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Considerations of Human Intrusion in U.S. Programs for Deep Geologic Disposal of Radioactive Waste

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Abstract

Regulations in the United States that govern the permanent disposal of spent nuclear fuel and high-level radioactive waste in deep geologic repositories require the explicit consideration of hypothetical future human intrusions that disrupt the waste. Specific regulatory requirements regarding the consideration of human intrusion differ in the two sets of regulations currently in effect in the United States; one defined by the Environmental Protection Agency's 40 Code of Federal Regulations part 197, applied only to the formerly proposed geologic repository at Yucca Mountain, Nevada, and the other defined by the Environmental Protection Agency's 40 Code of Federal Regulations part 191, applied to the Waste Isolation Pilot Plant in New Mexico and potentially applicable to any repository for spent nuclear fuel and high-level radioactive waste in the United States other than the proposed repository at Yucca Mountain. This report reviews the regulatory requirements relevant to human intrusion and the approaches taken by the Department of Energy to demonstrating compliance with those requirements.

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NOMENCLATURE

CFR	Code of Federal Regulations
DOE	Department of Energy
EPA	Environmental Protection Agency
NRC	Nuclear Regulatory Commission
U.S.	United States
WIPP	Waste Isolation Pilot Plant
YMRP	Yucca Mountain Review Plan

1. INTRODUCTION

Considerations of human intrusion in the United States' programs for deep geologic disposal of radioactive waste are prescribed by Federal regulations, and this discussion begins with a review of the two existing sets of regulations that govern permanent disposal of spent nuclear fuel and high-level radioactive waste. Consistent with the legal framework defined in the United States (U.S.) Nuclear Waste Policy Act, each set includes overall safety standards set by the U.S. Environmental Protection Agency (EPA) and implementing criteria defined by the U.S. Nuclear Regulatory Commission (NRC). One set, including EPA's 40 Code of Federal Regulations (CFR) part 197 and NRC's 10 CFR part 63, was written in the last fifteen years specifically for the proposed Yucca Mountain repository, and would not apply to any other disposal concept without new rule-making activities. The other set, EPA's 40 CFR part 191 and NRC's 10 CFR part 60, date from the middle 1980s, prior to the decision to focus solely on Yucca Mountain, and, in the absence of new rule-making, would still apply in principle to any disposal concept other than Yucca Mountain. The EPA's 40 CFR Part 191 has been implemented for disposal of transuranic defense-related waste at the Waste Isolation Pilot Plant (WIPP). The NRC's 10 CFR part 60 was not implemented at WIPP because the facility does not dispose of spent nuclear fuel or high-level radioactive waste, nor has it been implemented at any other site. Implementation of 40 CFR part 197 and 10 CFR part 63 was begun when the U.S. Department of Energy (DOE) submitted a license application for the proposed Yucca Mountain repository (DOE 2008), but licensing proceedings were halted before a decision was reached.

The older regulations, as framed by the EPA in 40 CFR part 191, defined the regulatory period to be 10,000 years and set quantitative limits for scenarios that include all release pathways on the probability that the total amount of radiation released during the entire period would exceed specified values, rather than on the peak release in any single year. These regulations also tied the magnitude of the allowable release to the initial mass of radionuclides placed in the repository: allowable releases were smaller for smaller repositories and larger for larger repositories. The newer regulations specific to the proposed Yucca Mountain repository, as framed by the EPA in 40 CFR part 197, are based on and consistent with guidance from the National Academy of Sciences (National Research Council 1995) and set limits on the peak dose allowable in any one year during the first one million years following disposal. (The period of one million years is consistent with the National Academy's guidance indicating that the period of long-term geologic stability at Yucca Mountain is on the order of one million years [National Research Council 1995, Section 2].) There is no provision for scaling the allowable release to the initial inventory of the repository: the peak dose limits apply regardless of the amount of waste emplaced at the site.

Both sets of regulations explicitly require consideration of the consequences of inadvertent human intrusion into a geologic repository, and therefore the U.S. DOE's applications for both the WIPP, regulated under 40 CFR part 191, and the proposed Yucca Mountain repository, regulated under 40 CFR part 197 and 10 CFR part 63, contained the required evaluations of human intrusion. The specific requirements differ sufficiently between the two sets of regulations that it is useful to consider them separately.

2. OVERVIEW OF REGULATORY REQUIREMENTS RELEVANT TO HUMAN INTRUSION

Both sets of existing regulations are based on similar assumptions that the consequences of deliberate acts of human sabotage or intrusion into repositories are beyond the scope of regulation, and both sets specify that intrusion by drilling is suitably representative of all forms of inadvertent intrusion and shall be evaluated in detail. The details of the treatment of human intrusion in the two regulations are different, however.

