DEVELOPMENT OF RISK INSIGHTS IN THE U.S. NUCLEAR REGULATORY COMMISSIONS HIGH-LEVEL WASTE PROGRAM

T. McCartin, J. Danna, C. Grossman
U.S. Nuclear Regulatory Commission
Mail Stop T7F3, Washington, D.C. 20555

G. Wittmeyer
Center for Nuclear Waste Regulatory Analyses
Southwest Research Institute
6220 Culebra Road, Bldg. 189, San Antonio, Texas 78238-5166

ABSTRACT

The NRC uses a "risk-informed" approach to regulatory decision-making, a philosophy whereby risk insights are considered together with other factors to establish requirements that better focus licensee and regulatory attention on design and operational issues commensurate with their importance to public health and safety. As part of this risk-informed approach, the U.S. Nuclear Regulatory Commission's (NRC's) high-level radioactive waste (HLW) program continues to improve its documentation of related risk information and synthesis of the information to better support a risk-informed regulatory program. Development of risk insights requires an understanding of the capabilities of the multiple barriers (i.e., both engineered and natural barriers) comprising a geologic repository. For example, the safety of geologic disposal is enhanced if the system includes: (1) a long-lived waste package; (2) slow release rates of radionuclides from the engineered barrier system after waste packages are breached; and (3) slow travel of radionuclides in the geosphere.

Although the entire inventory of high-level radioactive waste represents a significant risk if the inventory were to be quickly released to the biosphere, current performance assessments indicate that the vast majority (i.e., greater than 99 percent) of the inventory will be isolated from man during the regulatory period and beyond, because of the effectiveness of the engineered barriers and the attributes of the site (i.e., natural barriers). A repository comprised of multiple barriers, as a defense-in-depth approach, is expected to be a robust repository system that is more tolerant of failures and external challenges. The NRC has developed an approach for quantifying and explaining the safety attributes and capabilities of the each of the barriers of the overall repository system. These risk insights serve as a common reference for staff to use in risk-informing the Commission's HLW program, as it continues through pre-licensing regulatory activities and prepares to review a license application that may be submitted by the U.S. Department of Energy for a HLW repository at Yucca Mountain, Nevada.

INTRODUCTION

On November 2, 2001, the U.S. Nuclear Regulatory Commission (NRC) published licensing criteria at 10 CFR Part 63 for disposal of high-level radioactive waste in a potential geologic repository at Yucca Mountain, Nevada [1]. In setting forth these criteria, the Commission sought to establish a coherent body of risk-informed, performance based criteria for a potential Yucca Mountain facility that is compatible with the Commission=s overall philosophy of risk informed, performance based regulation. Risk-informed, performance-based regulation is an approach in which risk insights, engineering analysis and judgment (e.g., defense in depth), and performance history are used to 1) focus attention on the most important activities, 2) establish objective criteria for evaluating performance, 3) develop measurable or calculable parameters for monitoring system and licensee performance, 4) provide flexibility to determine how to meet the established performance criteria in a way that will encourage and reward improved outcomes, and 5) focus on the results as the primary basis for regulatory decision-making.

Risk insights are the results and findings drawn from risk assessments and help to convey the significance of specific features, events, and processes to waste isolation capabilities and calculated estimates of system risk. Risk insights are used to communicate and describe both qualitative and quantitative understanding of how a potential repository might perform. The understanding of the performance of a geologic repository is complicated in part due to the long time periods considered for the analysis (i.e., regulatory period of 10,000 years) and the variety of processes that need to be considered (e.g., effect of heat generating waste on hydrologic and geochemical conditions, seismic events, variation in climate, etc.). Communication of the performance of a geologic repository is also complicated due to the variety of technical disciplines associated with evaluation of performance (e.g., hydrology, geochemistry, corrosion science, geology, health physics, etc.).

Over the past 15 years, the NRC and its contractor (Center for Nuclear Waste Regulatory Analyses) have developed approaches for estimating performance of the proposed repository at Yucca Mountain, Nevada [2, 3, 4 and 5]. More recently, effort has been directed at enhancing methods and approaches for developing and communicating risk insights to help prioritize pre-licensing activities, focus staff reviews, and support risk-informed project management and decision-making in the high-level waste program. Risk insights can be used to summarize current understanding of how a repository system at Yucca Mountain might function to isolate waste and, thus, protect public health and safety during the period of regulatory interest.

