American Nuclear Society

Recommendations on Postclosure Aspects of Generic Standards for the Permanent Disposal of Spent Nuclear Fuel and High-Level and Transuranic Radioactive Wastes in the United States

American Nuclear Society
Special Committee on
Generic Standards for Disposal
of High-Level Radioactive Waste

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REVIEWER ACKNOWLEDGEMENT

This ANS Special Committee draft report was reviewed by selected individuals chosen for their knowledge of the subject matter and diverse perspectives. The peer reviewers were not asked to endorse the report, nor did they see the final version before its release. The peer reviewers were acting as individuals and not as representatives of their various employers. The peer review comments contributed significantly to the content and quality of this final report, and we thank the reviewers, listed below, for their input and perspectives. The conclusions of the report remain the responsibility of the ANS Special Committee, however, and this acknowledgment of their contribution in no way implies that the listed reviewers either agree or disagree with any content of the report.

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ANS also made the draft report available to stakeholders and members of the public for review and comment. The Committee received valuable input and perspectives through this avenue as well. Notably, most respondents agreed as to the need for up-to-date generic disposal standards in the United States. No respondents expressed the contrary view that the current disposal standards are adequate as is.

Portions of this report have appeared previously in draft form as conference papers presented at ANS's 2022 International High-Level Radioactive Waste Management Conference in Phoenix, Arizona [1], [2], [3].

CONTENTS

ACRONYMS AND ABBREVIATIONS

Organizations and Agencies

AEC	Atomic Energy Commission
ANS	American Nuclear Society
BRC	Blue Ribbon Commission on America's Nuclear Future
DOE	U.S. Department of Energy
EPA	Environmental Protection Agency
ERDA	Energy Research and Development Administration
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
NAS	National Academy of Sciences
NASEM	National Academies of Sciences, Engineering, and Medicine
NRC	Nuclear Regulatory Commission
NWTRB	Nuclear Waste Technical Review Board
OECD NEA	Organisation for Economic Co-operation and Development Nuclear Energy Agency
STUK	Radiation and Nuclear Safety Authority (Finland)

Legislation

AEA	Atomic Energy Act
EnPA	Energy Policy Act
NWPA	Nuclear Waste Policy Act
NWPAA	Nuclear Waste Policy Amendments Act
WIPP LWA	WIPP Land Withdrawal Act

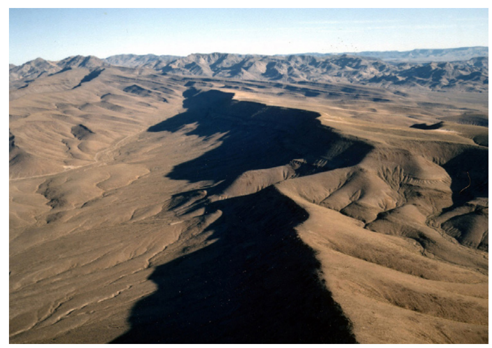
Terms

CEDE	committed effective dose equivalent
FEP	features, events, and processes
HLW	high-level radioactive waste
KMS	knowledge management systems
SNF	spent nuclear fuel
TRU	transuranic (relating to elements with atomic numbers greater than 92)
WIPP	Waste Isolation Pilot Plant

PREFACE

WHAT ABOUT THE WASTE? “They don’t know what to do with the waste.” It’s a frequent criticism of nuclear energy—one that the nuclear industry has done a poor job of explaining.

In fact, the United States has a functioning system to safely manage nuclear waste from its nuclear power plants: low-level radioactive waste is compacted and shipped to regulated facilities for disposal. Highly radioactive waste materials, such as used nuclear fuel, are small in volume and exist in solid, stable forms. Used fuel is stored at reactor sites, first underwater in secure pools and then in robust, passively cooled dry storage systems.


Yucca Mountain

The U.S. nuclear waste management system is missing one important piece, however: a long-term geologic repository. Like most other nations with nuclear plants, the U.S. has elected to dispose of its commercial used fuel and high-level radioactive waste from defense programs directly in deep geologic formations, isolated from the environment. The site Congress and then-President George W. Bush chose for the U.S. repository, Yucca Mountain in Nevada, has been stalled by opposition from the state. Given the stalemate, policymakers are rethinking our nation’s approach, with consideration for adding consolidated interim storage and modified siting methods for waste facilities based on stakeholder consent. In addition, different and innovative technology approaches for management of used nuclear fuel and high-level radioactive waste are under development, such as advanced reprocessing methods for resource utilization and waste minimization, and deep borehole disposal of used fuel and other waste forms using well-established drilling techniques.


Dry spent fuel storage systems, Zion, Ill.

The future course in waste management is far from settled, but one fact is evident. There will be high-level radioactive waste that requires disposal, and that material will be emplaced in some sort of underground geologic repository or repositories. In fact, other countries are already proceeding down this path. Updated, transparent standards for long-term repository performance are needed to enable siting of future geologic disposal systems and engender public confidence in the safety of those facilities. The current U.S. geologic repository standards for all sites other than Yucca Mountain are codified in the Environmental Protection Agency (EPA) regulation 40 CFR Part 191, *Environmental Radiation Protection Standards for Management* *and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes*, and that regulation has served adequately for the Waste Isolation Pilot Plant near Carlsbad, N.M. However, 40 CFR 191 is inconsistent with current international standards, lacks transparency, and is difficult to apply to certain disposal technologies. Accordingly, the American Nuclear Society Special Committee on Generic Standards for Disposal of High-Level Radioactive Waste has developed recommendations for updated standards that will ensure adequate protection of future inhabitants from the potential hazards posed by material emplaced in a geologic repository.

WIPP underground rough cut

The country and the world need nuclear fission reactors as a clean, secure, reliable source of energy, both now and in the future. Those reactors have produced—and will continue to produce—relatively small volumes of waste that require geologic disposal. ANS has produced this report with the hope and expectation that it will prove to be a catalyst for the development of updated geologic repository standards by the EPA. That action will be a key building block for future progress on nuclear waste management, irrespective of what course of action policymakers ultimately choose to follow.

Steven Arndt
Immediate Past President (President 2022–2023)
American Nuclear Society
August 2023

EXECUTIVE SUMMARY

ES.1 Background

The Blue Ribbon Commission on America's Nuclear Future (BRC) recommended in 2012 that "the Environmental Protection Agency and the Nuclear Regulatory Commission should develop a generic disposal standard and supporting regulatory requirements early in the siting process" [4, p. ix]. The American Nuclear Society in its 2020 issue brief, "A Proposal for Progress on Nuclear Waste Management" [5, p. 2], endorsed the BRC's recommendation. To that end, ANS convened the Special Committee on Generic Standards for Disposal of High-Level Radioactive Waste (ANS Committee) to further consider the need for new standards and to develop recommendations on their content.

The ANS Committee agrees with past recommendations that new standards are needed for the following reasons:

- The current U.S. generic standards developed by the EPA for the disposal of spent nuclear fuel (SNF), high-level radioactive waste (HLW), and transuranic (TRU) waste[1] are more than 30 years old and are inconsistent with modern international approaches to such health and safety standards.
- The nexus between the release limits in the current U.S. generic standards and public health and safety is not readily apparent; as a result, the current standards are ill-suited for instilling public confidence in effective regulatory oversight of one or more potential geologic repositories.
- The current U.S. generic standards were developed with mined geologic repository disposal systems in mind, and it would be difficult to apply them to other disposal technologies, such as deep borehole repositories.

With these points in mind, the ANS Committee believes it would be useful to the radioactive waste disposal community to provide its recommendations and observations on the postclosure aspects of generic disposal standards that are protective of public health, safety, and the environment; consistent with international best practices; and implementable through established licensing processes.

Before stating its recommendations, the ANS Committee wants to make it clear what this report does not cover:

1 SNF, HLW, and TRU waste refer, respectively, to irradiated fuel removed from reactors, highly radioactive wastes resulting from processing of SNF, and other wastes containing significant quantities of radioactive elements heavier than uranium. The terms are defined by U.S. law (specifically, the Nuclear Waste Policy Act of 1982, as amended, and the Atomic Energy Act of 1954, as amended) and collectively represent the categories of radioactive waste requiring deep geologic disposal in the United States.

- **Risks associated with the construction and operation of disposal facilities**. As described further in Section I, our recommendations are focused entirely on the long-term postclosure standards.
- **Nonradiological hazards potentially posed by the wastes and risks to the nonhuman environment**. Consistent with the scope of the existing EPA generic standards, our recommendations do not address regulation of the chemically toxic and hazardous constituents of the waste or potential risks to the nonhuman environment. These risks are regulated under the Resource Conservation and Recovery Act and related laws, and the National Environmental Policy Act, respectively, and are outside the scope of the generic disposal standards.
- **The merits of specific technologies for disposal** (e.g., mined repositories or deep boreholes). To the extent practical, standards should be technology independent and based on protecting public health and safety. These recommendations do not indicate a preference for any disposal technology; all proposed disposal facilities must comply with the generic standards.
- **The merits of specific geologic media for disposal of radionuclides**. The United States has multiple types of stable geologic formations that would likely be suitable for the long-term isolation of radioactive waste; health and safety standards should be independent of the geologic media employed.
- **The merits, or lack thereof, of any proposed repository sites in the United States or abroad**.
- **The merits, or lack thereof, of any proposed siting process for a geologic repository** (e.g., consent-based siting). Effective regulatory oversight of geologic disposal, including transparent and protective public health and safety standards, is essential for building and maintaining public support for a repository program, irrespective of the siting process used.

ES.2 Recommendations

As described in more detail in Sections III.1 and III.2 of this report, the recommendations of the ANS Committee can be broadly summarized as follows: Use the EPA's existing Yucca Mountain standards at 40 CFR Part 197, rather than the existing generic standards at 40 CFR Part 191, as a starting point for developing new standards, modified as necessary for general applicability. In general, the ANS Committee considers the Yucca Mountain standards to be representative of international best practices and implementable using established licensing processes.

Specific recommendations include the following:

- Retain the individual health consequence standard (i.e., estimated mean annual dose[2] to an individual) as the primary quantitative metric.
- Retain the concepts of reasonable expectation and risk-informed decision-making as a recognition of the limitations of quantitative modeling of the far future.
- Retain the concept of basing the characteristics of the reasonably maximally exposed individual on current practice in the vicinity of the disposal site, and retain regulatory specificity regarding characteristics of and future changes to the biosphere and certain aspects of the geologic environment.

2 Limits associated with radiation exposure to individuals are often referred to as "dose limits," a shorthand term that is not always consistent with the units that are used. Radiation dose is the amount of energy deposited in tissue by ionizing radiation, and it is expressed in units of grays or rads. In current practice, regulatory limits are usually established in terms of "dose equivalent" rather than dose. Dose equivalent is a measure of radiological risk associated with radiation exposure, and it is calculated from dose and other factors, including the type of radiation and the location in the body receiving the radiation. Dose equivalent is expressed in units of sievert or rem. In this report, the term "dose limit" should be understood to encompass regulatory limits on dose equivalent.

- Retain the requirements for the identification and screening of the comprehensive set of features, events, and processes that are potentially relevant to the long-term performance of the repository.
- Retain the human intrusion requirement, but revise it to make it generally applicable to all potential sites and repository design concepts.

In addition to general modifications needed to make the Yucca Mountain standards generic, the ANS Committee recommends the following changes to the EPA generic standards:

- Limit the regulatory time period for quantitative standards to 10,000 years.
- Replace the quantitative dose limits for the period beyond 10,000 years and before 1,000,000 years with a requirement to evaluate potentially relevant features, events, and processes to demonstrate that they are unlikely to result in substantially different behavior of the disposal system during that period.
- Adopt requirements for the multiple barriers implemented by the NRC for Yucca Mountain in 10 CFR Part 63, to ensure their applicability to all future repositories, including those developed outside the NWPA and not regulated by the NRC.[3]
- Adopt requirements for retrievability of the wastes as prescribed by the NWPA §122 and implemented by the NRC for Yucca Mountain in 10 CFR Part 63 to ensure their applicability to all future repositories, including those developed outside the NWPA and not regulated by the NRC.
- Adopt requirements for active and passive institutional controls consistent with the approach taken by the NRC in 10 CFR Part 63 for Yucca Mountain, to ensure their applicability to all future repositories, including those developed outside the NWPA and not regulated by the NRC.
- Adopt requirements for postclosure monitoring of the repository consistent with the approaches taken by the EPA in 40 CFR Part 191 for repositories developed outside the NWPA and by the NRC in 10 CFR Part 63 for Yucca Mountain, to ensure their applicability to all future repositories, including those developed outside the NWPA and not regulated by the NRC.
- Remove the concept of the "period of geologic stability" from generic disposal standards while retaining an upper bound on the regulatory period of 1,000,000 years.
- Adopt the definition of the controlled area provided in 40 CFR Part 191, with site-specific implementation to be determined by the implementor and the regulating agency.
- Make generic disposal standards applicable to deep borehole disposal concepts as well as mined repositories.
- Remove specificity regarding the establishment of the DOE as the implementing organization for disposal of spent nuclear fuel and high-level radioactive wastes.

In addition, the ANS Committee provides observations on other topics the Committee believes could benefit from further consideration by the EPA:

- The approaches specified in existing regulations for determining health consequences from radiation exposures are in some instances out of date with respect to current international practice.
- The separate "Ground Water Protection Standards" (40 CFR 197.30 and 197.31) add no additional protection to the standards for human health, safety, or the environment, while introducing the

3 40 CFR Part 191, *Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes*; 10 CFR Part 63, *Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada*.

potential for incentivizing the selection of sites with pristine groundwater and disqualifying sites with high naturally occurring radionuclide concentrations in their groundwater.

- Regarding the specific limits applied to estimates of annual radiation doses to individuals, values in the range of 0.15–1 mSv (15–100 mrem) per year are appropriately conservative for a public health and safety standard.

I. INTRODUCTION

The Blue Ribbon Commission on America's Nuclear Future (BRC) observed in 2012 that "America's nuclear waste management program is at an impasse" and recommended that as the first step toward developing a new, consent-based approach to siting storage or disposal facilities, "the Environmental Protection Agency and the Nuclear Regulatory Commission should develop a generic disposal standard and supporting regulatory requirements early in the siting process" [4, p. ix]. The American Nuclear Society endorsed the NRC's recommendation in its 2020 issue brief, "A Proposal for Progress on Nuclear Waste Management" [5, p. 2], as have other groups and organizations making recommendations related to the management of used fuel and high-level radioactive waste in the U.S. The ANS Special Committee on Generic Standards for Disposal of High-Level Radioactive Waste ("the ANS Committee"), which has authored this report, agrees with these observations and notes that they remain timely more than ten years after the BRC report was published. The primary reasons that new standards are needed are summarized below.

- The current U.S. generic standards developed by the EPA for the disposal of spent nuclear fuel (SNF), high-level radioactive waste (HLW), and transuranic (TRU) waste[1] are more than 30 years old and are inconsistent with modern international approaches to such health and safety standards.
- The nexus between the release limits in the current U.S. generic standards and public health and safety is not readily apparent; as a result, the current standards are ill-suited for instilling public confidence in effective regulatory oversight of one or more potential geologic repositories.
- The current U.S. generic standards were developed with mined geologic repository disposal systems in mind, and would be difficult to apply to other disposal technologies such as deep borehole repositories.

The ANS Committee has chosen to limit its recommendations to those portions of the generic disposal standards that address the long-term performance of repositories after they have been closed. The Committee recognizes that the EPA's existing generic standards (40 CFR Part 191) address the period of operations (i.e., preclosure) for repositories as well as long-term performance. Some modifications of the operational standards and regulations may be necessary, but in general these aspects of the existing generic standards have not been the focus of concern regarding the licensing of future facilities. Thus we have only addressed the postclosure portion of the standards.

1 SNF, HLW, and TRU waste refer to irradiated fuel removed from reactors, highly radioactive wastes resulting from processing of SNF, and other wastes containing significant quantities of radioactive elements heavier than uranium, respectively. The terms are defined by U.S. law (specifically, the Nuclear Waste Policy Act of 1982 and the Atomic Energy Act of 1954) and collectively represent the categories of radioactive waste requiring deep geologic disposal in the United States.

The ANS Committee recognizes that constraints on nuclear waste management exist at multiple levels, including federal legislation (principally the Nuclear Waste Policy Act of 1982, as amended [NWPA], which tasks the EPA with developing generic standards); regulatory requirements (both generic and site specific); and site selection guidelines developed in the past by the U.S. Department of Energy. Nonbinding recommendations regarding best practices may also be developed in the future by both regulators and the implementing organization. Most of these topics are outside the scope of the ANS Committee's consideration; the Committee recognizes that much remains to be done in each of these areas but we have focused our recommendations on topics we believe are appropriately addressed in generic standards governing all potential deep geologic disposal concepts and sites and all present and future waste forms requiring deep geologic disposal, regardless of reactor technology and commercial or defense origin. We also note that there are statutory constraints placed on the EPA (and also on the NRC, which is responsible for developing and implementing licensing criteria for repositories for commercial-origin wastes) by the terms of the NWPA and other laws and that future congressional action may be helpful to facilitate new rulemaking. The Committee has chosen not to comment on possible future legislation; our recommendations are limited narrowly to the scientific public health and safety and environmental protection content of the EPA's generic disposal standards.

With these points in mind, the ANS Committee believes it would be useful to the radioactive waste disposal community to provide its recommendations and observations on the postclosure aspects of generic disposal standards that are protective of public health, safety, and the environment; consistent with international best practices; and implementable through established licensing processes.

The ANS Committee also wants to make it clear what these recommendations do not cover:

- **Risks associated with the construction and operation of disposal facilities**. As noted above, our recommendations are focused entirely on the long-term postclosure standards.
- **Nonradiological hazards potentially posed by the wastes and risks to the nonhuman environment**. Consistent with the scope of the existing EPA generic standards, our recommendations do not address regulation of the chemically toxic and hazardous constituents of the waste or potential risks to the nonhuman environment. These risks are regulated under the Resource Conservation and Recovery Act and related laws and the National Environmental Policy Act, respectively, and are outside the scope of the generic disposal standards.
- **The merits of specific technologies for disposal** (e.g., mined repositories or deep boreholes). To the extent practical, standards should be technology independent and based on protecting public health and safety. These recommendations do not indicate a preference for any disposal technology; all proposed disposal facilities must comply with the generic standards.
- **The merits of specific geologic media for disposal of radionuclides**. The United States has multiple types of stable geologic formations that would likely be suitable for the long-term isolation of radioactive waste; health and safety standards should be independent of the geologic media employed.
- **The merits, or lack thereof, of any proposed repository sites in the United States or abroad**.
- **The merits, or lack thereof, of any proposed siting process for a geologic repository (e.g., consent-based siting)**. Effective regulatory oversight of geologic disposal, including transparent and protective public health and safety standards, is essential for building and maintaining public support for a repository program, irrespective of the siting process used.

II. BACKGROUND INFORMATION

The path by which the nation's nuclear waste disposal program reached the present impasse has been documented by others, including the BRC [4, pp. 9–26], and is familiar to most who have worked in the field. For those who may not be familiar with the history of the legislative and regulatory framework that provides the starting point for future rulemaking, the following sections provide a brief summary of national policy and the major aspects of the currently applicable regulatory standards. Appendix A of this report provides a more detailed discussion of the major statutes governing management and disposal of SNF, HLW, and TRU waste, and the history of the development of the specific radioactive waste disposal standards and regulations enacted by the EPA and the NRC.

II.1. National Policy Evolution

U.S. national policy regarding the management and disposal of radioactive materials has been defined by Congress through the NWPA of 1982, as amended—most significantly through the Nuclear Waste Policy Amendments Act (NWPAA) of 1987. For the purposes of this discussion, key points of national policy that are defined by statute are as follows.

