1990).
28. Barnard, R. W., and Dockery, H. A., editors, "Yucca Mountain Site Characterization Project Technical Summary of the Performance Assessment Computational Exercises for 1990 (PACE-90), Vol 1: Nominal Configuration Hydrologic Parameters and Computational Results," SAND90-2726, Sandia National Laboratories (1991).
29. Apted, M. J., O'Connell, W. J., Lee, K. H., McIntyre, A. T., Ueng, T. S., Pigford, T. H., and Lee, W. W., "Preliminary Calculations of Release Rates from Spent Fuel in a Tuff Repository," Proceedings of the High Level Radioactive Waste Management meeting, Las Vegas, NV, pp. 1080-1090, (May 1991).
30. Oversby, V. M., "Performance Testing of Waste Forms in a Tuff Environment," UCRL-90045, Lawrence Livermore National Laboratory (1983).
31. Park, U., personal communication with H. Shaw, LLNL (1991)
32. Montazer, P., Weeks, E. P., Thamir, F., Yard, S. N., and Hofrichter, P. B., "Monitoring the Vadose Zone in Fractured Tuff, Yucca Mountain, Nevada," Proceedings of the NWWA Conference on Characterization and Monitoring of the Vadose (Unsaturated) Zone, Denver, CO, (November 19-21, 1985).
33. Conca, J., "Diffusion Barrier Transport Properties of Unsaturated Paintbrush Tuff Rubble Backfill," Proceedings of the American Nuclear Society Topical Meeting, Las Vegas, NV, High Level Radioactive Waste Management, pp. 394-401 (1990).
34. Lu, N., Amter, S., and Ross, B., "Effect of a Low-Permeability Layer on Calculated Gas Flow at Yucca Mountain," Proceedings of the American Nuclear Society Topical Meeting, Las Vegas, NV, High Level Radioactive Waste Management, pp. 853-860 (1991).
35. Weeks, E. P., "Effect of Topography on Gas Flow in Unsaturated Fractured Rock--Concepts and Observations," in Flow and Transport through Unsaturated Fractured Rock, D.D. Evans and T.J. Nicholson editors, Geophysical Monograph 42, American Geophysical Union, 165-170 (1987)

WORKING PAPER

36. Nielson, R. H., Peterson, E. W., Lie, K. H., Burkhard, N. R., and Hearst, J. R., "Barometric Pumping of Contaminated Gases through Fractured Permeable Media," Proceedings of the High Level Radioactive Waste Management, Las Vegas, pp. 861-868 (1991).
37. Weeks, E. P., "Physical Characteristics of Air Circulation Through Yucca Mountain," presentation to the Nuclear Waste Technical Review Board, Denver, CO, (June 25-27, 1991).
38. Tsang, Y. W. and Preuss, K., "A study of Thermally Induced Convection Near a High-Level Nuclear Waste Repository in Partially Saturated Fractured Tuff," Water Resources Research, Vol. 23, No. 10, pp. 1958-1966 (1988).
39. Altenhofen, M. K. and Eslinger, P. W., "Evaluation of Near Field Thermal Environmental Conditions for a Spent Fuel Repository in Tuff," Proceedings of High Level Radioactive Waste Management, Las Vegas, NV, pp. 402-409 (1990).
40. Wang, J. S. Y., Mangold, D. C., and Tsang, C. F., "Thermal Impact of Waste Emplacement and Surface Cooling Associated with Geologic Disposal of High-Level Nuclear Waste," Environ. Geol. Water Sci., Vol. 11, No. 2, pp. 183-239 (1988).
41. Park, U., personal communication with Y.W. Tsang, Lawrence Berkeley Laboratory, (November 7, 1991).
42. Zhou, W., Chambre, P. L., Pigford, T. H., and Lee, W. W., "Heat-Pipe Effect of the Transport of Gaseous Radionuclides Released from a Nuclear Waste Container," U.C. Berkeley/Lawrence Berkeley Laboratory, paper presented at the DOE/YMPO Performance Assessment meeting, Las Vegas (October 3, 1990).
43. Ross, B., "Governing Equations for Gas-Transport of C-14 at Yucca Mountain," Disposal Safety Inc., contract report to Sandia National Laboratories (1987).
44. Ross, B., Amter, S., and Lu, N., "Numerical Studies of Rock-Gas Flow in Yucca Mountain," Disposal Safety Inc., contract report to Sandia National Laboratory, SAND 91-7034 (draft in review) (1991).
45. Knapp, R. B., "An Approximate Calculation of Advective Gas Phase Transport of C-14 at Yucca Mountain, Nevada," Lawrence Livermore Laboratory, (1987).
46. Light, W. B., Pigford, T. H., Chambre, P. L., and Lee, W. W., "Analytical Models for C-14 Transport in a Partially Saturated, Fractured, Porous Media," U.C. Berkeley/Lawrence Berkeley Laboratory, LBL-26827 (1989).
47. Park, U., personal communication with W. W. Lee, UC Berkeley/LBL, (November 6, 1991).