The approach taken in 40 CFR part 191 to human intrusion requires that consequences of human intrusion shall be included in the overall probabilistic assessment of cumulative releases, which means that for sites that are likely to have small releases due to natural processes during their regulatory period, such as WIPP, release estimates may be dominated by hypothetical intrusion events. As originally proposed in 40 CFR part 191 (EPA 1985, p. 38089), the likelihood of future intrusion could be assumed to be ten times higher in sedimentary rocks than in other formations, effectively lowering the allowable human-intrusion releases from repositories in sedimentary rocks (including salt) by a factor of ten. As implemented at WIPP in 40 CFR part 194 (EPA certification criteria specific for the WIPP) and discussed in detail in Section 3 below, the probability of future drilling intrusions at WIPP was based on past and current drilling rates in the surrounding region, resulting in a relatively high probability of human intrusion that became the dominant factor in evaluating the long-term performance of the repository.

As discussed in detail in Section 4 below, the approach taken for Yucca Mountain in 40 CFR part 197 was based on the 1995 guidance from the National Academy of Sciences. This approach avoids the potential for having highly uncertain estimates of future drilling rates become the dominant uncertainty in assessing long-term repository performance by specifying that human intrusion should be evaluated separately from the probabilistic assessment of natural evolution of the site. Human intrusion should be assumed to occur once, and only once, and resulting doses should be compared to a separate standard. Consistent with National Academy of Science's recommendations (National Research Council 1995, Section 4), the approach taken in 40 CFR part 197 focused on evaluating the long-term resilience of the repository and its surrounding geology to intrusion, rather than on risks to the intruders. Because exposures to the driller are immediate, rather than long-term, and because "the effects of direct removal depend on the specific parameters involved with the drilling [rather than] on the disposal system's containment characteristics," the EPA limited the regulatory dose to that due to releases occurring over longer periods of time, through groundwater contaminated after the intrusion occurred (EPA 2001, p. 32104 and 40 CFR 197.26(e)).

3. CONSIDERATION OF HUMAN INTRUSION FOR THE WIPP

3.1 Specific Human Intrusion Regulatory Requirements Applied to the WIPP

40 CFR 191.13 requires estimates of "the cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal from all significant processes and events that may affect the disposal system."

Guidance provided by the EPA in Appendix C of 40 CFR part 191 states that

> "inadvertent and intermittent intrusion by exploratory drilling for resources (other than any provided by the disposal system itself) can be the most severe intrusion scenario assumed by the implementing agencies. Furthermore, the implementing agencies can assume that passive institutional controls or the intruders' own exploratory procedures are adequate for the intruders to soon detect, or be warned of, the incompatibility of the area with their activities."

Guidance provided by the EPA in Appendix C of 40 CFR part 191 also states that

> "the [Environmental Protection] Agency assumes that the consequences of such inadvertent drilling need not be assumed to be more severe than: (1) Direct release to the land surface of all the ground water in the repository horizon that would promptly flow through the newly created borehole to the surface due to natural lithostatic pressure—or (if pumping would be required to raise water to the surface) release of 200 cubic meters of ground water pumped to the surface if that much water is readily available to be pumped; and (2) creation of a ground water flow path with a permeability typical of a borehole filled by the soil or gravel that would normally settle into an open hole over time—not the permeability of a carefully sealed borehole."

An additional element of guidance in Appendix C of 40 CFR part 191 that proved important in the consideration of human intrusion for the WIPP is as follows:

> "the implementing agency will assume that none of the active institutional controls prevent or reduce radionuclide releases for more than 100 years after disposal. However, the Federal Government is committed to retaining ownership of all disposal sites for spent nuclear fuel and high-level and transuranic radioactive wastes and will establish appropriate markers and records, consistent with § 191.14(c). The Agency assumes that, as long as such passive institutional controls endure and are understood, they: (1) Can be effective in deterring systematic or persistent exploitation of these disposal sites; and (2) can reduce the likelihood of inadvertent, intermittent human intrusion to a degree to be determined by the implementing agency. However, the Agency believes that passive institutional controls can never be assumed to eliminate the chance of inadvertent and intermittent human intrusion into these disposal sites."

In 1996 the EPA promulgated additional regulatory requirements specific only to the WIPP at 40 CFR part 194. These requirements, of which the portions relevant to human intrusion are quoted in their entirety in Appendix A of this document, provide explicit direction on how the applicant must treat human intrusion into the repository and other potential future human activities that may occur in the region. Specifically:

> Performance assessments must consider consequences of currently existing and near-future human activities such as existing boreholes and development of existing oil and gas leases in the region.
>
> Direct intrusion into the repository must be considered by evaluation of the probability and consequence of future drilling intrusions.
>
> Future drilling practices, including sealing of holes, should be assumed to be consistent with those of the present.
>
> Future drilling rates should be determined by extrapolation from the historical record of drilling in the surrounding geologic basis during the past 100 years.
>
> Natural processes should be assumed to degrade the intrusion boreholes (and their seals) over time.
>
> Performance assessments need not include consequences of attempts to recover resources from boreholes after intrusions (e.g., future humans will not intentionally pump fluids from a borehole that intrudes into the repository.)
>
> The applicant must provide passive institutional controls, such as markers at the site and records, that will help reduce the potential for future human intrusion. However, the effectiveness of these passive controls cannot be assumed to endure more than "several hundred years," and "in no case can [they] be assumed to eliminate the likelihood of human intrusion entirely."
>
> In addition to human intrusion, performance assessments must consider consequences of future mining events in the region that do not intersect the repository but that may influence hydrologic properties of nearby geologic units. The probability that a mining event occurs is specified to be 1 in 100 in each century of the 10,000-year regulatory period.