- **Permanent disposal of SNF and HLW, regardless of the civilian- or defense-related origin of the waste, and defense-origin TRU waste, is the responsibility of the DOE**. Specifically, the Atomic Energy Commission was given responsibility in the Atomic Energy Act of 1954 to "provide for safe storage, processing, transportation, and disposal of hazardous waste (including radioactive waste)" (§91(a)(3)) resulting from defense activities. That authority was transferred to the DOE by statute in the 1970s and was expanded by the NWPA to include the disposal of SNF and HLW of civilian origin. Costs for the storage and disposal of civilian-origin SNF and HLW remain the responsibility of the generators and owners of the wastes under the NWPA, however.
- **The EPA is the federal agency responsible for promulgating radiation protection standards for the permanent disposal of SNF, HLW, and TRU waste**. Specifically, the NWPA requires that the EPA "shall, by rule, promulgate generally applicable standards for protection of the general environment from offsite releases from radioactive material in repositories" (§121(a)). In practice, these standards apply to all deep geologic disposal concepts for all present and future waste forms requiring deep geologic disposal, regardless of reactor technology and commercial or defense origin and regardless of whether or not the repositories are developed under the NWPA.
- **The NRC is the federal agency responsible for approving or disapproving licenses for repositories for SNF and HLW, unless such repositories are used exclusively for defense-origin wastes**. Specifically, the NWPA requires that the NRC shall "promulgate technical requirements and criteria that it will apply in approving or disapproving" license applications for repositories developed under the NWPA, consistent with EPA standards (§121(b)).

Therefore, based on existing legislation, we will refer to the regulatory body promulgating protection standards for a generic site as the EPA and, for simplicity, we will refer to the regulatory body responsible for applying the EPA generic standards to specific sites and approving or disapproving site-specific licenses as the "implementing regulator." For repositories developed under the NWPA, which would include all repositories containing commercial-origin wastes, the NRC is the implementing regulator. Consistent with the NWPA (§8), the NRC is not the implementing regulator for repositories limited exclusively to defense-origin wastes. For the Waste Isolation Pilot Plant (WIPP), operating in New Mexico for the disposal of defense-related TRU waste, the EPA functions as the implementing regulator for the postclosure performance standards. Given the example of the WIPP and the possibility of future repositories limited exclusively to defense-origin wastes, the Committee notes that EPA's generic standards must be applicable to both NRC-regulated repositories developed under the NWPA and any future repositories developed outside of the NRC's scope.

II.2. Summary of Major Differences between Current U.S. Radioactive Waste Disposal Standards and Regulations

As shown in Fig. 1, congressional actions over the last four decades have left the United States with two sets of EPA standards for the permanent disposal of HLW and SNF (see Appendix A for a more detailed discussion). Both sets are consistent with the legal framework defined in the NWPA, and each has accompanying implementing criteria developed by the NRC for repositories developed under the NWPA.

Standards and Regulations	Generic	Yucca Mountain
EPA	40 CFR 191	40 CFR 197
NRC	10 CFR 60	10 CFR 63

Fig. 1. Public health and safety regulatory framework for disposal of SNF and HLW in an NRC-regulated repository.

The first set of disposal standards and implementing regulations, the EPA's 40 CFR Part 191 and the NRC's 10 CFR Part 60, date from the mid-1980s, predating the congressional decision in 1987 to focus solely on the proposed Yucca Mountain Site.[2] While 40 CFR Part 191 is the standard under which the EPA has certified the WIPP in New Mexico for disposal of defense-origin TRU waste, the NRC's 10 CFR Part 60 has not been implemented for any site. In the absence of new rulemaking, both regulations would still apply to any disposal sites other than WIPP and Yucca Mountain.

The second set of disposal standards and implementing regulations, EPA's 40 CFR Part 197 and NRC's 10 CFR Part 63, was written in the last 25 years specifically for the proposed Yucca Mountain repository in response to congressional direction (see Appendix A.2).[3] Without new rulemaking, these standards and regulations do not apply to any other disposal site.

Although both sets of standards and regulations are protective of future human health and the environment, there are significant differences in how they ensure those goals. The older standards, framed by the EPA in 40 CFR Part 191, defined the regulatory period as 10,000 years and set quantitative limits for scenarios involving all release pathways, including inadvertent human intrusion. Separate standards were established for (1) estimates of the probability that the total cumulative amount of

2 40 CFR Part 191, *Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes*; 10 CFR Part 60, *Disposal of High-Level Radioactive Wastes in Geologic Repositories*.

3 40 CFR Part 197, *Public Health and Environmental Radiation Protection Standards for Yucca Mountain, Nevada*; 10 CFR Part 63, 10 CFR Part 63, *Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada*.

radiation released during the entire period would exceed specified values (40 CFR 191.13, "Containment Requirements"), (2) the peak dose to an individual during 10,000 years of undisturbed performance (40 CFR 191.15, "Individual Protection Requirements"), and (3) radionuclide concentrations in groundwater (40 CFR 191 Subpart C, "Environmental Standards for Ground-Water Protection").

The decision to focus the Containment Requirements on the cumulative releases of radionuclides throughout the 10,000-year period, rather than on radiation doses that might be incurred by any single individual in the future, was intended to emphasize long-term isolation of the wastes from the human environment without considering credit for other mechanisms that might reduce individual doses, including dilution and dispersion. In part, the requirements were based on, and functioned as a surrogate for, the concept of a population dose standard, in which small doses to large numbers of people become equivalent to proportionally larger doses to fewer numbers of people. The decision to require a probabilistic uncertainty analysis (defined as "performance assessment" in 40 CFR 191.12 and further spelled out in the guidance provided in Appendix B of the 1985 version of 40 CFR Part 191) provided the regulatory basis for the design of the quantitative computational analyses that became a major component of regulatory compliance evaluations for both the WIPP and Yucca Mountain. Capabilities and limitations of quantitative performance assessment modeling are discussed below in Section III.2.1 of this report.

In practice, the Containment Requirements have proven to be the most restrictive aspect of 40 CFR Part 191 for the WIPP, primarily because consequences of inadvertent human intrusion by drilling were required to be included in the probabilistic compliance analysis of cumulative releases. For the WIPP—the only repository operating under 40 CFR Part 191—the approach to estimating the density of future drilling was specified by the EPA in the implementing criteria (40 CFR 194.33[4]) and was to be based on a survey of drilling practices within the region during the last century, with the specification that the observed rate would apply for the full 10,000-year regulatory period. As implemented, this requirement led to compliance being based on the consideration of multiple intrusion events during the regulatory period.

Two additional aspects of the older set of standards and regulations that were modified significantly in the newer set also merit further discussion. First, 40 CFR Part 191 explicitly links the magnitude of the allowable release to the amount of waste initially emplaced in the repository: allowable releases are smaller for smaller repositories and larger for larger repositories. This specification was intended to avoid incentivizing the creation of multiple smaller repositories. Second, 10 CFR Part 60 specifies subsystem performance requirements for waste package lifetime, the release rate from the engineered barriers, and groundwater travel time to the accessible environment that apply in addition to the system-level performance standards contained in 40 CFR Part 191.

The newer standards, framed by the EPA in 40 CFR Part 197 in response to congressional direction to follow guidance from a committee convened by the National Academies of Sciences, Engineering, and Medicine (NASEM) on behalf of the National Academy of Science (NAS; see Appendix A.2 in this report for further discussion), abandon the cumulative release limits of the Containment Requirements and focus instead on probabilistic estimates of the long-term annual risk (expressed as dose) from a repository. Limits are set on the estimated mean peak dose received by a single "reasonably maximally exposed individual" in any one year during the next 1,000,000 years. (As discussed further in Section III.2 and Appendix A, the period of 1,000,000 years was chosen to be consistent with the NAS's conclusion that the period of geologic stability at Yucca Mountain is on the order of 1,000,000 years [6].)

Although the general approach to probabilistic uncertainty analyses remains the same, the specific metrics for comparison to the standards change from a complementary cumulative distribution function displaying the probability of cumulative release to a more intuitively understandable display of estimated

4 40 CFR Part 194, *Criteria for the Certification and Re-Certification of the Waste Isolation Pilot Plant's Compliance With the 40 CFR Part 191 Disposal Regulations*.

mean annual radiation dose incurred by a hypothetical future human near the site. To limit speculation about the ways in which uncertain future human behaviors might affect radiation doses, 40 CFR Part 197 provides site-specific direction regarding assumptions about the future biosphere and the characteristics of the "reasonably maximally exposed individual." There is no provision for scaling the allowable release to the size of the repository; the peak dose limits apply regardless of the amount of waste emplaced at the site.

Human intrusion is required to be considered separately from overall performance in a stylized analysis. Releases directly to the land surface during drilling were excluded from consideration, in part because such releases "would be independent of whether the repository performs acceptably when breached by human intrusion" and would not provide a good test of the "resilience" of the disposal system.[5]

Specific to the NRC licensing criteria for Yucca Mountain, subsystem performance requirements (i.e., quantitative limits during the first 1,000 years on waste package and engineered barrier systems performance and groundwater travel time to the site boundary) specified in 10 CFR Part 60 are absent from 10 CFR Part 63. Quantitative aspects of compliance with the EPA's system-level standards for estimates of mean annual dose to an individual both with and without human intrusion and groundwater concentrations of radionuclides are supported by additional quantitative information provided in the description of the barrier capabilities, uncertainty analysis, and the performance confirmation program.

Drilling rig.

The NRC explained its basis for this change in direction in detail in the preamble to the 1999 publication of the proposed 10 CFR Part 63.[6] In summary, the NRC found the following:

- The subsystem requirements of 10 CFR Part 60 were not clearly linked to the intent of the EPA's system-level standards.
- The subsystem requirements did not serve their original purpose of independently compensating for uncertainty regarding the system-level analyses because they relied on the same input information.
- The subsystem requirements had the potential to result in a considerable expenditure of resources without commensurate increases in public health and safety.
- Defense in depth could be better demonstrated within the context of the system-level analyses.

Table 1 summarizes the major differences between the two sets of EPA disposal standards and NRC licensing requirements currently in effect.

5 Environmental Protection Agency, "Public Health and Environmental Radiation Protection Standards for Yucca Mountain, NV," 66 FR 32073–32135; 32104 (June 13, 2001).

6 Nuclear Regulatory Commission, "Disposal of High-Level Radioactive Wastes in a Proposed Geologic Repository at Yucca Mountain, Nevada; Proposed Rule," 64 FR 8640 (Feb. 22, 1999).

Table 1. Major differences between U.S. disposal standards.

Requirement	40 CFR Part 191/10 CFR Part 60	40 CFR Part 197/10 CFR Part 63
Generic or site specific	Generic	Site specific (Yucca Mountain only)
Regulatory period	10,000 years	1,000,000 years
Type of quantitative limits that have been shown in practice to be most restrictive	"Containment Requirements" (40 CFR 191.13): Estimated probability that cumulative releases of radionuclides during 10,000 years will exceed specified fractions of total inventory	"Individual-Protection Standard" (40 CFR 197.20): Estimated mean peak dose to an individual at any time during 1,000,000 years*
Primary quantitative metric required for comparison to the standard	Complementary cumulative distribution function displaying the probability that estimated cumulative releases during 10,000 years will exceed specified values**	Estimates of the mean annual dose incurred by a hypothetical future "reasonably maximally exposed individual" living near the site***
Consideration of the total inventory being disposed	Estimates of cumulative release are normalized to the total initial repository inventory to avoid incentivizing multiple small repositories	Estimates of mean annual dose are not normalized to the initial inventory; larger repositories should be expected to result in proportionally higher dose estimates, all other things being equal
Treatment of human intrusion	Consequences of human intrusion by drilling, including releases at the land surface during drilling, are included in probabilistic estimates of cumulative releases; at the WIPP these releases are shown to dominate estimates of long-term performance	Consequences of human intrusion are analyzed separately in a stylized scenario in which one intrusion is assumed to occur, and releases to the land surface during drilling are excluded from consideration
Subsystem performance standards	10 CFR Part 60 sets separate limits on waste package lifetime, release rate from the engineered barrier system, and groundwater travel time to the accessible environment	Subsystem performance standards are absent from 10 CFR Part 63, and quantitative aspects of compliance are based on system-level limits established in 40 CFR Part 197; the repository must include multiple barriers (both natural and engineered) and the demonstration of compliance must describe the capability of those barriers to isolate waste

**Limits are specified to be 0.15 mSv (15 mrem) per year for 10,000 years and 1 mSv (100 mrem) per year between 10,000 and 1,000,000 years.*

***Analyses must include consideration of all significant uncertainties, with regulatory specification of some aspects of the drilling intrusion scenario.*

****Analyses must include consideration of all significant uncertainties with regulatory specification of characteristics of the "reasonably maximally exposed individual," aspects of the biosphere, and some aspects of the drilling intrusion scenario.*

III. ANS COMMITTEE RECOMMENDATIONS AND OBSERVATIONS FOR GENERIC DISPOSAL STANDARDS

The ANS Committee recommendations and observations that follow are based on two broad assumptions.

First, the ANS Committee assumes that the relevant legislative framework for regulation defined in the 1982 NWPA, as amended, remains unchanged. Specifically, the Committee assumes that the EPA will be charged with promulgating environmental standards for disposal and that the NRC will be charged with approving or disapproving licenses for disposal facilities that are not restricted exclusively to defense-origin waste, using licensing requirements and criteria consistent with the EPA standards.

Second, the ANS Committee assumes that existing generic disposal standards and regulations will be replaced. This assumption is consistent both with recommendations from the BRC [4]; the NASEM [7], and other review groups (e.g., [8]), as well as with past commitments from NRC staff (e.g., [9]). The Committee strongly concurs with the conclusion that existing generic disposal standards should be replaced rather than simply revised. Revisions to 40 CFR Part 191 would needlessly complicate the EPA's ongoing certification of the WIPP under the existing generic standards. As written, 40 CFR Part 191 is highly protective as implemented at the WIPP and, in the interest of regulatory stability and continuity, 40 CFR Part 191 should continue to be the governing regulation for WIPP. The Committee recommends that the EPA promulgate new standards with public health and safety standards for all deep geologic repositories other than WIPP (which would continue to be covered by 40 CFR Part 191) and Yucca Mountain (which would continue to be covered by 40 CFR Part 197). In conjunction with promulgation of the new standards, the scope of 40 CFR Part 191, which now applies to all potential repositories other than Yucca Mountain, would be narrowed so that it applies only to the WIPP.

III.1. ANS Committee Recommendations for Adopting 40 CFR Part 197 and 10 CFR Part 63 as a Starting Point for Developing Generic Standards

The ANS Committee concludes that the regulatory standards developed for Yucca Mountain provide an appropriate starting point for the development of generic standards. As discussed for specific examples in the following sections, there is much in both the EPA and NRC Yucca Mountain rules with which the Committee agrees and which could be adapted with relatively little modification to be applicable to generic sites.

III.1.1. Retain the Individual Protection Standard as the Primary Quantitative Metric

The ANS Committee agrees with the approach taken for the Yucca Mountain Site by the EPA in 40 CFR

Part 197 of adopting an Individual Protection Standard expressed in terms of annual dose[7] as the primary quantitative metric to be used in licensing a repository. Specifically, the Committee concludes that this approach, which provides a clear link to individual health consequence, is preferable to the approach taken in the Containment Requirements of 40 CFR Part 191, where limits are placed on the probability that cumulative releases to the accessible environment during the regulatory period will exceed specified amounts. The approach taken in the Individual Protection Standard of setting limits on estimated mean annual dose rather than on cumulative releases is consistent with international practice (see Appendix B.4) and provides greater clarity than the approach taken in 40 CFR Part 191 to quantify probabilistic releases. The Committee believes both characteristics of a dose standard may enhance public confidence in the effectiveness of regulatory oversight.

The Committee also concludes that basing compliance on estimated future doses to a single representative individual is preferable to setting limits on total doses to a population of individuals, either regional or global. The 2016 report of the United Nations Scientific Committee on the Effects of Atomic Radiation states:

> Collective dose is not intended as a tool for epidemiological risk assessment. Moreover, the aggregation of very low individual doses over extended time periods is inappropriate for use in risk projections and, in particular, the calculation of numbers of cancer deaths from collective doses based on individual doses that are well within the variation in background exposure should be avoided. [10, App. B, p. 141]

We further note that the approach taken in the Individual Protection Standard of 40 CFR Part 197 was thoroughly evaluated by the EPA during the development of 40 CFR Part 197,[8] and that it is consistent with international practices (see Appendix B, Table B.1). Furthermore, it has withstood court challenges specific to its application for the Yucca Mountain Site.[9]

The ANS Committee acknowledges that dose is not the only form an individual protection standard could take. The NAS report Technical Bases for Yucca Mountain Standards [6] expressed a preference for a risk-based standard rather than a dose-based standard for the individual protection limit for a Yucca Mountain repository. The NAS committee that authored the report identified two advantages with a risk standard: (1) it would not require revision due to evolving knowledge of the relationship between committed effective dose equivalent and effects on human health, and (2) it would enable easier comparison between the risk posed by a nuclear waste repository and risks from other sources (e.g., toxic chemicals). Nevertheless, in promulgating its Yucca Mountain standards, the EPA elected to use a dose limit (expressed in terms of committed effective dose equivalent, or CEDE), not a risk limit, and the ANS Committee agrees with the EPA approach. CEDE is consistent with international norms and U.S. practices for radiation protection, so it enables comparisons to other radiation limits. Furthermore, if comparisons of repository risks to risks from typical nonradiological hazards are desired, the translation from individual CEDE to individual risk is straightforward.

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7 Limits associated with radiation exposure to individuals are often referred to as "dose limits," a shorthand term that is not always consistent with the units that are used. Radiation dose is the amount of energy deposited in tissue by ionizing radiation, and it is expressed in units of grays or rads. In current practice, regulatory limits are usually established in terms of "dose equivalent" rather than dose. Dose equivalent is a measure of radiological risk associated with radiation exposure, and it is calculated from dose and other factors, including the type of radiation and the location in the body receiving the radiation. Dose equivalent is expressed in units of sievert or rem. In this report, the term "dose limit" should be understood to encompass regulatory limits on dose equivalent.

8 See, e.g., EPA, 66 FR 32074 (2001).

9 Nuclear Energy Institute, Inc. v. Environmental Protection Agency, No. 01-1258, 373 F.3d 1251 (D.C. Cir. 2004).

III.1.2. Retain the Concept of Reasonable Expectation

The ANS Committee agrees with the EPA's and NRC's recognition that "proof of the future performance of a disposal system is not to be had in the ordinary sense of the word" (40 CFR 191.13(b); restated by the NRC at 10 CFR 63.201(a)(2)). The EPA codified this observation for the Yucca Mountain Site in the definition of reasonable expectation in 40 CFR 197.14(a), stating that reasonable expectation "requires less than absolute proof because absolute proof is impossible to attain for disposal due to the uncertainty of projecting long-term performance."

This straightforward observation provides the basis for the EPA's specifications for the treatment of uncertainty in the probabilistic performance assessment required to evaluate compliance with quantitative postclosure standards. The Committee concurs fully with the EPA's definition of reasonable expectation in 40 CFR 197.14 and with the probabilistic approach to postclosure performance assessment it prescribes. The Committee further notes that the concept of "reasonable expectation" is broadly consistent with international perspectives, as discussed in Appendix B.4.

III.1.3. Continue to Base the Characteristics of the Potentially Exposed Individuals on Current Practices

The ANS Committee agrees with the approach taken by the EPA for the Yucca Mountain Site in 40 CFR 197.21 regarding the characteristics of potentially exposed future individuals, and concurs in general with the technical basis presented by the EPA in support of the promulgation of 40 CFR Part 197.[10] Specifically, the EPA requires that the "reasonably maximally exposed individual . . . [h]as a diet and living style representative of the people who now reside" in the vicinity of the repository. As described in greater detail in Appendix C, the Committee concludes that this approach is both reasonable, in that it provides implementable specificity to a topic that would otherwise be subject to unbounded speculation, and conservative, because it focuses on that portion of the almost limitless range of future human conditions that would result in the greatest potential for exposure to radioactive releases from the repository. While this approach bases human characteristics and behaviors on current practices, it is conservative in that it assumes no use is made of currently available technology to detect and mitigate radiological hazards in the environment.

The ANS Committee agrees in general with the approach taken in multiple places in 40 CFR Part 197 with regard to providing direction about how the current characteristics of the biosphere should be determined and what future changes to the biosphere and the geologic environment must be considered. Specificity on these points is essential to limiting speculation, particularly regarding possible effects of future human actions on the disposal system.