CHARACTERISTICS OF GEOLOGICAL DISPOSAL

The high-level radioactive waste inventory contains a variety of radionuclides with very long radioactive half-lives (see Table I). Geologic disposal has been internationally adopted as an appropriate method for ensuring protection of public health and safety for very long time periods (e.g., 10,000 years) because deep geologic disposal: 1) limits the potential for humans to come into direct contact with the waste; 2) isolates the waste from a variety of natural, disruptive processes and events occurring on the surface of the earth; and 3) limits the transport of radionuclides, after release to ground water, by the natural hydrologic and chemical properties of geologic strata comprising a potential repository site. Additionally, it has been widely accepted that a geologic repository is to be comprised of Amultiple barriers@ as a means of providing defense-in-depth. The multiple barrier approach includes consideration of both natural (e.g., hydrologic properties of rock and soil units, and geochemical retardation) and engineered or man-made (e.g., waste package and waste form) barriers as a means to contain and isolate waste.

Table I Inventory (based on the curies present at 1,000 years) and weighted inventory (based on the curies present at 1,000 years weighted by the dose conversion factor) of radionuclides evaluated in ground-water releases.

Radionuclide	Half-Life (years)	Inventory at 1,000 years (percent of total)	Ground Water Dose Conversion Factor (mrem/yr/pCi/l)	Weighted Inventory at 1,000 years (percent of total)
Americium 241 (Am241)	430	54%	4.9	56%
Plutonium 240 (Pu240)	6,500	25%	4.7	25%
Plutonium 239 (Pu239)	24,000	18%	4.7	18%
Americium 243 (Am243)	7,400	1.2%	4.9	1.2%
Technetium 99 (Tc99)	210,000	0.73%	0.0022	0.00033%
Uranium 234 (U234)	240,000	0.13%	0.38	0.010%
Nickel 59 (Ni59)	76,000	0.12%	0.00032	0.0000083%
Carbon 14 (C14)	5,700	0.065%	0.0035	0.000048%
Neptunium 237 (Np237)	2,100,000	0.064%	6.0	0.080%
Niobium 94 (Nb94)	20,000	0.042%	0.0096	0.000052%
Cesium 135 (Cs135)	2,300,000	0.027%	0.012	0.000065%
Selenium 79 (Se79)	65,000	0.023%	0.013	0.000063%
Uranium 238 (U238)	4,500,000,000	0.016%	0.35	0.0012%
Curium 246 (Cm246)	4,700	0.0032%	4.9	0.0033%
Iodine 129 (I129)	16,000,000	0.0018%	0.43	0.00016%
Thorium 230 (Th230)	77,000	0.0011%	0.74	0.00017%
Chlorine 36 (Cl36)	300,000	0.00058%	0.0061	0.00000075%
Radium 226 (Ra226)	1,600	0.00019%	1.8	0.000074%
Lead 210 (Pb210)	22	0.00019%	7.3	0.00030%

The concept of defense-in-depth is a fundamental tenet of regulating nuclear facilities. Defense-in-depth is an element of the NRC's safety philosophy that employs successive compensatory measures to prevent accidents or mitigate damage if a malfunction, accident, or naturally caused event occurs at a nuclear facility. For the postclosure repository system, the regulation at 10 CFR Part 63 incorporates the defense-in-depth concept with a requirement that the repository be comprised of multiple barriers (i.e., both engineered and natural). The defense-in-depth philosophy ensures that safety will not be wholly dependent on any single element of the design, construction, maintenance, or operation of a nuclear facility. The net effect of incorporating defense-in-depth into design, construction, maintenance, and operation is that the facility or system in question tends to be more tolerant of failures and external challenges. Risk insights can make the elements of defense-in-depth clear by quantifying the effectiveness of each barrier.