3.2 Implementation of Human Intrusion in the WIPP Program

3.2.1. Passive Institutional Controls and the Probability of Future Human Intrusion

Early Work Using Expert Judgment: In the early 1990s, prior to receiving prescriptive direction from the EPA regarding the approach to estimating the probability of future human intrusion into the WIPP, the DOE conducted a substantial effort to establish a basis for probability estimates derived from expert judgment. The effort included identifying and convening two separate and independent panels containing experts from multiple disciplines

potentially relevant to evaluations of future human behavior. The first panel to be convened, called the "Futures Panel," included 16 members divided into four teams, and was tasked with identifying reasonably foreseeable future human societies, identifying how they might intrude into the repository, and what the likelihood of such future intrusions might be (Hora et al. 1991). Disciplines represented on the Futures Panel included history, future studies, law, physics, sociology, geography, engineering, political science, risk analysis, agriculture, climatology, and demographics. A second panel, convened after the first panel's work was complete, was tasked with developing design guidelines for markers and messages to be placed at the WIPP to communicate the hazard of the site to future societies such as those envisioned by the first panel (Trauth et al. 1993). The "Markers Panel" included 13 members grouped into two independent teams, and included representation from the disciplines of materials science, architecture, anthropology, linguistics, archeology, astronomy, astronomical communication, geomorphology, semiotics, and scientific illustration. Together, the work of these two panels represents the most ambitious effort known to this author ever to use expert judgment to provide insight into possible human behavior in the far future and advice on how to communicate with those humans.

Efforts to base quantitative estimates of the probability of future human intrusion at the WIPP on results of the expert judgment process ended in 1996 when the EPA provided prescriptive direction in 40 CFR part 194 to extrapolate drilling rates from the historical record, as described in Section 3.1. Results of the Markers Panel remained valuable as input to the design for site markers that was included in the DOE's 1996 WIPP Compliance Certification Application to the EPA (DOE 1996, Appendix PIC), although specific recommendations from the Markers Panel were modified as a result of practicability, constructability, and cost considerations that had not been imposed on the expert panel.

Consideration of Barriers to Intrusion. In parallel with the work of the expert panels evaluating the likelihood of future human intrusion at the WIPP, the DOE conducted a review of concepts for protective barriers that might deter human intrusion into a mined repository (Tolan 1993). This study reviewed existing concepts for deterring intrusion into near-surface disposal facilities (e.g., rock and earth covers) and identified examples of materials that have proven resistant to penetration by rotary drilling. For example, thick deposits of pliable rubber tires in landfills have been shown to pose a significant barrier to shallow drilling operations. Covering a topic examined in much greater detail by the Markers Panel (Trauth et al. 1993) discussed above, the study also considered the feasibility of incorporating markers into barrier systems between the waste and the land surface that would increase the likelihood that the intruder would recognize the potential hazard and abandon drilling operations before penetrating the waste. The study concluded with recommendations regarding desirable attributes of a protective barrier system, which should:

> "be capable of disabling a drill bit, be impervious to a drill bit or, at the minimum, be capable of deflecting the drill bit safely away from the disposal system;
>
> be potentially capable of withstanding multiple encounters with a drill bit without loss of function;

> be composed of materials with little or no economic value and that will not degrade over the 10,000-year, post-closure period; and
>
> not attract unwanted attention to the site or encourage exploration activities" (Tolan 1993, p. 44).

The DOE summarized this information in the 1996 WIPP Compliance Certification Application (DOE 1996 Appendix PIC, p. 44-47), but did not pursue the concept of protective barriers further for the WIPP, in part because of the perceived difficulty in designing effective subsurface barriers for a repository with relatively large disposal regions and in part because there was no potential benefit in demonstrations of regulatory compliance. When the U.S. EPA promulgated their WIPP-specific criteria at 40 CFR part 194 in 1996, the rule contained no provision for adjusting the probability of intrusion to take protective barriers into account, and the supplemental text accompanying the regulation stated

> "In determining the drilling rate or the amount of waste released from such drilling, performance assessments should not assume that drill operators would detect the waste and then cease the current drilling operations or otherwise mitigate the consequences of their actions" (EPA 1996, p. 5230).