The ANS Committee notes that regulatory direction regarding some characteristics of the biosphere may, in some cases, need to be site specific. This was not a concern for the EPA in 40 CFR Part 197, which was in itself specific only to the Yucca Mountain Site. In generic standards, this can be addressed by removing requirements specific to the Yucca Mountain Site from the standard and retaining language from 40 CFR 197.15: the implementing agency "should not project changes in society, the biosphere (other than climate), human biology, or increases or decreases of human knowledge or technology." The EPA generic standards could further allow the implementing regulator to provide guidance for the selection of site-specific biosphere characteristics. For example, regulatory direction contained in 40 CFR Part 197 for the Yucca Mountain Site includes the location of the reasonably maximally exposed individual, the specification of the representative volume of water to be considered in performance assessments, and methods to be used by the applicant in estimating concentrations of contaminants within the representative volume. It would not be feasible to include this level of site-specific detail in a generic standard, but determination of

10 See, e.g., EPA 66 FR 3280 (2001).

site-specific aspects of the biosphere could be accomplished by the repository license applicant proposing appropriate values, consistent with EPA requirements and subject to approval by the implementing regulator.

III.1.4. Retain the Requirements for the Identification and Screening of Potentially Relevant Features, Events, and Processes

The ANS Committee agrees that the general approach taken by the EPA in both 40 CFR Part 191 and 40 CFR Part 197 to the identification of potentially relevant features, events, and processes is sound and should be maintained. Similarly, we agree that the criteria provided for determining which of these features, events, and processes must be included in the quantitative performance assessment are appropriate. Specifically, past experience with both the WIPP and Yucca Mountain repository programs has demonstrated the value of allowing the applicant to omit features, events, and processes from the quantitative performance assessment that are shown to be either very unlikely to occur[11] or to result in insignificant changes to the results of the performance assessment [11], [12], [13]. This approach, as presented for the Yucca Mountain Site in 40 CFR 197.36(a)(1), provides important limits to boundless speculation while maintaining a focus on the protection of public health, safety, and the environment, and is consistent with the concept of reasonable expectation, as discussed in Section III.1.2. International disposal programs have adopted comparable approaches, in some cases enhanced by the systematic identification of safety functions that may be impacted by specific events or processes (see Appendix B.7).

For the purposes of developing generic standards, the ANS Committee recommends removing the Yucca Mountain–specific requirements in 40 CFR 197.36(c) for special consideration of individual events and processes.

III.1.5. Base the Human Intrusion Standard on Consideration of a Single Stylized Intrusion Event

The ANS Committee recognizes that the Human Intrusion Standard specified by the EPA for the Yucca Mountain in 40 CFR 197.25 and 40 CFR 197.26 is site specific and cannot be adopted as is for a generic site. We also conclude, however, that that approach specified by the EPA in 40 CFR Part 191 is inappropriate for a generally applicable standard. As seen in the compliance certification analyses done for the WIPP [11]), requiring inadvertent human intrusion to be included in probabilistic evaluations of the natural evolution of the site can create a situation where licensing decisions may be dominated by irreducible uncertainty regarding human actions in the far future, rather than on the merits of the site and repository design.

The Committee concludes that the general approach specified in 40 CFR Part 197, requiring analysis of the consequences of a stylized human intrusion scenario consisting of subsurface groundwater releases from a single inadvertent and undetected drilling event that penetrates a single waste package, regardless of the probability of its occurrence, is preferable to the approach taken in 40 CFR Part 191. This approach will appropriately emphasize the merits of the site geology and repository design while removing speculation about future human actions, and is consistent with the approach taken in many other national programs (See Appendix B.6).

The ANS Committee recommends specifying a separate standard for human intrusion using the approach taken for the Yucca Mountain Site in 40 CFR Part 197, modified to be generally applicable to generic

11 The EPA defines "very unlikely to occur" in 40 CFR Part 197 as "estimated to have less than one chance in 100,000,000 per year of occurring." The ANS Committee concurs with this definition and further recommends that the EPA provide an analogous definition of "unlikely to occur" that would be generally applicable to all future repositories. With respect to "unlikely to occur," the Committee recommends the range of "estimated to have less than one chance in 100,000 per year of occurring and at least one chance in 100,000,000" defined by the NRC in 10 CFR 63.342(b) specific to the proposed Yucca Mountain repository.

sites. Specifically, human intrusion could be specified to be the result of exploratory drilling for natural resources of any type (rather than just groundwater, the only resource considered at Yucca Mountain), and the intrusion borehole should be assumed to provide connections to both overlying and underlying aquifers (rather than just the underlying aquifer specified for Yucca Mountain). We recommend that EPA retain the requirement in 40 CFR 197.26(c) that "drillers use common techniques and practices that are currently employed." To require otherwise would lead to unbounded speculation about future technologies.

The ANS Committee suggests that the time of the intrusion event could be specified to be either the "earliest time after disposal that the waste package would degrade sufficiently that a human intrusion . . . could occur without recognition by the drillers," as specified in 40 CFR 197.25(a) for the proposed Yucca Mountain repository, or 1,000 years after repository closure, whichever comes first. Specifying the time for the event would remove speculation about future drilling practices and would be consistent with the recognition that the standard relies on a stylized—rather than a realistic—event. An intrusion at 1,000 years provides time for the effects on the rest of the disposal system to be manifested in quantitative comparisons with the dose rate limit and represents a conservative estimate for the earliest time of undetected intrusion for many disposal system engineered barrier designs.

The Committee agrees with the position taken by the EPA in promulgating 40 CFR Part 197 that including releases to the land surface during drilling would not provide useful information regarding the resilience of the disposal system following human intrusion.[12] We also note that all proposed repositories with similar waste emplacement designs and configurations would show similar releases to the ground surface following intrusion, and including those releases in the regulatory standard would not provide useful information for comparing multiple candidate sites or repository design concepts. Consistent with these observations, the Committee recommends retaining the specification that analysis should be limited to releases through groundwater pathways.

The ANS Committee further notes that specifying a single intrusion regardless of the presence or absence of resources in the region may remove useful information about the site-specific potential for intrusion from the evaluation of the suitability of the site for a geologic repository. In a generic standard this approach could remove the incentive provided in Appendix C of the existing generic standard, 40 CFR Part 191, to select sites with a lower potential for future natural resource exploration and exploitation. The Committee suggests that this incentive could be restored if the new generic standards were to allow an alternative approach. The applicant instead could forego the quantitative human intrusion analysis if a technical basis for the conclusion that inadvertent and undetected intrusion is very unlikely is presented, consistent with the configuration of the repository and the potential for the occurrence of exploitable natural resources at the site. Such a provision would provide an incentive to select sites in regions with little or no potential for resource development based on current understanding.

In addressing human intrusion, it is important to note that the threat posed to future humans is tempered by the capability of a future society to carry out the intrusion (which requires a certain level of technology) and the potential capability of an advanced future society to mitigate harm. The implications of the characteristics of a future society are discussed in more detail in Appendix C. While the ANS Committee considers it reasonable to include consideration of human intrusion in repository standards, that should not imply that human intrusion will actually occur or, even if it does, lead to harm caused to future inhabitants near the repository. Consistent with the recommendation below regarding the regulatory time period for quantitative standards, the ANS Committee recommends limiting the time period for quantitative consideration of the consequences of human intrusion to 10,000 years.

12 EPA, 66 FR 32073 (2001).

III.2. ANS Committee Recommendations for Changes from the Regulatory Approach Taken for Yucca Mountain

In addition to the recommendations of the previous section, there are several technical issues for which the ANS Committee believes generic standards could be significantly improved by modification of the approach taken for Yucca Mountain. These topics are discussed in more detail in the following sections.

III.2.1. Limit the Regulatory Time Period for Quantitative Standards

The Committee recommends limiting the time period for quantitative standards to 10,000 years following disposal. The primary quantitative metric applied to postclosure performance of repositories is the estimated annual radiation dose to future humans; this dose depends in large part on the behavior of the exposed individuals. As discussed above, the Committee agrees with the position taken by the EPA in text accompanying the initial promulgation of 40 CFR Part 197 that using the behavior of the individuals currently living in the region of the repository is a reasonable and conservative basis for limiting speculation about future behavior.[13] However, the projection becomes less valuable as input for decision-making when extended over time periods longer than recorded human civilization. With respect to modeling of physical and geological processes, the Committee notes that computational models can be and have been constructed that project behavior of natural and engineered systems for very long time periods. However, the capabilities of those models to cope with complex coupling of time-dependent boundary conditions remain problematic.

The ANS Committee concludes that the 10,000-year standard provided in 40 CFR Part 191 provides a more reasonable and defensible time period during which quantitative estimates of the protection to humans can be meaningfully assessed than does the 1,000,000-year period adopted for the Yucca Mountain Site in 40 CFR Part 197. Further, the Committee believes that basing regulatory decisions on quantitative estimates of health risks to humans beyond 10,000 years introduces a false precision into a decision-making process that can be better informed by considering multiple lines of evidence, including alternative safety indicators. As discussed in Section III.2.2, this recommendation is not intended to preclude the use of simplified, quantitative modeling over longer times by either the implementor or the regulator where appropriate; rather, it is intended to avoid creating unrealistic expectations about the interpretation of such model results by requiring their comparison to a quantitative dose standard.

It is important to understand the history associated with the EPA's establishment of a 1,000,000-year time period for quantitative standards for the Yucca Mountain regulation (40 CFR Part 197). In the first promulgation of these standards in 2001, the EPA retained the 10,000-year time period for quantitative demonstration of compliance. This was then challenged in the U.S. Court of Appeals, which agreed with the plaintiffs that the time period was not "based upon and consistent with" the recommendations of the NAS, as required by the Energy Policy Act (EnPA) of 1992.[14] The court made no finding on an appropriate time frame for quantitative demonstration of compliance for geologic repositories in general, but it did conclude that the direction of the EnPA of 1992 had not been carried out for the Yucca Mountain regulation. In repromulgating the regulation, the EPA extended the time period to 1,000,000 years based on the Court of Appeals ruling that the NAS found the period of geologic stability for Yucca Mountain to be on the order of 1,000,000 years. The EPA did provide for a higher regulatory limit on individual dose between 10,000 years and 1,000,000 years as an acknowledgement that projections in the longer time frame are inevitably more uncertain. The ANS Committee believes the use of the 1,000,000-year time period for the Yucca Mountain standards is predominantly an outcome of the process established by Congress for developing that regulation but that it does not constitute an inviolable precedent for all future geologic repository standards. (See Appendix A of this report for a more detailed history of the development of the Yucca Mountain regulation.)

13 See, e.g., EPA, 66 FR 32074 (2001).

14 Nuclear Energy Institute, Inc. v. Environmental Protection Agency (2004).

As discussed further in Appendix B.5, there is widespread recognition in the international community that safety standards should recognize the uncertainties inherent in time-dependent factors, notably those associated with human behavior. For example, the International Atomic Energy Agency notes that over longer time periods, safety should be assessed through "simplified estimates and qualitative arguments rather than through the application of quantitative safety criteria" [14, sec. 6.49]. Similarly, the International Commission on Radiological Protection (ICRP) notes that "the scientific basis for assessments of detriment to health at very long times into the future therefore becomes uncertain, and the strict application of numerical criteria may be inappropriate" [15, p. 16], and that the results of any dose or risk assessments need to be interpreted in a qualitative way at long timescales [15, p. 41]. Finland has adopted regulatory standards that are consistent with this approach, prescribing an annual dose limit only for the first several thousand years and basing constraints after that period on comparisons to the impacts of naturally occurring radioactive materials (see Appendix B.3 and Table B.1).

There is also precedent for the use of a 10,000-year time period for projecting performance of isolation of hazardous material in EPA regulations. Subpart C, "Petition Standards and Procedures," of 40 CFR Part 148 sets forth requirements that must be satisfied in a petition to allow the injection of a restricted hazardous waste into an injection well or wells.[15] In that instance, the EPA established a time period of 10,000 years for projections of retention of hazardous waste. Obviously, hazardous waste does not become harmless at year 10,001, but the EPA recognized the practical limitations associated with modeling geologic performance into the far future quantitatively for the purpose of direct comparison to a health limit. The ANS Committee also recognizes those limits on the utility of quantitative compliance requirements but believes it is important to assess geologic repository performance during time periods longer than 10,000 years.

III.2.2. Introduce a Separate Standard for Performance beyond 10,000 Years Based on Multiple Lines of Evidence

As an alternative to basing regulatory compliance on quantitative system-level dose assessments for 1,000,000 years, the ANS Committee recommends that the EPA require a demonstration that there is a reasonable expectation that the disposal system will continue to function as intended during years 10,000–1,000,000 following disposal. This could be accomplished in part by continuing to consider potentially relevant features, events, and processes over a 1,000,000-year time period. The applicant should identify and evaluate features, events, and processes, if any, that have the potential to initiate scenarios having significantly different (and detrimental) impacts on the safety functions of the disposal system after 10,000 years. Those evaluations—and the full range of evidence used to develop them—should be considered by the implementing regulator during the licensing process. Rather than specifying quantitative limits that would in effect require a full quantitative dose assessment for 1,000,000 years, the burden would fall on the applicant to provide a sufficient analysis using qualitative or, where appropriate, quantitative methods to demonstrate that features, events, or processes that might operate differently after 10,000 years would not significantly degrade the overall performance of the repository. This is akin to using probabilistic risk analysis to identify "cliff-edge" effects in reactor safety analysis [16, sec. 8].

Examples of such processes that might need further analysis could include the impacts of future glacial cycles (which may be unlikely within 10,000 years), extrapolation of continued degradation of engineered barriers, changes in regional hydrology, and consequences of continued erosion at the site. Examples of methods and metrics used by the applicant in evaluating safety functions of the disposal system after 10,000 years could include qualitative observations based on current understanding (e.g., many geologic processes can reasonably be assumed to continue to function in the future as they do today). Process-specific observations and modeling (e.g., estimates of regional rates of uplift and erosion could

15 40 CFR Part 148, Hazardous Waste Injection Restrictions.

be compared directly to the depth of the repository), and estimates of repository-derived radionuclide concentrations in groundwater could be compared to naturally occurring concentrations.

The proposed post-10,000-year standard would not preclude the use of long-term dose estimates in evaluating the impact of potential degradation of disposal system safety functions. Rather, the proposed standard would encourage consideration of multiple lines of evidence while avoiding the undue reliance on the precision of dose estimates over a period of time that far exceeds human history.

As proposed, the applicant would have the responsibility to identify the full set of potentially relevant post-10,000-year features, events, and process and to determine their impacts on the long-term safety of the repository. Determination of both the adequacy of the applicant's analysis and the relative significance of the impact would be the responsibility of the implementing regulator.

The Committee notes that this recommendation is consistent with many aspects of the international concept of the "Safety Case" (see Appendix B.2), in which the applicant bears the responsibility for presenting the full body of information supporting a determination of long-term safety of the repository. The Committee does not recommend adoption in U.S. generic standards of the term "Safety Case," however, noting that the details of specifying how the standards are met are appropriately the responsibility of the implementing regulator.

III.2.3. Replace "Period of Geologic Stability" with "1,000,000 Years"

The ANS Committee recommends that the EPA remove the term "period of geologic stability" from the regulation and replace it with a generally applicable specification of 1,000,000 years. The "period of geologic stability" was derived from the 1995 NAS report Technical Bases for Yucca Mountain Standards [6] and is not generally applicable to generic sites because some sites might reasonably be argued to be geologically stable for shorter or longer periods of time than others under consideration. Applying the term literally to generic sites could have the unintended and counterintuitive effect of incentivizing sites with a potential for geologic instability, however that might be defined, at earlier times. Specific to the Yucca Mountain site, the term is defined in 40 CFR 197.12 to be synonymous with one million years, and the ANS Committee recommends that the EPA adopt that time period as an appropriate basis for regulating all repositories. One million years is more than two orders of magnitude longer than recorded human history, and the ANS Committee believes that it is a sufficient and conservative time to consider the possible impacts of the behavior of geologic systems on human health.

III.2.4.Adopt Requirements for Multiple Barriers Based on the Approach Taken by the EPA in 40 CFR Part 191 and the NRC in 10 CFR Part 63

The ANS Committee agrees with the approach taken in 40 CFR 191.14(d) to require both engineered and natural barriers. This is also consistent with the NRC implementing regulations specific for the Yucca Mountain Site (see 10 CFR 63.102(h); 10 CFR 63.113(a); 10 CFR 63.115). We recommend that the EPA adopt the NRC's approach for Yucca Mountain in its generic standards to ensure their applicability to all repositories. Specifically, the Committee concludes that the requirements in 10 CFR 63.115—to identify the barriers, describe their capabilities, and provide the technical basis for those capabilities consistent with the technical basis for the overall performance assessment—will result in a sound basis for the

Disposal canister for spent nuclear fuel, Olkiluoto Nuclear Power Plant Visitor Centre.

evaluation of the defense-in-depth provided by the repository. Further, the Committee concludes that this approach is superior to the quantitative subsystem limits specified in 10 CFR Part 60 for the performance of selected components of the barrier system, because that approach carries the potential to encourage subsystem engineering solutions that may not correspond to improvements in overall disposal system performance.

This approach is consistent with the requirements of the NWPA "to provide for the use of a system of multiple barriers in the design of the repository" (§121(b)(1)(B)); NRC staff completed a thorough analysis of the requirements during the promulgation of 10 CFR Part 63.[16] Furthermore, this approach is consistent with international practice regarding the treatment of "safety functions" in repository performance (see Appendix B.7) and has withstood court challenges specific to its application for the Yucca Mountain Site.[17]

III.2.5. Adopt Requirements for Retrievability Consistent with NWPA §122

The ANS Committee perceives three potential reasons to provide for retrievability of waste from a geologic repository: (1) retrieval to address new information that calls into question the ability of the disposal system to provide adequate protection to current and future inhabitants, (2) retrieval as a confidence-building provision for residents in the vicinity of the repository, and (3) retrieval to recover resources (e.g., fissile material) needed by future generations. The last is not related to health and safety and therefore need not be addressed in the EPA's generic standards. The second is related to siting and public acceptability and is also arguably outside the bounds of a health and safety standard. The first, however, relates directly to the health and safety of future inhabitants and the Committee therefore believes provisions for retrievability should be included in the promulgation of new generic standards.

The Committee notes that the approach to regulating the retrievability of waste is prescribed in the NWPA for repositories developed under that Act. Specifically, §122 states that "any repository constructed on a site approved under this subtitle shall be designed and constructed to permit the retrieval of any spent nuclear fuel placed in such repository, during an appropriate period of operation of the facility . . . ." The Committee recognizes that the NWPA language effectively removes retrievability requirements from the scope of postclosure regulatory authority, and that it could be argued that the topic should be omitted entirely from generic postclosure standards. However, the NWPA requirements apply only to NRC-regulated repositories, and the EPA may develop alternative requirements that apply to other repositories. In the current generic disposal standards (40 CFR 191.14(f)), the EPA requires that, for repositories that are not regulated by the NRC, "disposal systems shall be selected so that removal of most of the wastes is not precluded for a reasonable period of time after disposal." The Committee contrasts this requirement to the NRC requirements for the proposed Yucca Mountain repository in 10 CFR 63.111(e) that "the geologic repository operations area must be designed so that any or all of the emplaced waste could be retrieved on a reasonable schedule starting at any time up to 50 years after waste emplacement operations are initiated, unless a different time period is approved or specified by the [NRC]" (emphasis added).

To ensure consistent application of retrievability requirements for all future repositories, the Committee recommends that the EPA adopt the NRC's approach for Yucca Mountain in the EPA's generic standards while leaving details of the implementation (e.g., providing further guidance on what constitutes "an appropriate period of operation") to be determined by the implementing regulator. As discussed in Section III.2.8 below, deep borehole disposal concepts, with operational periods for disposal that are inherently far shorter than those needed for mined repositories, warrant different considerations for a "reasonable schedule" for retrievability, consistent with the NWPA.

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16 See, e.g., Nuclear Regulatory Commission, "Disposal of High-Level Radioactive Wastes in a Proposed Geologic Repository at Yucca Mountain, NV; Final Rule," 66 FR 55732 (Dec. 3, 2001).

17 Nuclear Energy Institute, Inc. v. Environmental Protection Agency (2004).

The ANS Committee also notes that requirements and expectations regarding retrievability vary widely internationally and that the approach recommended here is consistent with those adopted in many other national programs (see Appendix B.8).