Understanding the potential risk of high-level radioactive waste involves consideration of information on the composition of high-level radioactive waste, which contains radionuclides that vary significantly with respect to inventory, radioactive half-life, and radiotoxicity. Table I provides information on the radionuclides relevant for evaluating releases in the ground-water pathway (i.e., radionuclides or daughters of radionuclides with radioactive half-lives of at least 100 years and sufficient inventory such that a portion of these radionuclides might be transported to the compliance location via ground water). As shown in Table I, the overall radionuclide activity at 1,000 years is dominated by relatively few radionuclides (i.e., Am-241, Pu-240, Pu-239, Am-243, and Tc-99). The potential risk of the overall radionuclide inventory is determined by weighting the inventory of each radionuclide by its dose conversion factor - a measure of radiotoxicity. It is similarly dominated by the same radionuclides with the exception of Tc-99, which is not as significant because of its low radiotoxicity (i.e., low dose conversion factor).

Although the entire inventory of high-level radioactive waste represents a significant risk if the inventory were to be quickly released to the biosphere, current performance assessments of a potential repository at Yucca Mountain indicate that the vast majority (i.e., greater than 99 percent) of the inventory is isolated from man during the regulatory period and beyond, because of the effectiveness of the engineered barriers and the attributes of the site (i.e., natural barriers). Evaluating the effectiveness of the multiple barriers requires an understanding of both the potential risk of the high-level waste inventory as well as the attributes of the design and site that affect the release and transport of each radionuclide. For example, 1) a long-lived waste package that retains its integrity during the period of the highest thermal output of the waste, when the waste form behavior is most uncertain; 2) radionuclides are expected to be released slowly from the engineered barrier system once the waste packages are breached; and 3) radionuclides are expected to travel slowly from the engineered barrier system to the area where potential exposures might occur because of the sorptive properties of the surrounding rock. Thus, multiple barriers, as a defense-in-depth approach, result in a robust repository system that is more tolerant of failures and external challenges.

QUANTIFYING AND DESCRIBING RISK

The risk insights for geologic disposal are developed by understanding the significance to waste isolation of the long-lived waste package, release rates of radionuclides, and transport of radionuclides in the context of the effect on risk estimates. One approach for understanding and communicating the waste isolation capability of attributes of geologic disposal is to evaluate the releases of radionuclides at certain well defined locations such as from the waste package and geologic setting (the potential receptor location or compliance location). This helps characterize the behavior of specific barriers or subsystems of the overall repository. Figures 1 and 2 represent the Aeffective@ curies released from the waste package and geologic setting, respectively. Effective curies are determined by weighting the curies for each radionuclide by its dose conversion factor, which allows the releases of radionuclides to be compared on a similar radiotoxicity basis. For the radionuclides shown in Figures 1 and 2, the vast majority of radionuclides that exit the waste package are not released from the geologic setting (i.e., at the compliance location) prior to 10,000 years. The radionuclides that tend to chemically sorb onto rock surfaces (e.g., plutonium, americium, neptunium) are not estimated to arrive at the compliance location, whereas, radionuclides such as iodine and technetium, which are less likely to chemically sorb do arrive at the compliance location. The releases of iodine and technetium are barely discernable in Figure 2; however, the release rates from the geologic setting are approximately three times smaller than the release rates from the waste package. These figures provide quantitative risk information regarding the magnitude of releases from the waste package and how the attributes of the geosphere attenuate these releases prior to reaching the compliance location.