Quantitative Estimates of Drilling Frequency and Practice Based on the Historical Record. As part of its 1996 Compliance Certification Application for the WIPP, the DOE conducted a thorough survey of past drilling activities in the Delaware Basin, which is the 23,000 km^2 geologic region surrounding the WIPP site (DOE 1996, Appendix DEL). This survey provided the basis both for the EPA-prescribed quantitative estimate of the future frequency of drilling events in region that would reach the depth of the repository or deeper (46.765 holes per km^2 during the next 10,000 years) and the descriptions of drilling practices (e.g., bit diameters, plugging and sealing practices) that allowed quantification of the intrusion scenario in the performance assessment modeling. Subsequent re-evaluations of drilling activity in the surrounding region have resulted in an increase in the drilling rates used in recertifications of the WIPP: in the 2009 WIPP Compliance Recertification Application, the DOE estimated a future drilling frequency in the Delaware Basin of 58.5 boreholes per km^2 during the next 10,000 years (DOE 2009, Section 33.6.2).

3.2.2 Implementation of the Human Intrusion Scenario in the WIPP Compliance Certification Application

As described in the WIPP Compliance Certification Application (DOE 1996, Section 6.4.12.1), drilling intrusions were assumed to happen occur randomly in the future within the 0.126 km^2 waste emplacement area, following a Poisson process with a rate constant equal to 46.8 events per km^2 during the 10,000 year period, except for modifications to the rate in the first 700 years to account for institutional controls. Active controls were assumed to be fully effective in preventing all intrusions for the first 100 years, and for the period between 100 and 700 years passive institutional controls were assumed to reduce the rate of intrusion events by 2 orders of magnitude. In practice, the efficacy of passive controls was shown to have little impact on overall performance because cumulative releases were dominated by intrusions that occurred

after 700 years regardless of controls prior to that time. The EPA chose in its certification of the WIPP to deny the DOE's use of passive controls to reduce the probability of intrusion during the period between 100 and 700 years, "because DOE did not use an expert judgment elicitation to derive the credit, as explicitly envisioned by the Agency" (EPA 1998, p. 27396).

Regardless of the assumed effectiveness of passive controls, implementation of the Poisson model for the time and number of intrusion events at the WIPP yielded relatively high probabilities for one or more intrusions into the waste during the 10,000-year period: even with the assumption of a reduced drilling rate between 100 and 700 years, the probability in the 1996 WIPP Compliance Certification Application that one or more intrusion events would occur during 10,000 years was 0.9959 (i.e., there was only a 0.0041 probability of zero intrusions). The most likely number of intrusions into the waste during the next 10,000 years was 5 (DOE 1996, Section 6.4.12.2). Thus, the 1996 WIPP application, and the subsequent certification of the site by the EPA (EPA 1998), was based in part on a performance assessment that was required to assume the essentially certain occurrence of multiple borehole intrusions during the next 10,000 years.

Implementation of the human intrusion scenario in the performance assessment consequence modeling is described in detail in various subsections of Section 6.4.12 of the WIPP Compliance Certification Application (DOE 1996), and in subsequent updates to the WIPP performance assessment documented in recertification applications for the WIPP in 2004 and 2009 (DOE 2004; DOE 2009). Details of the modeling implementation are beyond the scope of this review. However, key points are as follows:

> Human intrusion scenarios provided the only significant releases from the repository during 10,000 years. In the absence of human intrusions, estimated releases were essentially zero.
>
> Release pathways and mechanisms considered in the human intrusion scenarios included:
>
>> Cuttings and cavings, which are the solid material brought directly to the surface by a rotary drill bit.
>>
>> Spallings, which are the solid material that may be forced into a borehole during rapid depressurization when a drill bit intersects a pressurized formation.
>>
>> Brine releases, which include radionuclides transported in the aqueous phase up a borehole, both during drilling and during long-term flow following degradation of borehole seals.
>>
>> Scenarios considered single boreholes encountering isolated waste panels and multiple boreholes allowing for flow-through pathways accessing multiple panels. Boreholes had the potential to encounter pressurized brine reservoirs below the repository, creating pressure gradients that drove long-term flow up the borehole and into overlying aquifers.

Properties of the drilling operation, the borehole itself, and underlying pressurized fluids were based on past drilling experience in the region.

10,000-year cumulative radionuclide releases for all scenarios considered were within regulatory limits.

4. CONSIDERATION OF HUMAN INTRUSION FOR THE PROPOSED YUCCA MOUNTAIN REPOSITORY

4.1 Findings and Recommendations from the U.S. National Academy of Sciences Relevant to Considerations of Human Intrusion at the Proposed Yucca Mountain Repository

When the U.S. Congress determined in the early 1990s to create new regulations specific to the proposed Yucca Mountain repository site, they directed the EPA to create standards based on and consistent with the recommendations of the U.S. National Academy of Sciences:

> "The Administrator [of the EPA] shall, based upon and consistent with the findings and recommendations of the National Academy of Sciences, promulgate, by rule, public health and safety standards for protection of the public from releases from radioactive materials stored or disposed of in the repository at the Yucca Mountain site" (Energy Policy Act of 1992, Section 801(a)(1)).