III.2.6. Adopt Requirements for Active and Passive Institutional Controls Consistent with the Approach Taken by the NRC in 10 CFR Part 63

The ANS Committee recommends that the generic standards adopt requirements for both active and passive institutional controls consistent with approach taken by the NRC in 10 CFR 63.102(k) specific to Yucca Mountain, to ensure their applicability to all repositories. Specifically, the NRC states that "active and passive institutional controls will be maintained over the Yucca Mountain site, and are expected to reduce significantly, but not eliminate, the potential for human activity that could inadvertently cause or accelerate the release of radioactive material. However, because it is not possible to make scientifically sound forecasts of the long-term reliability of institutional controls, it is not appropriate to include consideration of human intrusion into a fully risk-based performance assessment . . . ." The Committee concurs with the concept of requiring both active institutional control over the site indefinitely (required by the EPA in 40 CFR 191.14(a) for repositories developed outside the NWPA as "as long a period of time as is practicable") and passive controls (required by the EPA in 40 CFR 191.14(c) for repositories developed outside the NWPA) that will continue to function indefinitely into the future. The Committee also concurs with the definition of passive institutional controls provided by the EPA in 40 CFR 197.12, including markers, records, archives, and government ownership, and with the NRC's specification at 10 CFR 63.51(a)(3), specific to Yucca Mountain, that descriptions of the passive institutional controls be provided in an application to close the repository.

Relevant to the requirement for retention of records and archives, the Committee notes that this is consistent with a growing international recognition of the importance of systematic knowledge management during the decades required for implementing radioactive waste disposal as well as in the more distant future following closure of the repository. Knowledge management systems are discussed further in Appendix B.9.

III.2.7. Adopt Requirements for Postclosure Monitoring of the Repository Consistent with the Approaches Taken by the EPA in 40 CFR Part 191 and the NRC in 10 CFR Part 63

The ANS Committee recommends that the generic standards adopt requirements for postclosure monitoring of the repository that are consistent with the approaches taken both by the EPA for repositories developed outside the NWPA in 40 CFR 191.14 and by the NRC, specific to Yucca Mountain, in 10 CFR 63.51(a)(2) to ensure consistent requirements applicable to all future repositories. The EPA requirements in 40 CFR 191.14(b) state, "Disposal systems shall be monitored after disposal to detect substantial and detrimental deviations from expected performance. This monitoring shall be done with techniques that do not jeopardize the isolation of the waste and shall be conducted until there are no significant concerns to be addressed by further monitoring." The NRC requirements in 10 CFR 63.51(a)(2) specific to Yucca Mountain simply state that an application to close the repository must include "a description of the program for post-permanent closure monitoring of the geologic repository."

The Committee notes that the EPA's requirement to continue monitoring activities "until there are no significant concerns to be addressed" is well intentioned but subject to unavoidable uncertainty about future institutional controls, as noted in Section III.2.6. The Committee concurs with the NRC's common-sense requirement for a monitoring plan to be submitted by the applicant at the end of the operational period, subject to approval by the implementing regulator before closure.

The Committee further concurs with the approaches taken by both the EPA and the NRC to make a careful distinction between postclosure monitoring and performance confirmation. The latter is defined by the NRC in 10 CFR 63.2 specific to Yucca Mountain to be "the program of tests, experiments, and analyses that is conducted to evaluate the adequacy of the information used to demonstrate compliance with the performance objectives." Consistent with this definition, the performance confirmation program ends when the implementing regulator amends the operating license of the repository to allow its permanent closure. The Committee agrees with the position previously taken by the EPA and NRC that specifications regarding a performance confirmation program are appropriately outside the scope of the generic standards and should be addressed by the implementing regulator.

III.2.8. Adopt a Modified Definition of the Controlled Area from 40 CFR Part 191

The 40 CFR Part 197 definition of the controlled area is specific to the Yucca Mountain Site and is clearly not appropriate for a generic repository. The ANS Committee recommends the use of a modification of the definition from 40 CFR Part 191, which specified an area "no more than 100 square kilometers [extending] horizontally no more than five kilometers in any direction from the outer boundary of the original location of the radioactive wastes in a disposal system." The Committee recommends retaining the concept of limiting the controlled area to a five-kilometer region around the waste disposal zones, but recommends deleting the overall limit of 100 square kilometers that could needlessly limit the dimensions of a repository. Details of the controlled area boundary for a specific site would be determined by the implementing organization based on the characteristics of that site, and it would be subject to approval of the implementing regulator. The Committee further notes that in parallel with adopting the definition of controlled area from 40 CFR Part 191, the EPA should retain the definition of the "accessible environment" from 40 CFR Part 197, which is consistent with the implementation of an Individual Protection Standard by requiring the estimation of mean annual dose at the controlled area boundary.

The controlled-area concept is well understood for a mined geological repository like WIPP or Yucca Mountain but has yet to be implemented for a deep borehole repository. The ANS Committee sees the concept as being fairly straightforward for a deep vertical borehole repository, including one with an array of boreholes (see Section III.2.9). However, a horizontal borehole repository with boreholes projecting in multiple directions presents a potentially more complicated situation that could be addressed as described above.

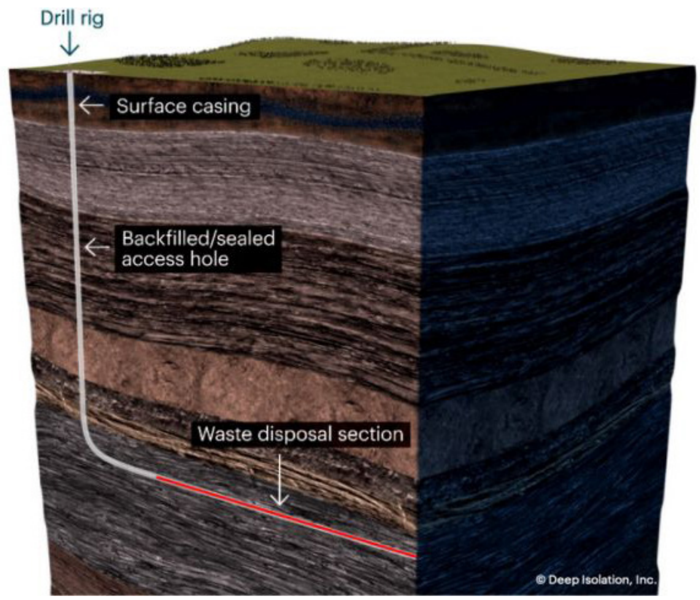
III.2.9. Make Generic Standards Applicable to Deep Borehole Disposal Concepts

The ANS Committee recommends that the EPA make generic disposal standards applicable to deep borehole disposal concepts as well as the mined repositories that have been the only application of the existing regulations. In this regard, the Committee agrees with intent of the EPA in their promulgation of 40 CFR Part 191 in 1985: "Although disposal of these materials in mined geologic repositories has received the most attention, the disposal standards apply to disposal by any means, except disposal directly into the oceans or ocean sediments."[18] There have been significant advances in drilling technology since the initial promulgation of 40 CFR Part 191, including directional drilling techniques that allow for horizontal as well as vertical boreholes of sufficient length to function as repositories. All potential types of deep borehole disposal should be covered by a new generic repository standard.

The ANS Committee recognizes multiple ways in which deep borehole disposal repositories could raise different regulatory issues than those posed by mined repositories. For example, the choice of whether to define the disposal system to be a single borehole or an array of multiple boreholes could impact many aspects of the compliance evaluation, ranging from the calculation of the estimated annual dose

18 Environmental Protection Agency, "Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes; Final Rule," 50 FR 38066 (Sep. 19, 1985).

to definition of the controlled area and the location of the accessible environment boundary. Other issues could arise with the phased nature of borehole disposal: Would compliance assessments be required for each separate borehole as it is characterized and constructed? Would operational retrievability requirements be established borehole by borehole, allowing for the plugging of one borehole before going on to the next? The Committee believes most such issues could be appropriately addressed by the implementing regulator in its licensing criteria for a deep borehole repository. Three topics, however, rise to the level of warranting inclusion in the generic standards.



Technical diagram from Deep Isolation demonstrating a horizontal borehole disposal concept.

First, the Committee recommends that the EPA define a deep borehole repository to be the full array of boreholes at a single site. This would allow applying quantitative limits to the full disposal inventory rather than applying them to single boreholes one at a time, and it would provide a logical basis for defining the boundaries of the accessible environment and the location of the reasonably maximally exposed individual using the same approach taken for mined repositories. The requirement should be written, however, to allow flexibility for the implementing regulator in its specification of phased licensing operations as individual disposal boreholes are characterized, constructed, and sealed.

Second, as discussed previously in Section III.1.5, the Committee recommends that the EPA provide the opportunity for the implementing regulator to address aspects of the human intrusion scenario that are dependent on the disposal concept, taking into account site-specific design and geometry considerations for deep borehole disposal systems.

Third, as noted above (Section III.2.5), the Committee recommends that the EPA specifically allow for consideration of a period of retrievability that is appropriately consistent with the operational periods likely for deep borehole disposal systems. This would be consistent with the requirements for retrievability provided by the NWPA §122 for repositories developed under the NWPA.

III.2.10. Remove Specificity Regarding the Implementing Organization

The ANS Committee recommends that the new standards refer throughout to simply the "implementing organization" or the "implementor" rather than to the DOE. Existing language in 40 CFR Part 197 refers specifically to the DOE and its responsibilities. That is understandable, given that the NWPA specifies the DOE as the implementing agency for a repository at Yucca Mountain or other sites developed under the provisions of the act. However, the EPA's generic regulation should be general where possible and need not presuppose that the DOE will be the only implementing organization for all geologic repositories in the U.S. for all time. Flexibility may be useful should the current statutory framework for management of geologic disposal change.

III.3. Other Topics

In this section, the ANS Committee provides discussions of other topics that it believes may benefit from further consideration in the development of generic standards, regardless of whether changes result in the final rules.

III.3.1. Consider Updating Guidance and Requirements for Radiation Dose Assessments to Be Consistent with the Most Recent Recommendations of the ICRP

In some instances, the approaches specified in existing regulations for determining health consequences from radiation exposures are out of date with respect to current international practice. The most recent recommendations on dose conversion methodology from the ICRP are an appropriate starting point for the EPA to consider [15], [17], [18]. The Committee notes that Appendix A of 40 CFR Part 197 used older ICRP dose conversion factors brought forward from 40 CFR Part 191 but left open the door for the DOE to use updated radiation weighting factors if allowed by the NRC. The NRC appropriately allowed for this possibility in 10 CFR Part 63, noting that "DOE may use the most current and appropriate (e.g., those accepted by the International Commission on Radiological Protection) scientific models and methodologies . . . " (10 CFR 63.102(0))." A future EPA disposal standard could be updated with comparable language to bring itself into alignment with international practice. Given the multigenerational operational lifetime anticipated for many deep geologic repository concepts, continued updating of the dose conversion methodology by either the EPA or the implementing regulator should be expected and welcomed.

III.3.2. Consider Removing the Ground Water Protection Standards

The ANS Committee recognizes that this topic was the subject of extensive comment and deliberation in the late 1990s during the drafting and promulgation of 40 CFR Part 197, and it may be unlikely that further recommendations at this point will be constructive. The Committee also recognizes that some will perceive a removal of the Ground Water Protection Standards as a weakening of the EPA's commitment to protect the health of future humans; as discussed further below, the Committee disagrees with this point. With these observations noted, the Committee concurs with the comments made by NRC staff in 1999 specific to the EPA's proposed Ground Water Protection Standards [19]. The Committee's recommendation, consistent with NRC's required "all-pathways" safety assessment requirement, is to have in place overall quantitative standards for protection of human health; the imposition of additional groundwater protection standards based on treated drinking water systems, as is the case with current U.S. repository standards, is unnecessary and counterproductive. Specifically, we believe that the Ground Water Protection Standards as implemented in 40 CFR 197 add no additional protection to the standards for human health, safety, or the environment beyond that already provided by the Individual Protection Standard. The Committee also shares the NRC's concern, expressed in 1999, that the allowable levels of radium, gross alpha activity, and combined beta and photon emitters specified in 40 CFR Part 197 were intended for application to treated sources of community drinking water (see 40 CFR 141.66) and are inappropriately and inconsistently applied to untreated groundwater in 40 CFR Part 197. If promulgated as part of a generic standard, applying drinking water standards to untreated groundwater has the potential to incentivize the selection of sites with otherwise pristine groundwater, because sites with higher background levels of radium or other sources of radioactivity would present greater challenges in meeting a standard that was never intended to be applied in this manner. In fact, as implemented in 40 CFR Part 197, the current Ground Water Protection Standards could disqualify otherwise desirable repository sites even without an adverse impact on potential nearby groundwater.

III.3.3. Establishing the Level of Protection

In this section, the Committee offers some context for establishing appropriate standards for the quantitative level of protection required. The individual protection limits in 40 CFR Part 191 and 40 CFR Part 197 are set at 0.15 mSv (15 mrem) per year for the first 10,000 years after repository closure. 40 CFR Part 197 applies a limit of 1 mSv (100 mrem) per year during 10,000–1,000,000 years after permanent closure. Note that these individual protection limits are often referred to as dose limits, but, as discussed in Section III.1.1, they are usually expressed in terms of CEDE, expressed in units of sievert or rem. CEDE characterizes the risk associated with the exposure to ionizing radiation.

Before delving too far, it is important to acknowledge that values of dose calculated by repository performance assessments are not true predictions of what will occur in the distant future to actual human beings. Uncertainties, particularly about the characteristics of future humans and their societies, are simply too great. Instead, the calculations are a stylized approach to putting calculated radionuclide releases from the repository into an understandable perspective. Comparing the results of such calculations to dose limits is an appropriate yet almost certainly conservative approach to providing a reasonable expectation of future public health and safety, as discussed in Appendix C.

Most other countries impose limits on projected dose as part of their repository standards. As discussed below in Appendix B, the levels of protection range from 0.1 to 1 mSv (10–100 mrem) per year. Both the IAEA and the ICRP recommend a dose limit for disposal facilities of 0.3 mSv (30 mrem) per year for members of the general public [20, sec. 2.15(b)], [18, p. 12]. From that perspective, the U.S. is toward the low (most restrictive) end of the spectrum for the first 10,000 years.

In addition, the average natural background dose for residents of the United States is approximately 3.1 mSv (310 mrem) per year [21]. The average total radiation dose to U.S. residents, including natural and man-made sources of radiation, is 6.2 mSv (620 mrem) per year [19]. Background radiation level varies significantly due to numerous factors, including elevation, rock and soil composition, that dwelling type, occupation, lifestyle, and medical treatment. According to a report prepared for the EPA, the average annual natural background dose varies between 1.31 mSv (131 mrem) in Florida and 9.63 mSv (963 mrem) in South Dakota [22]. The largest source of the variation is the amount of radon gas present. With respect to man-made sources, medical diagnosis and treatment is a significant variable; a single computed tomography scan can result in a dose of 1.5 mSv (150 mrem) [21]. Thus, doses in the range of 0.15–1 mSv per year, consistent with current geological repository standards, are significantly lower than current background radiation levels in the U.S. and lower than the variability of background radiation levels.

The NRC has established other regulatory limits for radiation dose to individual members of the public. For example, 10 CFR Part 20 sets a limit of 1 mSv (100 mrem) per year from the operation of a nuclear power plant. With respect to SNF management facilities, 10 CFR Part 72 sets a limit of 0.25 mSv (25 mrem) per year for radiation dose to the public from an independent spent fuel storage installation.[19] Both allowable annual doses are greater than the 10,000-year individual protection dose limits in 40 CFR Part 191 and 40 CFR Part 197.

The ANS Committee makes no specific recommendation on the regulatory limit for dose to an individual living near a proposed repository. For a health-based standard, the Committee puts substantial weight on the recommendations of international bodies such as IAEA and ICRP, which suggest a limit of 0.3 mSv per year (30 mrem per year). However, the Committee recognizes that the EPA must weigh multiple considerations when establishing an adequately protective and practical value for a limit. Ultimately, the limit will be a value that the regulator must establish and justify through a public process.

The ANS Committee expects that the EPA will establish an annual limit on projected individual dose due to a geologic repository in the range of 0.15–1 mSv (15–100 mrem) per year. A limit in that range is appropriately conservative for a public health and safety standard, with the lower end of the range being quite restrictive relative to many current U.S. and international practices.

19 10 CFR Part 20, Standards for Protection Against Radiation; 10 CFR Part 72, Licensing Requirements for the Independent Storage of Spent Nuclear Fuel, High-Level Radioactive Waste, and Reactor-Related Greater than Class C Waste.

IV. SUMMARY

The ANS Committee recommendations can be broadly summarized as follows: Use the existing Yucca Mountain standards as a template for developing new standards, modified as necessary for general applicability. In general, the Yucca Mountain standards are representative of international best practices and implementable using established licensing processes.

Specific recommendations include:

- Retain the individual health consequence standard (i.e., estimated mean annual dose to an individual) as the primary quantitative metric.
- Retain the concepts of reasonable expectation and risk-informed decision-making as a recognition of the limitations of quantitative modeling of the far future.
- Retain the concept of basing the characteristics of the reasonably maximally exposed individual on current practice in the vicinity of the disposal site, and retain regulatory specificity regarding characteristics of and future changes to the biosphere and certain aspects of the geologic environment.
- Retain the requirements for the identification and screening of the comprehensive set of features, events, and processes that are potentially relevant to the long-term performance of the repository.
- Retain the human intrusion requirement, but revise it to make it generally applicable to all potential sites and repository design concepts.

In addition to general modifications needed to make the Yucca Mountain standards generic, the ANS Committee recommends the following changes to the EPA generic standards:

- Limit the regulatory time period for quantitative standards to 10,000 years.
- Replace the quantitative dose limits for the period beyond 10,000 years and before 1,000,000 years with a requirement to evaluate potentially relevant features, events, and processes to demonstrate that they are unlikely to result in substantially different behavior of the disposal system during that period.
- Adopt requirements for the multiple barriers implemented by the NRC for Yucca Mountain in 10 CFR Part 63, to ensure their applicability to all future repositories, including those developed outside the NWPA and not regulated by the NRC.
- Adopt requirements for retrievability of the wastes as prescribed by the NWPA §122 and implemented by the NRC for Yucca Mountain in 10 CFR Part 63 to ensure their applicability to all future repositories, including those developed outside the NWPA and not regulated by the NRC.

- Adopt requirements for active and passive institutional controls consistent with the approach taken by the NRC in 10 CFR Part 63 for Yucca Mountain, to ensure their applicability to all future repositories, including those developed outside the NWPA and not regulated by the NRC.
- Adopt requirements for postclosure monitoring of the repository consistent with the approaches taken by the EPA in 40 CFR Part 191 for repositories developed outside the NWPA and by the NRC in 10 CFR Part 63 for Yucca Mountain to ensure their applicability to all future repositories, including those developed outside the NWPA and not regulated by the NRC.
- Remove the concept of the "period of geologic stability" from generic disposal standards while retaining an upper bound on the regulatory period of 1,000,000 years.
- Adopt the definition of the controlled area provided in 40 CFR Part 191, with site-specific implementation to be determined by the implementor and the regulating agency.
- Make generic disposal standards applicable to deep borehole disposal concepts as well as mined repositories.
- Remove specificity regarding the establishment of the DOE as the implementing organization for disposal of spent nuclear fuel and high-level radioactive wastes.

In addition, the ANS Committee provides observations on other topics the Committee believes could benefit from further consideration by the EPA:

- The approaches specified in existing regulations for determining health consequences from radiation exposures are in some instances out of date with respect to current international practice.
- The separate "Ground Water Protection Standards" (40 CFR 197.30 and 197.31) add no additional protection to the standards for human health, safety, or the environment, while introducing the potential for incentivizing the selection of sites with pristine groundwater and disqualifying site with high naturally occurring radionuclide concentrations in their groundwater.
- Regarding the specific limits applied to estimates of annual radiation doses to individuals, values in the range of 0.15–1 mSv (15–100 mrem) per year are appropriately conservative for a public health and safety standard.