WORKING PAPER

48. Yang, I. C., "Geochemical and Isotope Methods for Determining Flowpaths and Travel Time Using Carbon, Oxygen and Tritium," presentation to the Nuclear Waste Technical Review Board, Denver, CO, (June 25-27, 1991).
49. Lerman, A., "Transport of Gaseous Radionuclides from a Repository in an Unsaturated Rock Zone," (draft) report to DOE/HQ (1988).
50. Killough, G. G. and Till, J. E., "Scenarios of C-14 Releases from the World Nuclear Power Industry from 1975 to 2020 and the Estimated Radiological Impact," Nuclear Safety, 19(5), pp. 602-617 (1978).
51. Fairhall, A. W., Buddemeier, R. W., Yang, I. C., and Young, A. W., U.S. Atomic Energy Commission Report HASL-242 (1971).
52. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), "Sources and Effects of Ionizing Radiation - 1977 Report to the General Assembly with annexes," United Nations, NY (1977).
53. Nydal, R. and Lovseth, K., "Distribution of Radiocarbon from Nuclear Tests," Nature, Vol. 206, pp. 1029-1031 (1965).
54. McCartney, M., Baxter, M. S., McKay, K., and Scott, E. M., "Global and Local Effects of C-14 Discharges from the Nuclear Fuel Cycle," Radiocarbon, 28, No. 2A, pp. 634-643 (1986).
55. Smith, J. M., Fowler, T. W., and Goldin, A. S., "Environmental Pathway Models for Estimating Population Health Effects from Disposal of High-level Radioactive Waste in Geologic Repositories. Final Report," EPA 520/5-85-026, U.S. Environmental Protection Agency (1986).
56. Daer, G. R., two memoranda to U-Sun Park: (1) "External and Internal Dose Calculations from a Continuous Hypothetical Ground-Level Release of C-14," dated April 28, 1987, and (2) "Preliminary External and Internal Dose Calculations for a Hypothetical Continuous Ground-Level Area Source Release of C-14," dated July 21, 1987, Science Applications International Corporation, Las Vegas, NV (1987).
57. DOE/YMP internal study done by the Pacific Northwest Laboratory and Sandia National Laboratories as a part of PACE-91 exercise (to be published in 1992).
58. Bacastow, R. B. and Keeling, C. D., "Atmospheric Carbon Dioxide and Radiocarbon in the Natural Carbon Cycle: Changes from A.D. 1700 to 2070 as Deduced from a Geochemical Model," Carbon and Biosphere, G.M. Woodwell and E.V. Pecan, eds., U.S. Atomic Energy Commission, pp. 86-135 (1973).
59. U.S. Nuclear Regulatory Commission, "NRC Staff Site Characterization Analysis of the Department of Energy's Site Characterization Plan, Yucca Mountain Site, Nevada," NUREG-1347 (1989).

WORKING PAPER

60. U.S. Environmental Protection Agency, "High-level and Transuranic Radioactive Wastes: Background Information Document for Final Rule," EPA 520/1-85-023 (1985).
61. Smith, C. B., Egan, Jr., D. J., Williams, W. A., Gruhlke, J. M., Hung, C. Y., and Serini, B. L., "Population Risks from Disposal of High-Level Radioactive Wastes in Geologic Repositories," U.S. Environmental Protection Agency, PA 520/3-80-006 (1982).
62. Williams, W. A., "Population Risks from Uranium Ore Bodies," U.S. Environmental Protection Agency, EPA 520/3-80-009 (1980).
63. Park, U., testimony at the ACNW Working Group Meeting on Carbon-14 in Washington, D.C., (October 26, 1990).
64. Moeller, D., memo to K.M. Carr, Chairman, U.S. Nuclear Regulatory Commission, "Stringency of U.S. Environmental Protection Agency High-Level Radioactive Waste Repository Standards," ACNWR-0045 dated (January 29, 1991).
65. U.S. Environmental Protection Agency, "Draft Environmental Impact Statement for 40 CFR 191," EPA 520/1-82-025 (1982).
66. Thomas, T. R. and Brown, R. A., "Control Decisions for H-3, C-14, Kr-85, and I-129 Released from the Commercial Fuel Cycle," Proceedings of the 18th DOE Nuclear Airborne Waste Management and Air Cleaning Conference, Baltimore, Maryland, August 12-14, 1984, pp. 998-1003 (1984).
67. Science Advisory Board, "Report on the Review of Proposed Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes," U.S. Environmental Protection Agency (1984).
68. National Council on Radiation Protection and Measurements, "Recommendations on Limits for Exposure to Ionizing Radiation," Report No. 91, (1987).
69. Waste Isolation Systems Panel Report, "A Study of Isolation System for Geologic Disposal of Radioactive Wastes," Board on Radioactive Waste Management, National Research Council, National Academic Press (1983).
70. Galpin, F. L., Clark, R. L., and Petti, C., "An Inside Look at the 40 CFR Part 191 - Containment Requirements," paper-presented at the EPRI Workshop on 40 CFR 191, Arlington, Va., (September 24-26, 1991)
71. U.S. Environmental Protection Agency, 44 FR 76738, (December 27, 1979).
72. U.S. Environmental Protection Agency, 40 CFR Part 61, "National Emission Standards for Hazardous Air Pollutants; Radionuclides; Final Rule and Notice of Reconsideration," Federal Register, Vol. 54, No. 240, pp. 51654 - 51715, (December 15, 1989).

WORKING PAPER

73. Park, U., personal communication with T. McLaughlin, EPA, at the EPRI Workshop on 40 CFR 191 in Arlington, VA, (November 13-14, 1991)
74. Clean Air Act, 42 U.S.C. 7401 et seq., as amended, including the Clean Air Amendment Act of 1990 (PL-101-549, November 15, 1990) (1990)
75. Travis, C. C., "Cancer Risk Management," Environmental Science Technology, Vol. 21, No. 5, pp. 415 ff (1987).
76. Milvy, P., "A General Guideline for Management of Risk from Carcinogens," Society of Risk Analysis, Vol. 6, No. 1 (1986).