Congress further tasked the U.S. National Academy of Sciences with explicitly considering the efficacy of active institutional controls and the scientific basis for estimating the probability of future human intrusion into a geologic repository at Yucca Mountain. Requirements for findings and recommendations from the National Academy of Sciences included two questions specific to human intrusion:

> "whether it is reasonable to assume that a system for post-closure oversight of the repository can be developed, based upon active institutional controls, that will prevent an unreasonable risk of breaching the repository's engineered or geologic barriers or increasing the exposure of individual members of the public to radiation beyond allowable limits, and"
>
> "whether it is possible to make scientifically supportable predictions of the probability that the repository's engineered or geologic barriers will be breached as a result of human intrusion over a period of 10,000 years" (Energy Policy Act of 1992, Section 801(a)(2)(B,C)).

The U.S. National Academy of Sciences addressed these two questions explicitly in the 1995 report prepared by the National Research Council Committee on Technical Bases for Yucca Mountain Standards (National Research Council 1995). As described in detail in the Section 4 of the National Research Council report, the committee concluded that the answer to both questions was "no"; it is neither reasonable to assume that active controls can prevent human intrusion in the future, nor is there a scientific basis for estimating the probability of future human intrusion at Yucca Mountain.

Specifically:

> "…there is no scientific basis for making projections over the long term of either the social, institutional, or technological status of future societies. Relying on active controls

> implies requiring future generations to dedicate resources to the effort. There is, however, no scientific basis from which to project the durability of governmental institutions over the period of interest, which exceeds that of all recorded human history. On this time scale, human institutions have come and gone. We might expect some degree of continuity of institutions, and hence of the potential for active institutional controls, into the future, but there is no basis in experience for such an assumption beyond a time scale of centuries.
>
> Similarly, there is no scientific basis for assuming the long-term effectiveness of active institutional controls to protect against human intrusion. Although it may be reasonable to assume that a system of post closure oversight can be developed and relied on for some initial period of time, there is no defensible basis for assuming that such a system can be relied on for times far into the future. Between these limits, the ability to rely on such active institutional systems presumably diminishes in a way that is intrinsically unknowable. We have seen no evidence to support a claim to the contrary. People might disagree, of course, on their predictions for how long into the future active institutional controls might survive and remain effective" (National Research Council 1995, Section 4)

and

> "…we also conclude that there is no scientific basis for estimating the probability of intrusion at far-future times. Several types of intrusion can be considered: inadvertent intrusion into the repository in the process of exploring for or producing other resources in the vicinity, intrusion driven by curiosity about the markers and what might lie below them, or intentional intrusion for malicious purposes or to recover the repository contents. (The malicious intrusion might be by a hostile nation or sub-national group assuming a societal or institutional presence.) In our view, there is simply no scientific basis for estimating the probability of inadvertent, willful, or malicious human action.
>
> Estimating the probability of inadvertent intrusion as a consequence of exploration or production of resources might seem more plausible than for the cases of willful or malicious intrusion. Doing so, however, requires knowledge of which materials at or near the site will be regarded as resources in the future and the technologies that will exist for exploration and production. We cannot predict future economic conditions that help to define what a valuable resource is nor can we forecast future exploration technology, although we can observe that, if the past is an adequate guide, economic conditions and technology will change rapidly in the future. It might very well be, for example, that subsurface exploration technology in the future could be based on remote sensing so that penetration of the surface is no longer required. We therefore do not think that it is feasible to make meaningful predictions about the probability of advertent or inadvertent intrusion" (National Research Council 1995, Section 4).

After answering the direct questions posed by Congress, the National Research Council Committee went on to offer two additional recommendations relevant to considerations of human intrusion. First, a repository at Yucca Mountain should be required to have both active

and passive institutional controls to help reduce the risk of intrusion, even thought that benefit is scientifically unquantifiable, and second, the EPA should specify a human intrusion scenario for consequence analysis without consideration of its likelihood of occurrence.

The National Research Council Committee report provided a detailed description of how an intrusion scenario could be specified in regulations:

> "For simplicity, we considered a stylized intrusion scenario consisting of one borehole of a specified diameter drilled from the surface through a canister of waste to the underlying aquifer. One can always conceive of worse cases, such as multiple boreholes with each penetrating a canister, but this single-borehole scenario seems to us to hold the promise of providing considerable insight into repository performance with the minimum complication.
>
> An example of a scenario that we believe provides a reasonable basis for evaluation would postulate current drilling technology but assume sloppy practice, such as not plugging the hole carefully when abandoning it, after which natural processes would gradually modify the hole. Although the time at which the intrusion occurs in the future is arbitrary in any hypothetical scenario, we believe it is useful to assume that the intrusion occurs during a period when some of the canisters will have failed but the released materials would not otherwise have had time to reach the ground water. This assumption places emphasis in the consequence analysis on the creation of enhanced pathways to the environment (both to the atmosphere and to the aquifer) as opposed to emphasis on the intrusion's breaching of the canister, which will happen eventually even without human intrusion" (National Research Council 1995, Section 4).