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APPENDIX A. Summary Chronology of U.S. Legislation and Regulation Governing Permanent Disposal of High-Level Radioactive Waste and Spent Nuclear Fuel

A.1. Legislation

Key aspects of the statutory framework governing regulations for the disposal of spent nuclear fuel (SNF) and high-level radioactive waste (HLW) come from a relatively small body of federal legislation. The Atomic Energy Acts (AEAs) of 1946 and 1954 created the basis for federal authority; the federal Energy Reorganization Acts of 1974 and 1977 created the U.S. Department of Energy and the Nuclear Regulatory Commission, two of the three primary agencies responsible for implementing national policy (the third, the Environmental Protection Agency, was created by executive order in 1970); and the Nuclear Waste Policy Act (NWPA) of 1982 defined the national policy for nuclear waste management and disposal. Subsequent modifications to policy and statute in the Nuclear Waste Policy Amendments Act of 1987 (NWPAA; included in the Omnibus Budget Reconciliation Act of 1987), the Waste Isolation Pilot Plant Land Withdrawal Act (WIPP LWA) of 1992, and the Energy Policy Act (EnPA) of 1992 have impacted the course of the national program and have provided the EPA and NRC with specific direction regarding the development of their standards and regulations. A Joint Resolution of Congress in 2002 approving the Yucca Mountain Site for development did not constrain the development of the EPA standards and NRC regulations but did confirm the intent of Congress to focus solely on the Yucca Mountain Site, consistent with the requirements of the NWPAA of 1987.[1]

The Atomic Energy Act of 1946 sets national nuclear policy. The AEA of 1946 is silent on the subject of radioactive waste management and disposal, but it created a basis for civilian nuclear energy activities and established the Atomic Energy Commission (AEC) authority to oversee nuclear research and the control of nuclear materials in the private and public sectors. Specifically, the AEA stated as a national policy goal that "the development and utilization of atomic energy shall, so far as practicable, be directed toward improving public welfare, increasing the standard of living, strengthening free competition in private enterprise, and promoting world peace" (§1(a)). The AEC was the agency tasked with implementing programs to achieve this goal, in addition to its defense-related responsibilities.

1 Atomic Energy Act of 1946, Pub. L. No. 585, 79th Cong. (1946); Atomic Energy Act of 1954, Pub. L. No. 83-703, 68 Stat. 919 (1954); Energy Reorganization Act of 1974, Pub. L. No. 93-438, H.R. 11510, 93rd Cong. (1974); Energy Reorganization Act of 1977, Pub. L. No. 95-91 Stat. 565, 95th Cong. (1977); Nuclear Waste Policy Act of 1982, Pub. L. No. 97-425, 96 Stat. 2201, 97th Cong. (1982); the Omnibus Budget Reconciliation Act of 1987, Pub. L. No. 100-203, H.R. 3545, 100th Cong. (1987); Waste Isolation Pilot Plant Land Withdrawal Act, Pub. L. No. 102-579, 106 Stat. 4777, 102nd Cong. (1992); Energy Policy Act of 1992, Pub. L. No. 102-486, H.R. 776, 102nd Cong. (1992); Joint Resolution Approving the Site at Yucca Mountain, Nevada, Pub. L. No. 107-200, 116 Stat. 735, 107th Cong. (2002).

The Atomic Energy Act of 1954 expands federal responsibility to include defense-origin wastes. The AEA of 1954 provided significantly more authority and specificity to the roles and responsibilities of the AEC, including, as noted above, the first statutory obligation for the management of radioactive wastes. The AEC's responsibility was limited at this point to wastes generated by defense-related activities. This responsibility has shifted to the DOE but remains in effect.

The Energy Reorganization Act of 1974 and the Department of Energy Organization Act of 1977 create the NRC and the DOE and define their scopes. Congress dismantled the AEC in 1974, separating its regulatory responsibilities from those related to nuclear defense and energy programs. The NRC was established as an independent regulator of commercial nuclear activities, and the Energy Research and Development Administration (ERDA) was established to oversee both the AEC's nuclear defense and energy programs and a wide range of federal nonnuclear energy research and development activities. Congress reorganized the ERDA into the DOE in 1977, specifically ensuring that responsibilities for nuclear activities originally assigned to the AEC were transferred to the DOE.

The Nuclear Waste Policy Act of 1982 defines national policy. The NWPA provides a comprehensive framework for federal storage and permanent disposal of SNF and HLW of civilian (i.e., commercial) origin, with provisions for the inclusion of defense-origin wastes in the federally managed civilian disposal program. For the purposes of this discussion, the most important aspect of the NWPA is the clear definition of roles and responsibilities for the EPA and the NRC in developing standards and regulations for permanent disposal. The NWPA also provides specific direction to the NRC regarding the content of its implementing regulations with respect to the requirement of a system of multiple barriers in the design of the repository and restrictions on the retrievability of the wastes from the repository (§121(b)(1)(B); §122).

The Nuclear Waste Policy Amendments Act of 1987 redirects national policy. The NWPAA provided a major redirection of the national program by selecting Yucca Mountain as the only site to be evaluated by the DOE under the "first repository" provisions of the NWPA for potential submittal of a license application to the NRC, terminating the NWPA-prescribed site-selection process before it was complete. The NWPAA had no direct impact on the EPA and NRC regulatory frameworks for the repository, but the combination of the redirection of the national program and court actions vacating the EPA's generally applicable standard led to the creation of a new set of EPA and NRC regulations specific to Yucca Mountain (as discussed above in Sec. II.1.2).

The WIPP Land Withdrawal Act and the Energy Policy Act of 1992 provide regulatory direction to EPA and NRC. In 1992, Congress provided clarity regarding changes in the roles and responsibilities of the EPA and the NRC resulting from the 1987 legislation focusing solely on the Yucca Mountain Site for disposal of SNF and HLW. The EnPA of 1992 directed the EPA and the NRC to prepare new standards and regulations specific to the Yucca Mountain Site, and WIPP LWA clarified that the generally applicable EPA standards used for the WIPP would not apply to the Yucca Mountain Site. As discussed in more detail above (Sec. II.1.2), the EnPA of 1992 provided specific direction to the EPA and NRC regarding the content of the new standards and regulations for Yucca Mountain, and both acts provided a timeline for the completion of rulemaking activities.

2002 Joint Resolution of Congress approving the Yucca Mountain Site. In July 2002, Congress passed a joint resolution "approving the site at Yucca Mountain, Nevada, for the development of a repository for the disposal of high-level radioactive waste and spent nuclear fuel, pursuant to the Nuclear Waste Policy Act of 1982." Consistent with the requirements of the NWPA, as amended (§116(b)), this law was passed to override the governor of Nevada's disapproval earlier that year of the President George W. Bush's recommendation of the site to Congress. Passage of the joint resolution required the DOE to proceed with submitting an application for construction authorization at the site to the NRC within 90 days (NWPA §114(b)). The 2002 joint resolution placed no constraints on the content of the EPA standards or the NRC regulations for Yucca Mountain, nor did it place any constraints on the outcome of the licensing process.

Current status of federal legislation relevant to EPA and NRC rulemaking for generic disposal standards. In the absence of new legislation, the NWPA, as amended by the NWPAA and as supplemented by the WIPP LWA and the EnPA of 1992, remains the governing statute that EPA and NRC must follow in developing new, generally applicable standards and regulations for the disposal of SNF and HLW.

A.2. Regulation

As noted above, the NWPA tasked the EPA with creating the regulatory standards and tasked the NRC with establishing and enforcing licensing criteria consistent with those standards for repositories developed under the NWPA. The following sections and Table A.1 summarize the history of the actions taken by the EPA and NRC to fulfill these obligations.

Promulgation of initial EPA and NRC regulations as required by the NWPA. Both the EPA and the NRC regulations were to have been promulgated by January 1984, one year after the enactment of the NWPA in January 1983. The NRC had already issued its first iteration of 10 CFR Part 60, Disposal of High-Level Radioactive Wastes in Geologic Repositories, in February 1981 and worked quickly once the NWPA was enacted to have licensing criteria in place in 10 CFR Part 60 by June 1983. Because final EPA standards were not yet available, the 1983 criteria simply noted that, with respect to quantitative long-term performance, releases of radioactive materials must remain within "such generally applicable standards for radioactivity as may have been established by the Environmental Protection Agency." The EPA standards, specifically 40 CFR Part 191, Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes, were promulgated in September 1985, providing the U.S. with a complete regulatory framework for geologic disposal, as envisioned by the NWPA.[2]

The 1987 court-ordered remand of the EPA standard. The regulatory framework for geologic disposal did not remain intact for long. In response to lawsuits brought by the Natural Resources Defense Council and other parties, the U.S. Court of Appeals for the First Circuit found in July 1987 that aspects of 40 CFR Part 191 were inconsistent with the requirements of the Safe Drinking Water Act, and the court vacated those portions of the rule and remanded it to the EPA for further consideration.[3] The court also noted that the EPA had not provided an adequate explanation for selecting the 1,000-year design criterion for the Individual Protection Requirement and that the Ground-water Protection Requirements were promulgated without proper notice and comment. The court rejected other challenges to the rule, but the remand had the effect of leaving the nation without SNF and HLW disposal standards until revisions could be promulgated.

Congressional direction in 1992. Following the remand of 40 CFR Part 191 in 1987, the U.S. disposal program proceeded with evaluation and development of the candidate repository sites at Yucca Mountain in Nevada (for HLW and SNF) and at the WIPP in southeastern New Mexico (for defense-related transuranic [TRU] waste) under the assumption that the EPA would repromulgate final disposal standards in a timely manner. Ambiguity about the regulatory framework for both Yucca Mountain and the WIPP remained until October 1992, when Congress enacted two laws. The WIPP LWA (P.L. 102-579), in addition to transferring formal ownership of the site from the U.S. Bureau of Land Management to the DOE, reinstated those portions of 40 CFR Part 191 that were not affected by the 1987 court decision and directed the EPA to repromulgate the final rule addressing the court's concerns within six months. The act also

2 Nuclear Regulatory Commission, "Part 60—Disposal of High Level Radioactive Wastes in Geologic Repositories," 46 FR 13980 (Feb. 25, 1981); NRC, "Part 60 . . . Subpart E—Technical Criteria," 48 FR 28222 (June 21, 1983); 10 CFR 60.111, in NRC, "Part 60 . . . Subpart E," 48 FR 28223; Environmental Protection Agency, "Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes; Final Rule," 50 FR 38066 (Sep. 19, 1985).

3 Natural Resources Defense Council, Inc., et al. v. U.S. Environmental Protection Agency, et al., 824 F.2d 1258 (1st Cir. 1987).

established the EPA's role as the certifying agency for WIPP, directed the EPA to promulgate certification criteria specific to WIPP, and stipulated that the reinstated requirements of 40 CFR Part 191 would not apply to any site required to be characterized under the NWPA (i.e., Yucca Mountain). The EnPA of 1992 (P.L. 102-486) included provisions directing the EPA to promulgate "generally applicable standards for the Yucca Mountain Site . . . based upon and consistent with the findings and recommendations of the National Academy of Sciences" (§801). The NAS was, in turn, directed by the EnPA of 1992 to conduct a study and provide findings and recommendations to the EPA by December 31, 1993, regarding three aspects of a disposal standard: (1) whether a dose-based standard would be protective, (2) whether active institutional controls at the site can prevent unreasonable risks of exposures to individual members of the public after the repository has been closed, and (3) "whether it is possible to make scientifically supportable predictions of the probability . . . of human intrusion" over a period of 10,000 years. NAS's recommendations and the EPA's rulemaking were specified to apply to only the Yucca Mountain Site. The EnPA of 1992 further directed the NRC to update its licensing requirements and criteria for Yucca Mountain to be consistent with the new EPA standards.

EPA and NRC rulemaking in response to congressional direction of 1992. Consistent with the requirements of the WIPP LWA, the EPA issued a revised version of 40 CFR Part 191 in December 1993 and provided WIPP-specific certification criteria in 40 CFR Part 194 in February 1996.[4]

Consistent with the requirements of the EnPA of 1992, the NAS convened a committee of experts to provide the EPA with findings and recommendations regarding a regulatory standard for the proposed Yucca Mountain Site. Those recommendations were published in 1995 [1] and provided input that both the EPA and the NRC used in subsequent rulemaking. The EPA promulgated a final version of 40 CFR Part 197, *Public Health and Environmental Radiation Protection Standards for Yucca Mountain, NV*, in June 2001. The NRC followed the EPA release of 40 CFR 197 with the promulgation of 10 CFR Part 63, *Disposal of High-Level Radioactive Wastes in a Proposed Geologic Repository at Yucca Mountain*, NV, in November 2001.[5]

2004 Court decision vacates portions of 40 CFR Part 197 and 10 CFR Part 63. In July 2004, the U.S. Circuit Court of Appeals for the District of Columbia found, in adjudicating a case brought by the State of Nevada and others against the EPA, that the 10,000-year compliance period specified in 40 CFR 197 and repeated in 10 CFR 63 was not "based upon and consistent with" the recommendations of the NAS, as required by the EnPA of 1992.[6] The NAS committee had concluded that the timescale of long-term stability at Yucca Mountain was on the order of 1,000,000 years and recommended that "compliance assessment be conducted for the time when the greatest risk occurs, within the limits imposed by the long-term stability of the geologic environment" [1, p. 5]. All other aspects of the legal challenges brought against the EPA and NRC rules for Yucca Mountain were found to be without merit and were dismissed. The court's action effectively vacated both the EPA and NRC rules for Yucca Mountain and returned them to the agencies for revision. No date was set for repromulgation of the rules.

2008 and 2009 Promulgation of final regulatory standards for Yucca Mountain. The EPA addressed the D.C. Circuit Court of Appeals decision in a final version of 40 CFR Part 197 promulgated in October 2008 by extending the regulatory period to 1,000,000 years. With the NRC's subsequent promulgation in

4 Environmental Protection Agency, "Environmental Radiation Protection Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes; Final Rule," 58 FR 66398 (Dec. 20, 1993); EPA, Criteria for the Certification and Re-Certification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations," 61 FR 5224 (Feb. 9, 1996).

5 Environmental Protection Agency, "Public Health and Environmental Radiation Protection Standards for Yucca Mountain, NV," 66 FR 32073–32135; 32074 (June 13, 2001); Nuclear Regulatory Commission, "Disposal of High-Level Radioactive Wastes in a Proposed Geologic Repository at Yucca Mountain, NV; Final Rule," 66 FR 55732 (Dec. 3, 2001).

6 Nuclear Energy Institute, Inc. v. Environmental Protection Agency, No. 01-1258, 373 F.3d 1251 (D.C. Cir. 2004).

March 2009 of a final version of 10 CFR Part 63, the U.S. repository program had a final set of regulatory standards for permanent disposal.[7] The State of Nevada filed suits in the D.C. Circuit Court of Appeals against both the EPA and the NRC,[8] challenging the final rules; the court held those suits in abeyance in 2010 pending congressional resolution of uncertainty regarding the Yucca Mountain licensing process. As of this writing, these suits remain in abeyance, and the regulatory standards in 40 CFR Part 197 and 10 CFR Part 63 remain in effect for Yucca Mountain.

Current status of regulatory standards for disposal of SNF, HLW, and TRU waste. In the absence of additional rulemaking by the EPA, disposal of SNF, HLW, or TRU waste at any site other than Yucca Mountain would be regulated under 40 CFR Part 191. In the absence of additional rulemaking by the NRC, repositories that are not used exclusively for the disposal of wastes resulting from atomic energy defense activities would also be regulated by the NRC under 10 CFR Part 60.

Table A.1. Summary history of U.S. regulatory standards for permanent disposal of HLW, TRU waste, and SNF.

Year	Law, regulation, or event relevant to HLW, TRU, and SNF disposal regulations	Actions for the EPA and the NRC	Date actions completed
1982	NWPA of 1982	Act of Congress establishes roles and responsibilities for the EPA and the NRC	Jan. 7, 1983
1983	NRC 10 CFR Part 60 (generic licensing criteria)	The NWPA requires the NRC to promulgate criteria for licensing "not later than January 1, 1984"	June 21, 1983
1985	EPA 40 CFR Part 191 (generic disposal standards)	The NWPA requires the EPA to promulgate general standards for disposal within one year, by Jan. 7, 1984	Sep. 19, 1985
1987	Federal court decision	First Circuit Court of Appeals remand of 40 CFR Part 191; no date set for repromulgation	July 17, 1987
1992	WIPP LWA	Act of Congress directs EPA repromulgation of 40 CFR Part 191 by Apr. 30, 1993, and promulgation of EPA certification criteria by Oct. 30, 1994	Oct. 30, 1992
1992	EnPA of 1992	Act of Congress requires National Academy of Sciences (NAS) standards report for Yucca Mountain by Dec. 31, 1993; EPA standards one year later, and NRC criteria one year after EPA standards	Oct. 24, 1992
1993	EPA 40 CFR Part 191 revision	EPA repromulgation of generic standards for disposal as directed by Congress in the WIPP LWA	Dec. 20, 1993
1995	NAS Yucca Mountain standards report	As directed by Congress in the EnPA of 1992, NAS report provides findings and recommendations to EPA regarding disposal standards for Yucca Mountain	Aug. 1, 1995
1996	EPA 40 CFR Part 194 (WIPP certification criteria)	As directed by Congress in the WIPP LWA to have been promulgated by Oct. 30, 1994	Feb. 9, 1996
2001	EPA 40 CFR Part 197 (Yucca Mountain disposal standards)	The EnPA of 1992 sets due date of Dec. 31, 1994, for EPA promulgation of Yucca Mountain disposal standards	June 13, 2001

7 Environmental Protection Agency, "Public Health and Environmental Radiation Protection Standards for Yucca Mountain, Nevada; Final Rule," 73 FR 61256 (Oct. 15, 2008); Nuclear Regulatory Commission, "Implementation of a Dose Standard After 10,000 Years; Final Rule," 74 FR 10811 (Mar. 13, 2009).

8 State of Nevada v. U.S. Environmental Protection Agency, No. 08-1327 (D.C. Cir. 2008); State of Nevada v. U.S. Environmental Protection Agency et al., No. 08-1345 (D.C. Cir. 2008); State of Nevada v. U.S. Nuclear Regulatory Commission, No. 09-1133 (D.C. Cir. 2009).

Year	Law, regulation, or event relevant to HLW, TRU, and SNF disposal regulations	Actions for the EPA and the NRC	Date actions completed
2001	NRC 10 CFR Part 63 (Yucca Mountain licensing criteria)	The EnPA of 1992 sets date for NRC promulgation of licensing criteria one year after EPA standards (i.e., June 13, 2002)	Nov. 2, 2001
2004	Federal court decision	Court of Appeals for the District of Columbia vacates portions of 40 CFR Part 197; no date set for repromulgation	July 9, 2004
2008	EPA 40 CFR Part 197 (final Yucca Mountain disposal standards)	EPA repromulgation of Yucca Mountain standards for disposal	Oct. 15, 2008
2009	NRC 10 CFR Part 63 (final Yucca Mountain licensing criteria)	NRC repromulgation of Yucca Mountain licensing criteria	Mar. 13, 2009

A.3. Reference

[1] National Research Council, *Technical Bases for Yucca Mountain Standards*, National Academies Press, Washington, D.C. (1995); doi.org/10.17226/4943.

APPENDIX B. International Overview

In addition to the United States, other countries operating nuclear power plants are confronted with developing and applying safety standards and licensing regulations for safe, final disposal of high-level radioactive waste (HLW)[1] in deep geological repositories. Separate national safety standards and regulations have been formulated for many of these countries, and in some cases been successfully applied in initial licensing steps for national disposal program, such as those in Finland and Sweden.

The purpose of Appendix B is to identify, review, and discuss various national safety standards and licensing regulations, linking such information to proposed recommendations on topics presented in Section III of this report. The diverse historical background, development, and bases for individual, national regulatory approaches, however, are beyond the scope of this overview appendix.

In addition, advisory documents from international agencies, such as the International Atomic Energy Agency (IAEA), the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (OECD NEA), and the International Commission on Radiological Protection (ICRP), are also presented in an overview manner. As this appendix attempts to illustrate, while there is a range in the details across national standards and regulations for the disposal of HLW, there is also broad consensus on many guiding principles and safety policies.

There is no intent by this appendix, however, to suggest that revisions to the Environmental Protection Agency generic disposal standards should match the specific regulatory framework of any other nation.

B.1. International Programs and Agencies

International programs pursuing final geological disposal of HLW are linked to and guided by their national radiological safety regulators. Because of different enabling legislation, societal and cultural perspectives, and past regulatory precedents, diverse international approaches have been implemented in establishing regulatory agencies.[2] This has led to promulgation of international safety regulations that are broadly similar yet distinct in detail.

A leading international advisory agency is the IAEA, having a founding statute that authorizes it to establish or adopt standards of safety for protection of health and minimization of danger to life and property [1, "Background"]. Such standards are continuously reviewed and updated. The IAEA believes international cooperation serves to promote and enhance safety globally by exchanging technical insights and experience. That regulating safety is a national responsibility is clearly recognized by the IAEA. Many

1 HLW and spent nuclear fuel (SNF) are different waste forms but may be disposed of in the same geologic repository. For the purpose of this discussion, HLW is taken to include SNF.