The National Research Council Committee also recommended that the analyses of an intrusion scenario focus on risks from long-term releases through the groundwater pathway, rather than on releases at the land surface during drilling, concluding that

> "analyzing the risks the intrusion crew and the risks from any material brought directly to the surface as a consequence of intrusion is unlikely to provide useful information about a specific repository site or design and therefore should not provide a basis for judging the resilience of the proposed repository to intrusion"
>
> and
>
> "we believe that it would not be feasible to take regulatory actions today to protect the intrusion crew itself against the risks of its actions, except that requirements identified above associated with active or passive institutional controls might be helpful in this regard" National Research Council 1995, Section 4).

Regarding consideration of the potential long-term risk to members of the public from radioactive drill cuttings abandoned on the land surface at the site of a future intrusion, the Committee observed that

> "the amount of such future cuttings might not be very different from one repository site or design to another, especially given the unknown nature of an intrusion. Analysis of this hazard too, therefore does not provide information that is useful for judging the ability of the particular repository site and design to protect the public (National Research Council 1995, Section 4).

The National Research Council Committee provided further guidance on what an appropriate regulatory risk standard might be for the consequences of this intrusion scenario at the proposed Yucca Mountain repository:

> "Our recommendation is that EPA should require that the conditional risk as a result of the assumed intrusion scenario should be no greater than the risk levels that would be acceptable for the undisturbed-repository case. The conditional risk calculation would not include risks to the intruder or those arising from the material brought directly to the surface as a consequence of the intrusion" (National Research Council 1995, Section 4).

4.2 Specific Human Intrusion Regulatory Requirements for the Proposed Yucca Mountain Repository

The human intrusion standard for the proposed Yucca Mountain repository that the U.S. EPA promulgated in 40 CFR part 197 (final modifications published in 2008) follows the recommendations from the National Research Council Committee closely. The full text of the EPA's human intrusion standard in 40 CFR part 197 is reproduced in Appendix B of this report. Key requirements are as follows:

> Consequences must be estimated for a single drilling intrusion occurring "at the earliest time after disposal that the waste package would degrade sufficiently that a human intrusion could occur without recognition by the drillers"
>
> Drilling should be assumed to use current practice
>
> Careful sealing of the borehole does not occur
>
> Consequences are limited to penetration of a single waste package and subsequent releases into the underlying aquifer
>
> Human intrusion analyses do not include consequences of unlikely natural processes and events (e.g., volcanism)
>
> Dose limits are the same as those set for overall performance in the absence of human intrusion.

The U.S. NRC reproduces the EPA's requirements for human intrusion at 40 CFR part 197 verbatim in 10 CFR part 63, sections 63.321 and 63.322, and adds the clarifying specification that "no particulate waste material falls into the borehole." The NRC provides further guidance

regarding its expectations for evaluating compliance with the Yucca-Mountain-specific human intrusion standard in the Yucca Mountain Review Plan (YMRP) (NRC 2003, Section 2.2.1.4.2).

Both the EPA and NRC regulations require that the "controlled area" above the repository be identified by "passive institutional controls," including "markers, as permanent as practicable, placed on the Earth's surface" (40 CFR 197.12 and 10 CFR 63.302). The NRC provides further guidance regarding its expectations for evaluating compliance with the Yucca-Mountain-specific requirements for marking the site after permanent closure in the YYMRP (NRC 2003, Section 2.5.8.2). Consistent with the National Research Council's finding, no estimates are required of the efficacy of these controls in preventing future human intrusion, nor would they be useful in a demonstration of regulatory compliance, because the probability of the intrusion event is assumed to be one. However, the EPA and NRC requirements to assume that the intrusion occurs at the earliest time at which the driller would fail to detect the repository implicitly allow and encourage the use of engineered barriers that would complicate the drilling process. For the proposed Yucca Mountain repository, the long-lived waste package and drip shield barriers served such a function without additional modifications.

4.3 Implementation of the Human Intrusion Scenario in the Yucca Mountain License Application

The DOE provided a detailed description in the 2008 license application for the proposed Yucca Mountain repository (DOE 2008, Section 2.4.2) of consequence analyses to demonstrate compliance with the human intrusion requirements of 10 CFR part 63 (and thereby also 40 CFR part 197).

The DOE concluded, based on analysis of drilling techniques and estimates of the degradation of the waste package and drip shield in the repository environment, that the earliest time at which a drilling intrusion could occur at the Yucca Mountain repository without being recognized was 200,000 years after repository closure (DOE 2008, Section 2.4.3.2.4). Estimates of the consequences of a drilling intrusion into a single waste package at that time were calculated using the same performance assessment models used for the overall probabilistic assessment of performance in the absence of human intrusion with modifications consistent with the regulatory specifications for the human intrusion scenario (DOE 2008, Section 2.4.3.1). The resulting estimates of mean annual dose to the reasonably maximally exposed individual, as specified in 40 CFR part 197 and 10 CFR part 63, were below regulatory limits (DOE 2008, section 2.4.3.3). In its technical evaluation of the DOE's license application for the proposed Yucca Mountain repository, the NRC staff noted that "DOE's representation of repository performance in its Total System Performance Assessment (TSPA) for the human intrusion calculation is consistent with the guidance in the YMRP" (NRC 2011a, Section 2.2.1.4.2.4).