2 A key difference relative to the U.S. is that most nations have a single entity responsible for setting safety standards and licensing, rather than the separated EPA and NRC roles.

smaller member-nations of the IAEA with limited resources to support development of independent safety standards and licensing regulations, however, have adopted the IAEA's safety standards for use in their national regulations.

As the IAEA acknowledges, "National regulations often establish standards and criteria relating to specific indicators (for example, dose or risk indicators), expressed as targets, constraints, or limits. Such indicators may differ from State to State" [1, sec. 4.80].

In response to this diversity in national regulations, the IAEA has become a primary source for summary compilations regarding national implementer and regulatory programs [2].[3] The agency also prepares technical reports regarding topics of mutual interest among nations, for example, identifying, where possible, common approaches to postclosure regulations and safety assessment approaches, as published in "The Safety Case and Safety Assessment for the Disposal of Radioactive Waste" [1], a report that will be extensively cited here. While national differences in specific regulations and terminology are recognized and respected in IAEA reports, there is an attempt made by the agency to identify broad principles and policies on which there is consensus.

The OECD NEA is another collective review organization in which international repository programs, including the U.S., participate [3], [4]. OECD NEA's stated mission is to assist, through international cooperation, its member countries in maintaining and developing the scientific, technological and legal bases that are needed for the safe, economical and peaceful use of nuclear energy.

The ICRP is an independent, international, nongovernmental organization with the mission to protect people, animals, and the environment from the harmful effects of ionizing radiation, including geological disposal [5]. Basic radiological hazard indices for human health are developed through ICRP studies and are continuously updated.

The U.S. Nuclear Waste Technical Review Board (NWTRB) was established in the 1987 Nuclear Waste Policy Amendments Act (NWPAA) with the purpose of providing independent evaluation and advice to Congress and the secretary of energy regarding the technical and scientific validity of the U.S. Department of Energy's implementation of the NWPAA. The NWTRB has published a useful synopsis of postclosure health and safety requirements for HLW disposal based on 13 of the IAEA's country reports [6]. Table B.1 (adapted from the NWTRB report) shows, for example, some key postclosure health and safety requirements of 13 nations. Numerous other tables collated by the NWTRB [6] detail further aspects of these same countries. Table B.2 in this report summarizes national policies on retrievability of disposed waste based on a NWTRB tabulation [6].

Other sources also provide international perspectives on safety standards and their implementation. As a specific example, the Finnish radiological safety regulator STUK published a thorough account of its regulations and bases for decisions regarding Posiva's postclosure safety case [7]. STUK's review supported subsequent acceptance of Posiva's construction license application by the Finnish government. A parallel perspective on that licensing process from the implementor side, which focuses on the need for early, clear, fixed, quantitative compliance requirements, has also been published [8]. On a more general basis, Chapman and McCombie [9] reviewed the development and basis of safety regulations as of that date, with a strong focus on guiding principles and "lessons learned" for the development of newer regulations.

3 This IAEA project is the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, which has published individual country reports since 2003 and is currently updated through the seventh review. meeting of 2022. A searchable database of convention documents can be found at iaea.org/topics/nuclear-safety-conventions/joint-convention-safety-spent-fuel-management-and-safety-radioactive-waste/documents.

TABLE B.1. Summary of some key postclosure health and safety requirements for 13 countries.

Country	Dose constraint	Risk limit*	Compliance period
United States	Yucca Mountain:		
	0.15 millisievert (mSv)/year	Not specified	Less than 10,000 years
	1.0 mSv/year	Not specified	Greater than 10,000 years but less than 1,000,000 years
Belgium	No decision has been made	No decision has been made	No decision has been made
Canada	An upper dose limit of 1.0 mSv/year established; implementer is required to provide a rationale for the dose constraint, which is a fraction of the dose limit	Not specified	Not specified
China	No decision has been made	No decision has been made	At least 10,000 years
Finland	Less than 0.1 mSv/year, for normal events Release limits for various radionuclides established	Not specified	First several thousand years
	Impacts should be comparable to those arising from natural radioactive materials but should remain insignificantly low	Not specified	Beyond first several thousand years
France	0.25 mSv/year for normal scenarios	Not specified	10,000 years
Germany	0.01 mSv/year for probable developments; 0.1 mSv/year for less probable developments	Not specified	1,000,000 years
Japan	No decision has been made	No decision has been made	No decision has been made
Republic of Korea	10 mSv/year for a single scenario, including low-probability natural phenomena and human intrusion	10^{-6}/year for a scenario, which includes natural phenomena and human intrusion	At least 10,000 years
Spain	No decision has been made	No decision has been made	No decision has been made
Sweden	Not specified	Less than 10^{-6}/year for a representative individual in the group exposed to the greatest risk	Minimum of 100,000 years and can extend up to 1,000,000 years
Switzerland	0.1 mSv/year for expected scenarios	10^{-5}/year for expected scenarios	1,000,000 years
United Kingdom	0.5 mSv/year for the operational period	Guidance calls for less than 10^{-6}/year for those at greatest risk	Not specified

Source: Adapted from [6], Table 6 (p. 9).

**The risk limit for a given consequence (e.g., dose constraint) is measured in terms of the probability per year, e.g., 1 in 1,000,000 (or, 10–6/year).*

Applications for initial construction of underground facilities at specific sites for disposal of spent fuel have been accepted by regulatory authorities and national governments in Sweden and Finland; the Finnish site has been approved and repository construction has begun. France and Switzerland are in the processes of evaluating potential sites. All four of these countries have been conducting detailed design and safety assessments since the 1980s and 1990s. Accordingly, subsequent subsections will focus on postclosure aspects of these nations.

B.2. Safety Case

The concept of a "safety case" as applied to regulation of radioactive waste disposal mainly originated in the United Kingdom in the 1990s [10]. It draws a parallel between what should be considered in regulating safe, final disposal and what strategies, actions, evidence, and argumentations are involved in preparing a legal case. The concept was further refined by review groups [2], [4], although similar but slightly different definitions emerged from these separate agencies.

Today, the safety case methodology has been widely applied to radioactive waste disposal programs on low- and intermediate-level waste, borehole disposal of sealed sources and, most relevant to the U.S. situation, HLW disposal. The two recent, successful regulatory licensing of national programs for the disposal of SNF—Finland [11], [12] and Sweden [13]—each adopted and applied a safety case approach.

A guide was prepared by the IAEA to provide guidance and recommendations on meeting the safety requirements with respect to the safety case and supporting safety assessment for the disposal of radioactive waste [1]. It defines a safety case thus:

> The safety case is the collection of scientific, technical, administrative, and managerial arguments and evidence in support of the safety of a disposal facility, covering the suitability of the site and the design, construction and operation of the facility, the assessment of radiation risks, and assurance of the adequacy and quality of all of the safety related work associated with the disposal facility.
>
> The safety case and supporting safety assessment provide the basis for demonstration of safety and for licensing. They will evolve with the development of the disposal facility and will assist and guide decisions on siting, design, and operations. The safety case will also be the main basis on which dialogue with interested parties will be conducted. [1, sec. 1.3]

Note that "safety case" and "safety assessment" are identified and defined as distinct concepts. A "safety assessment" is described by the IAEA thus:

> Safety assessment is the process of systematically analysing the hazards associated with a disposal facility and assessing the ability of the site and the design of the facility to provide for the fulfilment of safety functions and to meet technical requirements. Safety assessment has to include quantification of the overall level of performance, analysis of the associated uncertainties and comparison with the relevant design requirements and safety standards. The assessments have to be site specific since the host environment of a disposal system, in contrast to engineered systems, cannot be standardized . . . . Depending on the stage of development of the facility, safety assessment may be used in focusing research, and its results may be used to assess compliance with the safety objective and safety criteria. [14, secs. 4.10–4.11]

The IAEA has also offered further guidance on the relationship of safety assessments to the overall safety case:

> 5.13. The safety case for the period after closure should be based on quantitative analyses and should be further supported by qualitative arguments. It may include the presentation of multiple lines of reasoning based, for example, on studies of natural analogues and palaeohydrogeological studies. A major part of the safety case is concerned with demonstrating that consideration has been given to all the important uncertainties. [15]
>
> 5.14. The regulatory body should stipulate or provide guidance concerning timescales for safety assessments. Comparison of calculated doses or risks to dose limits or risk limits specified in regulatory requirements may be required for at least several thousand years and may be extended to timescales beyond this, for example, to estimate peak dose. However, it is recognized that for timescales beyond several thousand years, uncertainty concerning future conditions of the geosphere and biosphere is such that reference calculations based on appropriate simplifying assumptions may be sufficient, with account taken of scenarios for evolution of the natural characteristics of the disposal system and "stylized" approaches (i.e. under certain prescribed conditions) to human behaviour and characteristics, for example, using reference biospheres. [15]
>
> 5.17. Calculations of doses and/or risks will be undertaken over the time periods and for the exposure scenarios specified in regulatory requirements. Regulatory criteria will typically specify characteristics of exposed groups or individuals to be used in dose calculations (the concepts of critical group and average member of the critical group have been used in some States in specifying exposure scenarios). For very long timescales for which dose estimates can be very uncertain, complementary arguments may be useful to illustrate safety, for example, safety indicators, such as concentrations and fluxes of radionuclides of natural origin. [15]

With respect to defining the role of complementary considerations, the national Finnish program Posiva Oy states the following:

> Complementary considerations are evaluations, evidence and qualitative supporting arguments that lie outside the scope of the other reports of the quantitative safety assessment. These arguments include, for example:
>
> 1. Support from natural systems for both key process understanding and total system performance;
> 2. Comparison of the methodology and results of safety cases made for other repository projects to ensure comprehensiveness, consistency and reasonableness of the present assessment;
> 3. Simplified bounding analyses of extreme, unrealistic cases for scenarios not considered in the quantitative safety assessment;
> 4. Use of safety indicators other than dose to avoid having to take account of uncertainties in future human lifestyles (e.g. food production and consumption);
> 5. Use of complementary indicators that avoid having to account for biosphere evolution and geological processes on very long timescales;
> 6. Consideration of the calculation results from a wider perspective to consider significance of their assessed impact on human health and the environment compared with other risks. [16, pp.14–16] . . .

> . . . [C]omplementary arguments can also be made to address other aspects of safety, especially continuing isolation, even at times beyond when quantitative safety assessments can be supported. [16, p. 17]

When such guidance and recommendations are merged, there is a clear need for quantitative analyses to demonstrate compliance with dose/risk standards for an initial period of several to many thousands of years. Qualitative complementary considerations and evidence can and should support such compliance analyses.

At longer timescales, however, increasing uncertainties regarding future conditions of the geosphere and biosphere argue for simpler, stylized assessments. Such stylized safety assessments necessarily rely more on complementary evidence (e.g., natural analogs), bounding assumptions, and multiple lines of reasoning. Supplemental safety indicators, in parallel with speculative dose calculations to future humans with unknown characteristics and behavior, might be considered. An example of an alternative safety indicator from international groups is comparison of future radionuclide releases from the repository to the geosphere (so-called geosphere-biosphere interface) with known concentrations or fluxes of naturally occurring radionuclides crossing the same barrier [16, 17]. This could allow the significance of the repository releases to be assessed within the context of the natural background radiation of the environment without needing to consider exposure of a hypothetical future human population.

The IAEA clarified:

> As a minimum, the safety assessment is to be updated in the periodic safety review carried out at predefined intervals in accordance with regulatory requirements. [1, sec. 3.11]

They also acknowledged the following as further confirmation:

> The concept of developing a safety case for disposal facilities . . . is used in many States. The terminology used is different, though, in some States. For example, in the United States of America the term "total system performance analysis" is used (together with the regulations relevant to the specific disposal method), covering all aspects of the safety case as described in this Safety Guide. [1, sec. 1.2n2]

Previous U.S. safety regulations and licensing guidelines by the EPA and the Nuclear Regulatory Commission were promulgated prior to the advent and widespread use of the safety case terminology and method; hence, previous U.S. regulations do not explicitly use the safety case terminology. In 2003, the National Academies of Sciences, Engineering, and Medicine examined this situation:

> When comparing these [U.S. regulations] with the characteristics of the safety case, the technical content appears to be equivalent. The primary differences are that the safety case presents key safety arguments understandably by a wider audience and it is updated more often. [18]

It is notable that recently the NRC [19], in its current draft of 10 CFR Part 61 for the disposal of low-level radioactive waste, has begun to include the use of the term "safety case":

> 1.1.2 Safety Case
>
> Section 10 CFR 61.2 defines a safety case as a collection of information that demonstrates the assessment of the safety of a land disposal facility. This includes the technical analyses discussed in Section 1.1.4, as well as information on defense-in-depth and supporting evidence and reasoning on the strength and reliability of the technical analyses and the assumptions made therein. The safety case also includes a description of the safety relevant

aspects of the site, the design of the facility, and the managerial control measures and regulatory controls. [19, p. 1–3]

The application of this definition of "safety case" for the comprehensive set of information that satisfies regulatory requirements in a future revision to 10 CFR Part 60 would semantically align it with usage in other national programs. It must be stressed, as the NASEM has [18], that past NRC regulations have been equivalent to the content of 'safety case' as defined internationally.

B.3. Dose/Risk Criteria

Consistent with the ANS Committee's recommendation above (Sec. III.1.1), the IAEA endorses use of dose and risk criteria in safety requirements [1, sec. 4.22].

Table B.1 further confirms specific dose and risk requirements that have been established by 13 leading international disposal programs. Dose criteria range from 0.1 to 1 mSv per year (10–100 mrem per year), and it is noteworthy that some national programs identify different dose values for different time periods or for consideration between expected and less probable scenarios for the disposal system far into the future. In addition, Finland's safety regulations adopt the view that potential far-future releases should more appropriately be compared to natural radiological fluxes in the environment rather than to hypothetical doses to people at such remote time periods.

Early safety standards for geological disposal of radioactive waste from the 1980s used ICRP dosimetry values based on 1950s data. These data, however, have been significantly updated based on the best-available scientific evidence that has been peer-reviewed by the ICRP. International safety standards for geological disposal, other than those in the U.S., are now, appropriately and uniformly, based on modern ICRP's dose-conversion factors [21], [22].

Following earlier ICRP guidance [22], the IAEA recommends the following:

> 5.31. For long term dose assessments, it can be assumed that radioactive contamination of the biosphere due to releases of radioactive material from the disposal facility is likely to remain relatively constant over periods that are considerably longer than the human lifespan. It is then reasonable to calculate the annual dose or risk by averaging over the lifetime of the individuals, which means that it is not necessary to calculate doses to different age groups; the average annual dose can be adequately represented by the annual dose or risk to an adult.
>
> 5.32. It should be ensured that the characteristics assumed for the individuals in the group are consistent with the capability of the biosphere to support such a group. For example, depending on the assumed environmental conditions (location, climate, etc.), the agricultural capacity or other productivity of a particular setting may limit the size of the group that can reasonably be expected to be present. [1]

More recently, the ICRP has stated:

> (93) As stated in Publication 101 (ICRP, 2006 [22]), for the purpose of protection of the public, the representative person corresponds to an individual receiving a dose that is representative of the more highly exposed individuals in the population. Therefore, it should be assumed that the representative person is located at the time and place of the maximum concentration of radionuclides in the accessible biosphere, with due regard to the assumed climatic conditions for that evolution scenario (e.g., considerations of ice coverage). This is an assumption as humans may no longer inhabit these areas in the distant future.
>
> (94) A representative person cannot be defined independently of the assumed biosphere. Major changes may occur in the biosphere in the long term due to the action of natural

> forces in a similar manner to those occurring in the past. Human actions may also affect the biosphere, but one can only speculate about human behaviour in the long term. In the definition of the scenarios, consideration of biosphere changes should be limited to those due to natural forces. A representative person and biosphere should be defined using either a site-specific approach based on site- or region-specific information, or a stylised approach based on more general habits and conditions; the use of stylised approaches will become more important for longer time scales. [23

B.4. Risk-Informed, Reasonable Assurance, and Reasonable Expectation

The concept of "risk informed" that characterizes current U.S. safety regulations can be found in international safety case reports:

> The results of the safety assessment shall be used to specify the programme for maintenance, surveillance and inspection; to specify the procedures to be put in place for all operational activities significant to safety and for responding to anticipated operational occurrences and accidents; to specify the necessary competences for the staff involved in the facility or activity and to make decisions in an integrated, risk informed approach. [1, sec. 3.17]

> Within the step by step approach, the scientific understanding of the disposal system and the design of the disposal facility should be progressively advanced, and the safety case should become more focused on key areas of concern. It should not only be scientific understanding that is advanced, but also an understanding of the important contributors to risk. [1, sec. 4.13]

> The scientific considerations underlying the IAEA safety standards provide an objective basis for decisions concerning safety; however, decision makers must also make informed judgements and must determine how best to balance the benefits of an action or an activity against the associated radiation risks and any other detrimental impacts to which it gives rise. [1, "Foreword"]

With respect to reasonable assurance and risk reduction, the IAEA states the following:

> There is reasonable assurance that the doses and/or risks resulting from the expected evolution of the disposal system will not exceed the constraints, over time frames for which the uncertainties are not so large as to prevent meaningful interpretation of the results. The likelihood of events that might disturb the performance of the disposal facility so as to give rise to higher doses or risks has been reduced as far as is reasonably possible by siting and design. [1, sec. 4.67]

Regarding the EPA and NRC acknowledgment that "proof of future performance of a disposal system is not to be had in the ordinary sense of the word" (discussed above in Sec. III.1.2), the IAEA also affirms:

> It is recognized that radiation dose to individuals in the future, including those that may occur after institutional management of a waste disposal facility has ceased, can only be estimated. Nevertheless, estimates of possible doses and risks for long time can be made and used as indicators for comparison with the safety criteria. [1, sec 3.10n7]

B.5. Regulatory Time Period for Quantitative Standards

Figure B.1 presents a schematic, summary representation for timescales related to key time-dependent factors affecting safety assessments, developed by an international group of repository programs for the OECD NEA [3].

Four basic "elements" considered within a repository safety assessment are identified by the OECD NEA group. These are the engineered barrier system (EBS) and surrounding host rock, the hydrogeological system, surface processes, and radiological exposure modes.[4] Laterally, potential changes to these repository elements are represented as arrows indicating the approximate range in time over which changes might occur for a specific site. In a qualitative manner, potential changes (representing uncertainties in this element) arising at earlier times are shown on the right side of the figure, and those changes/increasing uncertainties arising at later times are shown on the left.

Of particular relevance to establishing a timescale for regulatory requirements, estimated time ranges for confidence (predictability[5]) in each of the four elements are presented by the OECD NEA as vertical bars [3]. The fading of the bars is meant to suggest limits to predictability, attributable to likelihood of the identified changes. Of particular note is the extremely short time interval (decades) for which radiological exposure models, dependent on changing human and environmental factors, can be applied with confidence.

Thus, there is a clear distinction in confidence between potential rapid change in future human behavior and the present-day environment, versus much higher confidence in the estimated future behavior and isolation performance of a geological site. Indeed, reliance of isolation and long-term, passive safety imposed by the geological site is a fundamental argument for permanent, deep geological disposal [9].