Consistent with regulatory requirements regarding passive institutional controls, the DOE's license application for the proposed Yucca Mountain repository contained a description of markers and monuments to be constructed at the repository site (DOE 2008, Section 5.8.5) and records to be maintained at other locations (DOE 2008, Section 5.8.6). Design of the markers took into account the information developed for the WIPP (DOE 1996, Appendix PIC). Consistent with requirements that the human intrusion scenario be evaluated without

consideration of its probability, the potential for these markers to reduce the likelihood of human intrusion is not considered in the license application. In its technical evaluation of the DOE's license application for the proposed Yucca Mountain repository, the NRC staff noted that "the conceptual design of the monuments is consistent with the guidance in the YMRP" (NRC 2011b, Section 2.5.8.4).

5. OBSERVATIONS ON THE CONSIDERATION OF HUMAN INTRUSION IN FUTURE U.S. REPOSITORY PROGRAMS

Both the findings and recommendations of the National Research Council (1995) and the regulatory requirements established for the proposed Yucca Mountain repository at 40 CFR part 197 and 10 CFR part 63 are specific to that site, and do not apply to any future repository programs in the U.S.

In the absence of new regulatory standards, any future repository for spent nuclear fuel or high-level radioactive waste in the U.S. other than the previously proposed Yucca Mountain repository would be regulated under 40 CFR part 191, and the requirements for human intrusion would be based on the guidance provided in Appendix C of that regulation. The detailed specification given in 40 CFR part 194 for the WIPP requiring determination of a drilling rate based on the past historical record in the surrounding region would not apply, but the approach would otherwise be analogous to that implemented for the WIPP. Consequences of human intrusion would be included in probabilistic analyses of overall 10,000-year performance, including both releases at the land surface during drilling and subsequent long-term releases due to groundwater flow through pathways "with a permeability typical of a borehole filled by the soil or gravel that would normally settle into an open hole over time." In the absence of additional direction comparable to that provided for WIPP in 40 CFR part 194, the probability of intrusion would be based on generic guidance given in 40 CFR part 191, Appendix C:

> "the Agency assumes that the likelihood of such inadvertent and intermittent drilling need not be taken to be greater than 30 boreholes per square kilometer of repository area per 10,000 years for geologic repositories in proximity to sedimentary rock formations, or more than 3 boreholes per square kilometer per 10,000 years for repositories in other geologic formations."

The NRC's implementing criteria for geologic repositories other than Yucca Mountain, 10 CFR part 60, would also apply to any repository for spent nuclear fuel or high-level radioactive waste. These criteria include further specifications of institutional controls, both active and passive, that would be required for any future repository, but they do not include additional requirements relevant to the consideration of human intrusion beyond those provided by the EPA in 40 CFR part 191.

With that said, it is appropriate to note that the NRC stated in the supplementary information accompanying the 2001 promulgation of 10 CFR part 63 that "generic part 60 requirements will need updating if applied to sites other than Yucca Mountain" (NRC 2001, p. 55736). NRC staff has reiterated this position in recent years, indicating in presentations and publications that they intend to update or replace 10 CFR part 60 prior to licensing disposal at locations other than Yucca Mountain (e.g., Kokajko 2011; Rubenstone 2012, p. 34). In addition, the Blue Ribbon Commission on America's Nuclear Future has concluded that "the generic regulations that would currently apply to all other sites will need to be revisited and revised in any case" (BRC 2012, p. 90), although this conclusion carries no binding force with respect to rule-making by the U.S. EPA or U.S. NRC. The content of any new regulatory requirements relevant to the consideration of human intrusion is unknown at this time.

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APPENDIX A: WIPP-SPECIFIC REQUIREMENTS RELEVANT TO HUMAN INTRUSION, FROM THE U.S. EPA'S 40 CFR PART 194

§ 194.32 Scope of performance assessments.
(a) Performance assessments shall consider natural processes and events, mining, deep drilling, and shallow drilling that may affect the disposal system during the regulatory time frame.
(b) Assessments of mining effects may be limited to changes in the hydraulic conductivity of the hydrogeologic units of the disposal system from excavation mining for natural resources. Mining shall be assumed to occur with a one in 100 probability in each century of the regulatory time frame. Performance assessments shall assume that mineral deposits of those resources, similar in quality and type to those resources currently extracted from the Delaware Basin, will be completely removed from the controlled area during the century in which such mining is randomly calculated to occur. Complete removal of such mineral resources shall be assumed to occur only once during the regulatory time frame.
(c) Performance assessments shall include an analysis of the effects on the disposal system of any activities that occur in the vicinity of the disposal system prior to disposal and are expected to occur in the vicinity of the disposal system soon after disposal. Such activities shall include, but shall not be limited to, existing boreholes and the development of any existing leases that can be reasonably expected to be developed in the near future, including boreholes and leases that may be used for fluid injection activities.