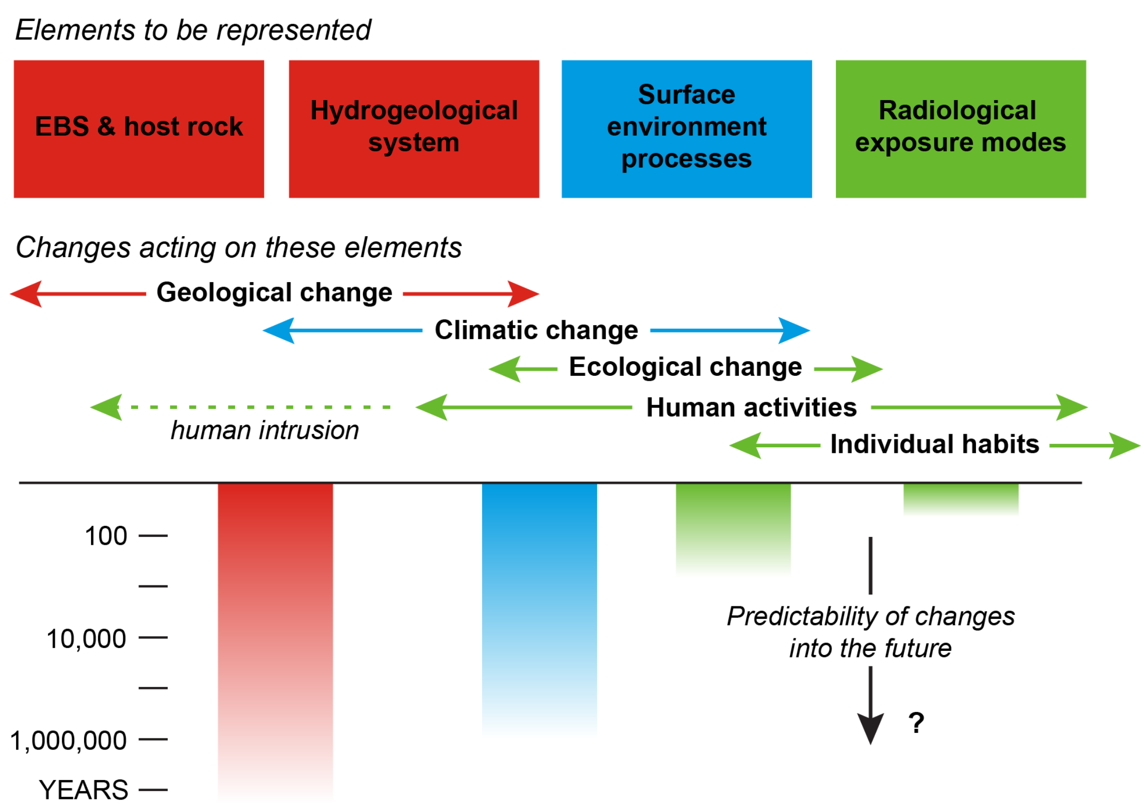

Fig. B.1. Time-dependent factors affecting safety assessment modeling. (Source: [3], p. 28, Fig. 2.3).

4 Of course, different types of sites and repository concepts will affect estimated long-term performance.

5 This term of "predictability" misunderstands that the purpose of safety assessments is not to provide precise predictions of future behavior but rather to provide broad estimates of future safety.

Regarding time periods for quantitative and qualitative assessments, the IAEA states the following:

> In view of the complexity and variability of [many uncertain] factors, it is not possible to establish a universal timescale over which meaningful quantitative results from modeling can be obtained . . . . For deeper facilities, such as geological disposal facilities for high-level waste, modelling for periods of tens of thousands of years and beyond may still result in meaningful estimates of upper bounds of possible radiation doses. [1, sec. 6.45] . . .
>
> The safety case should also address the evolution of the disposal facility and its potential impacts for times beyond the end of the safety assessment calculations, if at that point in time nonnegligible hazards are still expected to exist. This should be done by means of simplified estimates and qualitative arguments rather than through the application of quantitative safety criteria. For example, for deep geological disposal facilities, this may be done by using arguments about the geological stability of the site. [1, sec. 6.49]

Several ICRP reports on dose/risk analyses stress that

> The process of evaluating the potential exposure from emplaced waste includes understanding the potential mechanisms of radionuclide release from the engineered facility, including modelling transport through the geosphere to the biosphere, and the resultant release into an appropriate environmental compartment that could give rise to exposures to humans and the environment. Depending on the level of knowledge, probabilities may be estimated for these release scenarios. However, at the long time scales considered in geological disposal, evolution of the biosphere and, possibly, the geosphere and the engineered system will increase the uncertainty of these probabilities. Hence, the results of any dose or risk assessments need to be interpreted in a qualitative way at long timescales. [23, sec. 53]

and

> However, Publication 103 [The 2007 Recommendations of the International Commission on Radiological Protection] also warns that effective dose loses its direct connection to health detriment for doses in the future after a time span of a few generations, given the evolution of society, human habits, and characteristics. Furthermore, in the distant future, the geosphere, the engineered system and, even more so, the biosphere will evolve in a less predictable way. The scientific basis for assessments of detriment to health at very long times into the future therefore becomes uncertain, and the strict application of numerical criteria may be inappropriate. In the very long term, dose and risk criteria should be used for the comparison of options rather than a means of assessing health detriment. [23, "Executive Summary" (f)]

Thus, the guidance from international organizations is that safety standards and licensing regulations need to recognize the inherent uncertainties and changes in time-dependent factors, notably human behavior, affecting repository safety assessment. Accordingly, two basic timeframes can be envisioned for postclosure regulatory safety assessments:

- Quantitative, risk-informed assessment over a time period from permanent closure to a future time for which assuming future human activities and associated biosphere can be reasonably linked to a present-day conditions (perhaps on the order of several thousand years up to 10,000 years).
- Analyses in which concerns regarding possible scenario-initiating events are evaluated more qualitatively and comparatively within a risk-considered framework in which safety relies more on the stability/resilience of the geological site and physical-chemical constraints (e.g., solubilities of radioelement-bearing solids, including the UO2 matrix of spent fuel) imposed by the site host rock.

B.6. Human Intrusion

The "collect-and-consolidate" principle that underlies disposal of radioactive waste in deep geological repository systems is internationally recognized and accepted as the most appropriate means of safely isolating such wastes from the biosphere [9]. The potential for future intrusion and disturbance of such a concentrated repository, however, is an unavoidable consequence of this guiding principle.

It has been long accepted by the international waste management community [18] that regulatory requirements should not seek to protect future societies from intentional intrusion; rather, they should focus on measures to minimize the probability (thus, consequences) of speculative, inadvertent human intrusion.

Different approaches to setting standards for the possibility of future inadvertent intrusion into a geological repository have been cogently reviewed [9], [14], [20], [24]. Two leading approaches have been implemented and successfully conducted in several countries.

In the first approach, during siting the implementor would be tasked to demonstrate in selecting a site that appropriate consideration has been made to minimize intrusion probability. This would be achieved by evaluating and giving preference to a site with negligible exploitable resources. There would be no requirement to conduct quantitative analyses of a hypothetical intrusion, or to consider human intrusion in the final licensing of such a selected site. According to the IAEA:

> Consideration has to be given to locating the facility away from significant known mineral resources, geothermal water, and other valuable subsurface resources. This is to reduce the risk of human intrusion into the site and to reduce the potential for use of the surrounding area to be in conflict with the facility. [14, sec. 3.20]

For example, the successful license applications for both the Finnish and the Swedish repositories initially addressed human intrusion requirements by locating their respective repositories at great depth at sites where the host rock can be assumed to be of no economic interest to future generations, so that the risk of human intrusion was minimized. Furthermore, the role of surface plugs and borehole seals in their KBS-3 design concept is to close off any connection to the surface and to limit the likelihood of inadvertent human intrusion in the repository.

An alternate approach, typically required in addition to the siting approach, is to conduct a stylized analysis, as described by the ICRP:

> Because the occurrence of human intrusion cannot be totally ruled out, the consequences of one or more typical plausible stylized intrusion scenarios should be considered by the decision maker to evaluate the resilience of the repository to potential intrusion . . . . Since no scientific basis exists for predicting the nature or probability of future human actions, it is not appropriate to include the probabilities of such events in a quantitative performance assessment that is to be compared with dose or risk constraints. [24, sec. 62]

The IAEA addresses this same alternative approach:

> It is not possible to predict the behaviour of people in the future with any certainty, and its representation in assessment models is necessarily stylized . . . .
>
> The possibility exists that in the future, an activity or activities undertaken by people could cause some type of intrusion into a disposal facility for radioactive waste. It is not possible to say definitively what form such an intrusion will take or what the likelihood of the intrusion event will be, owing to the unpredictability of the behaviour of people in the future. Nevertheless, the impact of certain generic intrusion events, such as construction work, mining, or drilling, can be evaluated as reference scenarios. [14, secs. A.5, A.6]

The Swedish license application, for example, included analysis of human intrusion scenarios resulting in a degradation of system performance. Under Swedish regulations, such stylized scenarios were to be considered as "less probable" and the analyses not included in the risk summation [13]. In a similar manner, Finnish safety regulations required analysis of unintentional disturbance of or intrusion into the repository by humans subsequent to repository closure [12]. Uncertainties in the evolution of human society and of the state-of-the-art in science and technology were noted. Estimates of consequences of human intrusion scenarios were based on "stylized assumptions" that were acknowledged as unable to be fully substantiated or evaluated in respect to conservatism of radiological consequence estimates. Such illustrative analyses were therefore treated as a class of speculative scenarios, separate from repository assessment scenarios.

B.7. Multiple Barriers/Safety Functions/Features, Events, and Processes

Internationally, past formulation of a "multiple barriers" requirement to assure long-term isolation and safety of disposed radioactive waste has been updated by the "multiple safety functions" approach. This safety function approach has been adopted and applied by regulatory agencies and disposal programs leading to successful review and approval of construction license applications for disposal of spent fuel [12]. A safety function is a feature of the disposal system that provides a specific function that is relevant to the performance (or safety) of the system. The set of these safety functions presents a high-level summary of the strategy by which the performance of the disposal system is assured.

With respect to safety functions, the IAEA recommends the following:

> The host environment shall be selected, the engineered barrier of the disposal facility shall be designed . . . to ensure that safety is provided by means of *multiple safety functions* [emphasis added]. Containment and isolation of the waste shall be provided by means of a number of physical barriers of the disposal system. The performance of these physical barriers shall be achieved by means of diverse physical and chemical processes . . . . The capability of the individual barriers . . . shall be demonstrated. The overall performance of the disposal system shall not be unduly dependent on a single safety function. [14, "Requirement 7: Multiple safety functions"]

The connection between multiple barriers and multiple safety functions as a defense-in-depth is evident. A main reason for evolving to multiple safety functions is that this methodology has been found to provide a technical, transparent approach to development of scenarios between the applicant and regulators, as well as enhance overall communication of safety with stakeholders during licensing [12], [13]. This approach also focuses attention on a system of multiple barriers and processes that act in concert to provide confidence in long-term safety.

The safety function approach also links to the previous use of features, events, and processes (FEPs) to identify conditions that may occur in the future, and that may affect the ability of the disposal system to perform successfully. While FEP analyses have been widely conducted by HLW repository programs, they have also been identified to have a number of drawbacks [25]. In particular, as a bottom-up approach, a FEP-based approach seeks to identify all conditions of concern without necessarily focusing on key safety-significant/risk-informed issues. In contrast, the safety function approach is "top-down," in which environmental perturbations arising from any credible scenario-initiating event can be evaluated on the basis of their impact on intended safety functions of different barriers. In this way, "categories" for different scenarios based on impacts to safety functions can be identified and analyzed.

There has been increasing emphasis in the performance assessment literature and construction license applications on the use of the top-down safety-functions approach as an augmentation to FEP analyses [25]. In particular, the safety-functions approach has proved effective in attaining regulatory closure on "What if?" scenarios and contentions in the context of licensing [12], [13].

It is noted that the NRC, regarding the disposal of low-level waste, has begun to use the "safety function" concept in alignment with FEPS analyses:

> Formal approaches to scenario development are usually either bottom-up or top-down (see Section 2.5.3 for more detail). The bottom-up approach involves the identification, categorization, and systematic screening of FEPs. The bottom-up approach is commonly used for complex sites. The top-down approach uses analyses such as a safety assessment and the identified safety functions to develop scenarios. Both approaches may be iterative. . . . A safety function is defined as a function through which a component of the disposal system contributes to safety and achieves its safety objective throughout the analysis timeframe. Safety functions are used in the top-down approach to scenario development. [19, pp. 2.33–2.34]

B.8. Monitoring and Retrievability

Monitoring of a site includes activities starting with site characterization through the operational/waste emplacement phase, to final sealing and closure of a repository [1, sec 1.22]. The IAEA presents general principles and recommendations with respect to monitoring and surveillance for activities up to the point of permanent closure of a repository:

> 2.10. The development of a disposal facility usually involves an extensive programme of research, design and assessment work that may last for several years or decades. Once established, a disposal facility may be operated for several more decades. The lifetime of a radioactive waste disposal facility may be defined in three periods: the pre-operational period, the operational period and the post-closure period:
>
> - Activities commonly undertaken during the pre-operational period include the development of the disposal concept and the safety strategy, site evaluation (selection, verification and confirmation), environmental impact assessment, initial design studies for the facility, the development of plans for research and development and monitoring, and the development of the detailed facility design. Licensing and construction of the facility also take place in this period.
> - The operational period begins when waste is first received at the facility and continues up to the final closure of all parts of the facility. Radiation exposures may occur in this period as a result of waste management activities and these are, therefore, subject to regulatory control in accordance with requirements for radiation protection and safety of workers. Safety assessment, monitoring, and research and development programmes should be used to inform management decisions on the operation and closure of the facility. During the operational period, construction activities may take place at the same time as waste emplacement in and closure of other parts of the facility.
> - The post-closure period begins after the facility is closed. After closure, a period of institutional control may contribute to the safety of certain disposal facilities (in particular, near surface disposal facilities). [1]
>
> 4.47. The operator should demonstrate that, to the extent possible, the safety of the disposal system is ensured by passive means. This means that no active components or actions (e.g. monitoring) are necessary for the long term safety of the facility, . . .
>
> 4.48. In the design of the facility, passive safety measures are required to be taken into account to minimize the dependence of safety on active systems during operation and after closure. [1]

> 4.74. The safety case and supporting assessment should also be used to establish a monitoring and surveillance programme for the site and the surrounding area that is appropriate for the specific disposal facility and for subsequent review of the programme. Surveillance and monitoring programmes should be developed and implemented to provide evidence for a certain period of time that the disposal facility is performing as predicted and that the components are able to fulfil their safety functions. [1]

Note that for the postclosure period, the safety of the disposal system is provided by means of passive features inherent in the characteristics of the site and the engineered barriers and does not rely on continued monitoring. Institutional controls, however, will likely be put in place to prevent intrusion into facilities for a designated time after closure. Hypothetically, a far-future, postclosure decision for continuation of monitoring and surveillance will be made on whether that future society seeks further confirmation that the disposal system is performing as expected.

One of the rationales for monitoring during the preclosure/operational period is that evidence may be found supporting a decision to retrieve some or all of emplaced waste. Another reason for making a retrieval decision might be for the purpose of recycling spent/used fuel.

The IAEA provides guidance on considerations related to a preclosure decision on retrievability of waste:

> 6.76. The introduction of measures to facilitate retrievability does not lessen the need for a thorough safety assessment and may introduce the need for additional assurances regarding certain operational aspects (e.g. the long-term durability of waste packages under operational conditions before closure of the facility; provisions for facility closure). In particular, retrievability should not be made an excuse for an indefinite delay in making decisions concerning the development of the disposal facility and is not a substitute for a well designed and well sited disposal facility for which the basis for closure of the facility at the end of its lifetime can be justified. Clear plans for development of the disposal facility, including its closure, should be prepared even if flexibility is allowed to future decision makers in their implementation of the plans. Safety assessment calculations should be made to determine the consequences of failure to close the disposal facility as originally intended.
>
> 6.77. If retrievability of waste is a design option, the safety case should address administrative and technical arrangements that ensure that: an appropriate level of technical ability to retrieve waste is maintained at each stage following emplacement of the waste; the methods for retrieval are specified; and periodic evaluations are made of the appropriateness and necessity of proceeding with the next step towards closure of the facility, maintaining the facility at the current step, or reversing a step, including retrieval of the waste if necessary. The safety case should further address monitoring provisions to verify that the conditions under which retrieval could be performed safely prevail.
>
> 6.78. In most States, regulatory guidelines have not yet been issued on when retrieval is necessary and how requirements for retrievability, if any, should be implemented. Where retrievability is mentioned in national regulatory guidelines, there is usually an overriding requirement that any measures to enhance retrievability should not compromise the passive long term safety of a disposal facility. [1]

The technical feasibility of waste package retrieval has already been demonstrated for certain disposal concepts, such as the so-called KBS-3 concept planned in Sweden and Finland, basically using similar methods as employed for emplacement of the waste packages [26]. In addition, it has been pointed out that retrieval of wastes in a deep mined repository is always technically possible [27], albeit at costs and radiological exposure of workers that depend on factors such as design, age of the deeply emplaced waste packages, radiation shielding of packages, and so forth.

The NWTRB summarized requirements/current views for 13 countries regarding retrievability of HLW, collated and presented here as Table B.2.

Plans, disposal designs,[6] and requirements regarding retrievability, are often a key issue with respect to stakeholder concerns [9] or related to considering retrieval for the possible reprocessing of spent fuel and re-cycle of fissile materials. It is worth noting there are proposed international disposal concepts based on already-licensed dry-cask technology that permit immediate, safe, inspectable storage of dual-purpose disposal containers in open, excavated caverns, equivalent to safe dry cask storage at the surface. This concept permits a decision to be made at a later time, to either backfill the cavern for final disposal, or to readily retrieve the waste back to the surface [28].

TABLE B.2. Requirements on retrievability of waste.

Country	Requirements for retrievability
Belgium	No decision has been made. A June 3, 2014, law requires that retrievability requirements need to be defined in the national policy.
Canada	In the Adaptive Phased Management plan, retrievability of the canisters is not planned after their emplacement in the repository. However, retrieval of the canisters is allowed if needed for safety or other reasons. This requirement has not yet been incorporated into regulations.
China	No decision has been made.
Finland	The government's Decision-in-Principle (2000) included a retrievability requirement that the regulator later removed. The government reimposed this requirement as a condition of the license to construct the repository.
France	The repository must be designed so that it is "reversible" for the entire life of the repository. Reversibility is a management concept that requires technical retrievability.
Germany	The repository design must provide for retrieval of waste during the operational period and the possibility of recovery for 500 years after repository closure (Site Selection Act).
Japan	Retrievability should be ensured until closure of the repository.
Republic of Korea	No decision has been made, but in the conceptual-level Korea Reference Disposal System, waste packages had to be retrievable for an indeterminate period.
Spain	No decision has been made for an HLW/SNF repository.
Sweden	While there are no regulatory requirements for retrievability, measures for retrieving waste during operations and postclosure can be implemented.
Switzerland	The design of the repository must accommodate the retrieval of canisters without "undue effort" until closure. Retrieval or partial retrieval of waste must be possible if the safety of repository is compromised and the barriers cannot be repaired.
United Kingdom	Guidance does not require waste to be retrievable. However, if provisions for retrievability are included in the repository design, these provisions should not affect the safety case.
United States	Repository must be designed so that any or all of the emplaced waste could be retrieved on a reasonable schedule starting at any time up to 50 years after waste emplacement operations are initiated.

Source: Adapted from [6].

6 E.g., at-depth cavern-retrievable (CARE) disposal concepts involving delayed backfilling have been specifically designed to promote and assure ease of long-term retrievability, enhancing programmatic flexibility with respect to addressing stakeholder concerns and final management decisions.

B.9. Knowledge Management Systems

The knowledge base for radioactive waste management has grown exponentially since the 1980s when the generic U.S. safety standard and licensing regulation were first established. This expansion of data and experiences has been driven not only by work in the United States but internationally, as many national disposal programs have been instituted and advanced over the last 40 years. The size and pace of this growth is a potential cause for concern for both implementing and regulatory agencies having an expected functioning period of many decades, as original workers retire and new staff are employed. To assure the strategic importance of retaining past knowledge for the multidecade endeavor of conducting and regulating a national geological disposal program, the need for formal, computer-based knowledge management systems (KMS) is now recognized [29], [30]. The aim of such a KMS is to facilitate intergenerational transfer of knowledge, decisions, and the bases for decisions, not only for implementing organizations, but also for regulatory agencies.

B.10. Summary

National standards and requirements for geologic disposal differ from one another, reflecting different enabling legislation, societal and cultural perspectives, and past regulatory precedents. Nevertheless, for many key elements of national standards there has been a broad convergence over the years, reflecting the development of technically sound and practical approaches that are informed by scientific work and stakeholder interactions. This convergence is reflected in reports and recommendations from the IAEA and other international organizations. Revisions and updates to U.S. standards should be informed by the current state of knowledge and best practices reflected in national and international standards.

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APPENDIX C. Characteristics of Future Human Society Assumed in Geologic Repository Standards

C.1. Introduction

Assumptions about the uncertain characteristics of far-future human societies will be necessary for assessments of compliance and should be well understood up-front during the development of geologic repository standards. Rather than attempting to address the infinite number of potential types of future society, the ANS Committee considered three potential future societies, described below. This evaluation informed the ultimate recommendations on appropriate assumptions for characteristics of future societies for demonstrations of compliance with repository environmental standards.

C.2. Background

It is generally accepted that the current generation has a responsibility to deal with its own waste products in a manner that will protect not only themselves but future generations. Accordingly, postclosure geologic repository standards are developed with the intent of protecting people who will not exist until many years in the future.