§ 194.33 Consideration of drilling events in performance assessments.
(a) Performance assessments shall examine deep drilling and shallow drilling that may potentially affect the disposal system during the regulatory time frame.
(b) The following assumptions and process shall be used in assessing the likelihood and consequences of drilling events, and the results of such process shall be documented in any compliance application:
(1) Inadvertent and intermittent intrusion by drilling for resources (other than those resources provided by the waste in the disposal system or engineered barriers designed to isolate such waste) is the most severe human intrusion scenario.
(2) In performance assessments, drilling events shall be assumed to occur in the Delaware Basin at random intervals in time and space during the regulatory time frame.
(3) The frequency of deep drilling shall be calculated in the following manner:
(i) Identify deep drilling that has occurred for each resource in the Delaware Basin over the past 100 years prior to the time at which a compliance application is prepared.
(ii) The total rate of deep drilling shall be the sum of the rates of deep drilling for each resource.
(4) The frequency of shallow drilling shall be calculated in the following manner:
(i) Identify shallow drilling that has occurred for each resource in the Delaware Basin over the past 100 years prior to the time at which a compliance application is prepared.
(ii) The total rate of shallow drilling shall be the sum of the rates of shallow drilling for each resource.
(iii) In considering the historical rate of all shallow drilling, the Department may, if justified, consider only the historical rate of shallow drilling for resources of similar type and quality to those in the controlled area.
(c) Performance assessments shall document that in analyzing the consequences of drilling events, the Department assumed that:

(1) Future drilling practices and technology will remain consistent with practices in the Delaware Basin at the time a compliance application is prepared. Such future drilling practices shall include, but shall not be limited to: The types and amounts of drilling fluids; borehole depths, diameters, and seals; and the fraction of such boreholes that are sealed by humans; and
(2) Natural processes will degrade or otherwise affect the capability of boreholes to transmit fluids over the regulatory time frame.
(d) With respect to future drilling events, performance assessments need not analyze the effects of techniques used for resource recovery subsequent to the drilling of the borehole.

§ 194.43 Passive institutional controls.
(a) Any compliance application shall include detailed descriptions of the measures that will be employed to preserve knowledge about the location, design, and contents of the disposal system. Such measures shall include:
(1) Identification of the controlled area by markers that have been designed and will be fabricated and emplaced to be as permanent as practicable;
(2) Placement of records in the archives and land record systems of local, State, and Federal governments, and international archives, that would likely be consulted by individuals in search of unexploited resources. Such records shall identify:
(i) The location of the controlled area and the disposal system;
(ii) The design of the disposal system;
(iii) The nature and hazard of the waste;
(iv) Geologic, geochemical, hydrologic, and other site data pertinent to the containment of waste in the disposal system, or the location of such information; and
(v) The results of tests, experiments, and other analyses relating to backfill of excavated areas, shaft sealing, waste interaction with the disposal system, and other tests, experiments, or analyses pertinent to the containment of waste in the disposal system, or the location of such information.
(3) Other passive institutional controls practicable to indicate the dangers of the waste and its location.
(b) Any compliance application shall include the period of time passive institutional controls are expected to endure and be understood.
(c) The Administrator may allow the Department to assume passive institutional control credit, in the form of reduced likelihood of human intrusion, if the Department demonstrates in the compliance application that such credit is justified because the passive institutional controls are expected to endure and be understood by potential intruders for the time period approved by the Administrator. Such credit, or a smaller credit as determined by the Administrator, cannot be used for more than several hundred years and may decrease over time. In no case, however, shall passive institutional controls be assumed to eliminate the likelihood of human intrusion entirely.

APPENDIX B: THE U.S. EPA'S HUMAN INTRUSION STANDARD FOR THE PROPOSED YUCCA MOUNTAIN REPOSITORY, FROM 40 CFR PART 197

HUMAN-INTRUSION STANDARD

§ 197.25 What standard must DOE meet?

(a) The DOE must determine the earliest time after disposal that the waste package would degrade sufficiently that a human intrusion (see §197.26) could occur without recognition by the drillers.

(b) The DOE must demonstrate that there is a reasonable expectation that the reasonably maximally exposed individual will receive an annual committed effective dose equivalent, as a result of the human intrusion, of no more than:

(1) 150 microsieverts (15 millirems) for 10,000 years following disposal; and

(2) 1 millisievert (100 millirems) after 10,000 years, but within the period of geologic stability.

(c) The analysis must include all potential environmental pathways of radionuclide transport and exposure.

§ 197.26 What are the circumstances of the human intrusion?

For the purposes of the analysis of human intrusion, DOE must make the following assumptions:

(a) There is a single human intrusion as a result of exploratory drilling for ground water;

(b) The intruders drill a borehole directly through a degraded waste package into the uppermost aquifer underlying the Yucca Mountain repository;

(c) The drillers use the common techniques and practices that are currently employed in exploratory drilling for ground water in the region surrounding Yucca Mountain;

(d) Careful sealing of the borehole does not occur, instead natural degradation processes gradually modify the borehole;

(e) Only releases of radionuclides that occur as a result of the intrusion and that are transported through the resulting borehole to the saturated zone are projected; and

(f) No releases are included which are caused by unlikely natural processes and events.

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