The primary hazard a repository poses to future inhabitants is the release of long-lived radionuclides into the biosphere where exposure of humans to radiation could increase the risk of premature death due to cancer. Of interest in calculating dose rates to future humans living in the vicinity of the repository are the "vectors" for radionuclide transfer within the biosphere. The major transfer vectors are radionuclide transfer via ingestion (e.g., drinking water, production and consumption of crops and livestock using contaminated groundwater, and edible aquatic species living in contaminated waters); inhalation of airborne radionuclides; and external exposure from radionuclides present in the soil. Based on performance assessments performed on many different repositories, the dominant vector is almost always contaminated groundwater. Radionuclide exposure via this vector will occur only if the society does not have an ability to detect harmful constituents in the water and avoid its use.

Public health and safety regulations typically assume that current human and societal behaviors relevant to radionuclide transfer vectors persist for the duration of the regulation, except that no credit is given for detecting and avoiding radiation. Standards are chosen to be sufficiently protective of humans based on those behaviors. That approach makes sense when addressing enterprises relatively short in duration (e.g., nuclear power plants, which are licensed to operate for 40 years, albeit with the possibility—or even expectation—of one or more 20-year license renewals). That may not be so reasonable for regulations requiring dose assessments for longer timespans, such as low-level waste repositories (effectively regulated for 1,000 years under 10 CFR Part 61), underground injection wells (effectively regulated for 10,000 years under 40 CFR Part 148), or high-level waste repositories (effectively regulated for 10,000 years under 40 CFR Part 191 or for 1,000,000 years at Yucca Mountain, under 40 CFR Part 197).

C.3. Future Human Characteristics

The theory of evolution holds that species, including humans, evolve over time, so that their biophysical characteristics change. Current thinking is that Homo sapiens (modern humans) evolved in Africa during a time of dramatic climate change approximately 300,000 years ago [1]. While human society has changed markedly since then, the physiological characteristics of Homo sapiens have not. However, the possibility that the intrinsic characteristics of humans could change again in a significant manner cannot be completely discounted. If repository performance were to be assessed only in the present or the immediate future, the probability of human evolution can be assumed to be vanishingly low.

From the standpoint of geologic repository public health and safety standards, an evolution in human biophysical characteristics would be important only if it affected the potential for harm to humans from exposure to radiation originating in material emplaced in a repository. For example, if future humans evolved to be more resistive to DNA damage from ionizing radiation, the hazard posed by repository material would be reduced and the level of protection could potentially be relaxed. It is not possible to know if any human evolution will take place in the time frame of interest, or, if it does, what type of changes would result. Therefore, from a practical perspective, it should be assumed that future humans will be as susceptible to harm from radiation as current humans.

C.4. Future Human Society

While the human species is relatively stable, human societies are not. The characteristics of societies that affect use of water and other resources in the biosphere have varied dramatically over the past several millennia. Even today, there are many different types of societies across the globe. The technological level of the given society will affect the likelihood those inhabitants would, among other radionuclide transfer vectors, use contaminated water supplies on a large scale. In addition, the technological level of future societies will impact the ability to detect radionuclides in water, soil, air, and food products and mitigate the effects of cancer.

For almost the whole time *Homo sapiens* has been present on the planet, people lived in small hunter-gatherer tribes with a very low level of technology, which affected the types of potential radionuclide transfer to humans. For example, lack of agriculture would mean that irrigation of crops and animal husbandry using contaminated water resources would not occur. Consumption of local wildlife and plants would require consideration of how radionuclides would transfer into those species via other pathways. Historically, life spans were very short, compared with those of today. Diseases that primarily afflict older humans (e.g., heart disease and cancer) were largely irrelevant due to the fact that people usually died of other causes before such diseases could arise. Over the past 10,000 years technology has improved as humans developed agriculture and animal husbandry practices. People began to use a wider range of water supplies. In the developed world, the average life span has lengthened to generally exceed 70 years, which results in longer exposures to radionuclides entering the biosphere. If technology continues to advance at the current rate, human societies of the future could soon be unrecognizable to us. Of course, there is no guarantee that the human race will continue to advance and thrive. Factors such as warfare, disease, and ecological change could reverse the current course and send humans back to technological levels characteristic of earlier times—or even extinction.

Paraphrasing a Danish proverb, Dr. Niels Bohr once observed that “prediction is very difficult, especially if it’s about the future.” Fortunately, in order to develop a public health and safety regulation that will be reasonably protective of future humans living near a geologic repository, it is not necessary to know everything about those people. The necessary knowledge about a future society that would impact doses received by repository neighbors is limited, and there are some reasonable suppositions that can be made relative to those future conditions. These include radionuclide transfer vectors for which transfer data exist or can be collected. Rather than trying to imagine every possible future society, we can bin potential future human societies into three rough groups based on technological capability: low, similar to current, and advanced. The low-technology possibility, referred to herein as the "Flintstones" group,[1] is consistent with human behavior from the hunter-gatherer era, prior to the development of agriculture and animal husbandry. The more current technology possibility, referred to as the "Waltons" group,[2] is largely consistent with the world of the past few hundred years through the present, with widespread use of agriculture and animal husbandry and a higher probability of long life spans, but with no ability to detect or mitigate radionuclides in the biosphere. The advanced-technology possibility of the future, referred to as the "Jetsons" group,[3] would reasonably be characterized by the ability to detect and mitigate the presence of radionuclides in the biosphere, availability of medical treatment to address mortality from most diseases (including many or most cancers), and presumably a longer life span.

C.4.1. Flintstones Society

In a Flintstones-like hunter-gatherer society, certain primary exposure pathways that would affect more technologically advanced societies do not apply, such as those related to agriculture, animal domestication, and use of wells to retrieve groundwater. Instead, consideration would be given to, for example, how the wildlife and plants a member of a Flintstones society consumes might ingest or uptake radionuclides from contaminated surface water and soil.

The Flintstones, Hanna Barbera

However, given the host of other factors limiting a Flintstones human lifespan (e.g., obtaining sufficient food, disease, and dangers from predators and other humans), the incremental morbidity due to potential exposure to radionuclides emanating from a geologic repository would almost certainly be relatively small.

C.4.2. Waltons Society

Unlike members of the Flintstones society, a person in the Waltons society would be capable of accessing radionuclides from a repository via irrigation or by drinking water from groundwater wells. These more advanced activities would put him or her at a higher risk from ionizing radiation. The greater number of radionuclide transfer pathways in this society would be exacerbated by the Waltons human's inability to detect radionuclides, recognize the hazard posed, and avoid it. Thus, for the effects of radionuclide release from repository and transfer to the biosphere to pose an acute hazard, the Waltons member would need to be in a technological "sweet spot": having the technology and energy resources to access contaminated water resources but lacking the technology and/or awareness to check for and avoid radiological hazards.

The Waltons, Moviestore Collection

In addition, the relatively longer life span of a Waltons society human would mean a potentially longer radionuclide exposure during his or her lifetime. Hence, the incremental morbidity caused by radionuclides entering the biosphere from the repository would be higher than that for a person in the Flintstones society.

1 The name of this group is based on *The Flintstones* animated television comedy by Hanna-Barbera Productions, which centered on a Stone Age family and originally aired on ABC from 1960 to 1966.

2 The name of this group is based on *The Waltons*, a historical drama television series about a rural family, set roughly during the Great Depression and World War II (1933–1946). The show originally aired on CBS from 1972 to 1981.

3 The name of this group is based on *The Jetsons* animated comedy by Hanna-Barbera Productions, a futuristic space-age counterpart to *The Flintstones*, which originally aired on ABC from 1962 to 1963.

Thinking about this in historical terms, Waltons living immediately before and after the beginning of the 20th century would be most at risk.

C.4.3. Jetsons Society

A Jetson should not come to harm due to radionuclides from material emplaced in a geologic repository for disposal. While a member of this society would certainly have the capability to access potentially contaminated groundwater, he or she would clearly have the ability and knowledge to detect and mitigate radionuclide releases and thereby prevent latent cancer deaths due to exposure to ionizing radiation from high-level radioactive waste. In fact, Jetsons may well have advanced to a level of medical technology in which cancer is simply another curable affliction.

The Jetsons, Universal PictureLux

C.5. Human Intrusion

The discussion to this point has focused on "undisturbed" repository performance in which the long-term degradation of repository system barriers by natural processes leads to migration of radionuclides to the biosphere. The other scenario of concern in repository regulation is human intrusion, which refers to advertent actions by future humans (e.g., drilling or mining) that disturb the repository itself and lead to transportation of radionuclides to the accessible environment. Repository regulations typically require consideration of the potential effects of human intrusion on repository performance.[4] With that being said, from an international perspective, regulations focus predominately on undisturbed performance and address scenarios involving human intrusion in a more qualitative manner. Nevertheless, the characteristics of future human societies impact the probability and consequences of human intrusion and deserve discussion in that context.

For the Flintstones scenario, human intrusion is clearly not possible. That society would lack the technological capability to drill deep enough to the material emplaced in a deep geologic repository. A Jetsons society human would certainly have the capability to access a repository well below the earth's surface; however, such a person would also possess imaging and detection techniques that would make him or her aware of the potential hazard so he or she could avoid it or manage it.

The concern for human intrusion centers on the Waltons society; in this scenario, a person could possess in some instances the capability to drill down to and disturb repository material but not have the wherewithal to detect and avoid or mitigate the hazard. This understanding informs the recommendation of the ANS Committee to address human intrusion through a single, site-specific intrusion analysis rather than attempting to incorporate human intrusion in a comprehensive performance evaluation (see Sec. III.1.9). Such an approach is consistent with the recommendations of the National Academies of Sciences and Engineering, and Institute of Medicine Committee on Technical Bases for Yucca Mountain Standards [2] and the approach taken by the EPA for human intrusion in its Yucca Mountain standards, found in 40 CFR Part 197.

4 From a regulatory perspective, it is important to note the significant practical limits on consideration of potential hazards posed by human intrusion into a repository. Regulators typically focus on the health effects to future humans due to the subsequent natural evolution of the repository system and radionuclide migration from the disturbed repository, and not on the immediate health effects to the intruders themselves.

C.6. Summary

We do not—and cannot—know whether humans will have fundamentally evolved many thousands of years from now in ways that would alter the effects of radionuclide exposure on the human body, nor can we know what kinds of human behavior will occur that would affect exposures from ingestion, inhalation, or other pathways. To avoid endless speculation, it is necessary for the regulator to specify in general terms future human biophysics and behavior for the purpose of conducting repository performance estimates.

As discussed above, it is appropriate to assume biophysical characteristics of future humans that are akin to present day Homo sapiens. Concerns about both undisturbed repository performance as well as a human intrusion scenario should be most acute for Waltons-type societies (the technological level of the United States in the decades surrounding the turn of the 20th century). Such a society would have a wide range of radionuclide transfer vectors within the biosphere, such as use of multiple water resources for agriculture, animal husbandry, and the like. It is assumed that a Waltons society member would lack the capability to detect radionuclides in the biosphere. A regulatory performance standard that is sufficiently protective for a Waltons society human would lead to health effects estimates that almost certainly bound those for societies at a lower (Flintstones) and higher (Jetsons) technology levels.

The ANS Committee recommends, therefore, that for the purpose of estimating health effects caused by radionuclides escaping the repository and entering the biosphere to humans living in the far future, the regulator provide guidance to limit speculation on future human biophysical characteristics and behavior as follows:

- No evolution of the human species would occur that would significantly alter the effects of internal or external radiation exposure on human health.
- Human behavior is characteristic of a Waltons society that makes significant use of water and land resources, but is not able to detect radionuclides in the biosphere. The specific behaviors making use of water and land resources as well as the nature of a human intrusion would need to be consistent with the site-specific characteristics of the local biosphere.

The Committee notes that these recommendations are broadly consistent with the approach taken by EPA in its Yucca Mountain standards (see Sec. III.1.2 of this report; 40 CFR Part 197).

C.7. References

[1] "What does it mean to be human?" Smithsonian Museum of Natural History website, updated January 22, 2021; humanorigins.si.edu/evidence/human-fossils/species/homo-sapiens.

[2] National Research Council, *Technical Bases for Yucca Mountain Standards*, National Academies Press, Washington, D.C. (1995); doi.org/10.17226/4943.

APPENDIX D. Members of the American Nuclear Society Special Committee on Generic Standards for Disposal of High-Level Radioactive Waste

Michael Apted has been involved for more than 40 years in planning, managing, and conducting regulatory compliance assessments related to nuclear waste management and disposal. His primary work has been in two areas: innovative design and testing of engineered containment systems for disposal of nuclear waste forms and assessment of long-term performance of such geological disposal systems.

As an independent consultant, Dr. Apted was the technical program manager for the Electric Power Research Institute's independent oversight of the Yucca Mountain Program, which included developing and conducting parallel but separate safety assessments to evaluate compliance of the program's disposal concept with the Environmental Protection Agency's safety criteria and the Nuclear Regulatory Commission's licensing requirements. He has consulted for Finnish, Swedish, Norwegian, Canadian, Spanish, Chinese, South Korean, South African, Taiwanese, German, French, and Swiss national programs investigating the implementation and regulation of nuclear waste disposal. He has also been a consultant to the International Atomic Energy Agency on used fuel disposal, disposal of spent medical sources and trained the Chinese national disposal program on HLW disposal.

Among Dr. Apted's publications are more than 100 papers, contractor documents, and confidential reports related to hazardous and nuclear waste disposal. He is the coauthor of *The Scientific and Regulatory Basis for the Geological Disposal of Radioactive Wastes* (John Wiley & Sons, 1995), based on his lectures from Oxford University. He is the coeditor and contributing author of *Geological Repository Systems for Safe Disposal of Spent Nuclear Fuels and Radioactive Wastes* (Woodhead Publishing, 2017). He served as the meeting organizer and proceedings editor for the OECD Nuclear Energy Agency's international symposium *Status of Near-Field Modeling* (1993). He has been a frequent invited instructor and mentor on areas of his expertise for courses conducted by the International Training Centre. He earned a B.S. in chemistry from the Massachusetts Institute of Technology and a Ph.D. in geochemistry from the University of California–Los Angeles, and completed a postdoctoral term at Stanford University.

Lake Barrett is an independent consultant in the energy field after serving in both government and commercial capacities in the nuclear energy and nuclear materials management areas for 56 years. He was the Nuclear Regulatory Commission's on-site director for the stabilization, recovery, and cleanup of the Three Mile Island reactor accident and currently is a senior nuclear advisor to the Japanese government's International Research Institute for Nuclear Decommissioning and the Tokyo Electric Power Company, aiding in recovery from the Fukushima Daiichi nuclear reactor accident.

At the Department of Energy, Mr. Barrett led the Yucca Mountain Geologic Repository program through the statutory site selection process and was responsible for commercial nuclear fuel transportation and nuclear fuel storage initiatives. Within defense programs, he was responsible for national security, safety, and environmental protection improvements at the Rocky Flats nuclear weapons plant, which led to the successful restoration of plutonium operations and safe decontamination and decommissioning. He currently serves on the DOE's Nuclear Energy Advisory Committee, focused on used nuclear fuel management.

He received a B.S. and M.S. in engineering from the University of Connecticut; is a registered Professional Engineer; Emeritus of the American Nuclear Society; has served on many national and international committees; and has received various honors such as the President's Meritorious Excellence Award, Secretary of Energy's Gold Award, DOE and NRC Meritorious Service Awards, and the Congressional Award for Exemplary Service Finalist. He is active as trustee and president at Christ Venice Church and aids in various international humanitarian missions.

John Kessler founded and is president of J Kessler and Associates following a 21-year career at EPRI, where he had been responsible for the overall management of the institute's Used Fuel and HLW Management Program. He performs strategic planning and management work in the area of used nuclear fuel and radioactive waste management. His clients include the DOE, consulting firms, universities, national laboratories, nuclear utilities, regulators, storage and transportation cask vendors, and nonprofits in the United States and internationally.

He led a panel of experts supporting the IAEA's coordinated research program on degradation of used fuel storage systems during long-term operation; supported the Emirates Nuclear Energy Corporation in the development of its waste management program for the Barakah nuclear plants in the UAE; and provided the DOE's Office of Nuclear Energy with programmatic support in their research into the feasibility of direct geologic disposal of dual-purpose (storage and transportation) spent fuel casks and canisters. He also developed a safety case description for deep borehole disposal applied to advanced reactor wastes.

During his tenure at EPRI, he directed a technical assessment of the appropriateness of proposed EPA and NRC performance standards for use at Yucca Mountain and was a coauthor of the EPRI-proposed standard for Yucca Mountain performance. In 2009, John organized the Extended Storage Collaboration Program—an international cooperative program for joint R&D on long-term behavior of spent fuel dry storage systems.

Dr. Kessler holds a B.S. and M.S. in nuclear engineering from the University of Illinois–Urbana-Champaign and a Ph.D. in mineral engineering (hydrogeology) from the University of California–Berkeley. He is a longtime member of the ANS and chaired its Fuel Cycle and Waste Management Division from July 2022 to June 2023. He has authored over 100 papers, journal articles, contractor documents, book sections, and reports related to SNF and HLW storage, transportation, and disposal.

Steven Nesbit is founder and president of LMNT Consulting, a company he started in 2019 following 37 years with Duke Energy Corporation. During his tenure, he worked on nuclear reactor modeling and simulation, including safety analysis methods development, and also managed used nuclear fuel activities, including both wet and dry storage of used fuel. For nine years he was the company's director of nuclear policy, responsible for developing policy positions related to nuclear power and interacting with industry and government groups on used fuel management and related issues.

In the 1990s, Mr. Nesbit supported the DOE's Office of Civilian Radioactive Waste Management, where his responsibilities included development of DOE positions on environmental and safety standards for the proposed Yucca Mountain repository and interactions with the National Academy of Sciences on its *Technical Bases for Yucca Mountain Standards* report.

Mr. Nesbit has been involved in used fuel issues through a number of industry groups and other organizations, including ANS, the U.S. Nuclear Industry Council (NIC), the Nuclear Energy Institute, and the Nuclear Waste Strategy Coalition. He has testified before Congress on used fuel issues: the U.S. House of Representatives Energy and Commerce Committee in 2017 and the U.S. Senate Committee on Energy and Natural Resources in 2019.

His publications include technical and policy papers on geologic repository seismic design methodology, centralized interim storage, an improved used fuel management organization, a proposed waste acceptance queue for shut-down nuclear power reactors, NIC recommendations for nuclear waste management reform, and characteristics of future human societies to be used in assessing compliance with geologic repository standards. Mr. Nesbit, a registered Professional Engineer in North Carolina and Maine, received his bachelor's and a master of engineering in nuclear engineering from the University of Virginia. He served ANS as president from June 2021 to June 2022.

Peter Swift is a consulting geoscientist with over 30 years of experience in high-level radioactive waste management and disposal. He was formerly a senior scientist at Sandia National Laboratories, where he most recently served from 2011 to 2020 as the national technical director of the DOE-NE's Spent Fuel and Waste Technology Research and Development Campaign. In that role he provided technical leadership for the DOE's research and development activities relevant to the storage, transportation, and permanent disposal of SNF and HLW. He also held a key role in the certification and licensing process for the proposed Yucca Mountain repository, where he led the total system performance assessment effort that developed estimates of the long-term safety of the site and then served as the chief scientist for the program's lead laboratory.

In addition to a broad background in the earth sciences, Dr. Swift has expertise in using results from probabilistic modeling of complex systems to address environmental regulatory requirements.

Dr. Swift has authored or coauthored more than 20 peer-reviewed publications, 35 technical reports, and 56 conference papers, and he has made more than 50 public presentations to regulators and external technical oversight boards, including testimony to the U.S. House of Representatives in 2011. He has been an invited speaker to the NAS Board on Radioactive Waste Management, the Blue Ribbon Commission on America's Nuclear Future, and multiple university programs. He has served as a member of the External Advisory Board for the University of California–Berkeley's Department of Nuclear Engineering, the Lawrence Berkeley National Laboratory's Earth Sciences Division Review Panel, Sandia's Geoscience Research Foundation Management Board, and the State of New York's Independent Expert Review Team for the West Valley Environmental Impact Statement.

After receiving a B.A. in English from Yale, followed by a B.S. and M.S. in geology from the University of Wyoming, Dr. Swift earned his Ph.D. in geosciences from the University of Arizona. He is a Fellow of the Geological Society of America and is a member or past member of several societies, including ANS, the American Geophysical Union, the American Association of Petroleum Geologists, and the Geochemical Society.

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