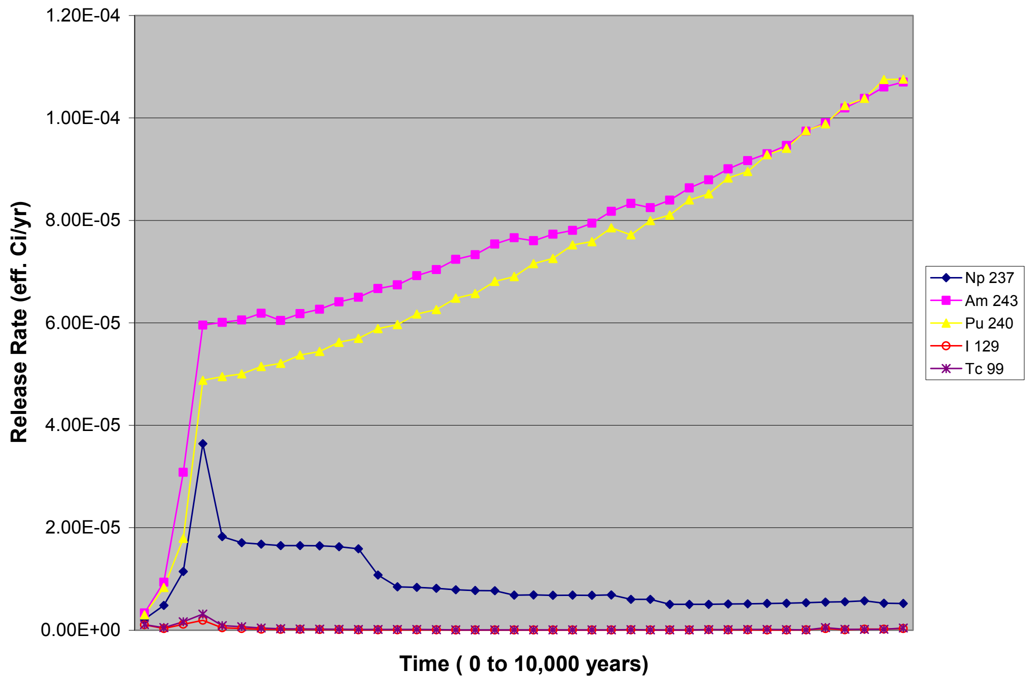

Fig. 1 Effective curies released from the waste package. Note: effective curies determined by weighting release for each radionuclide by its dose conversion factor.

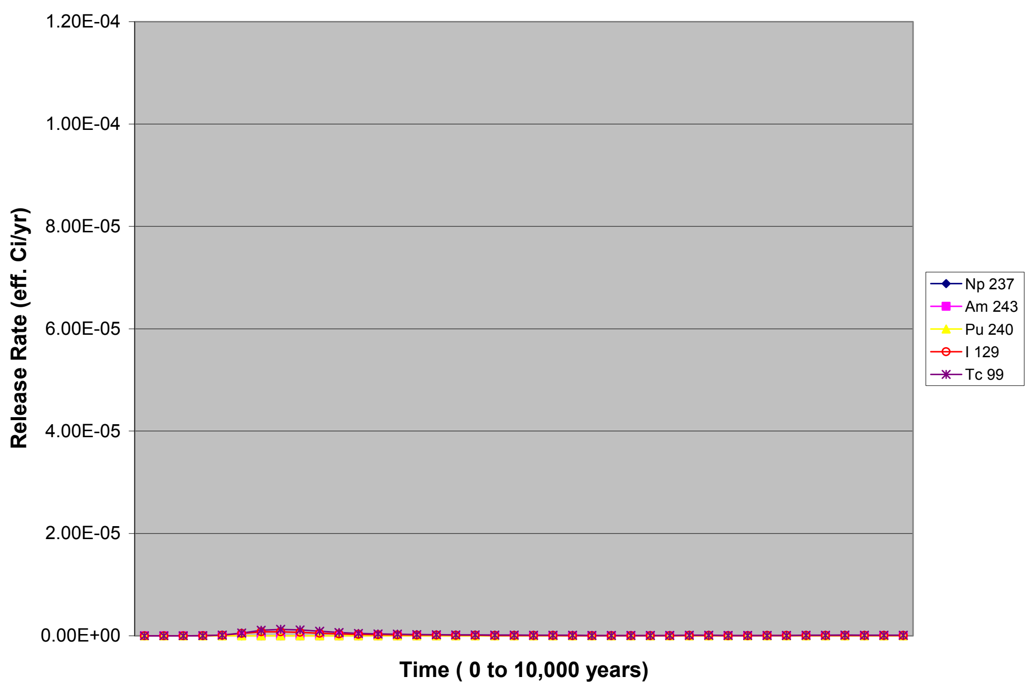

Fig. 2. Effective curies released from the geologic setting

Although the presentation of radionuclide release rates from specific subsystems are useful for understanding specific processes, this type of information does not readily convey the behavior of the spectrum of barriers of the repository system and the collective effectiveness for isolating waste. The staff has developed an approach for representing the waste isolation capabilities of specific attributes of the repository system in the context of the overall system as a means to enhance understanding and risk insights. This approach evaluates the three primary attributes for achieving waste isolation, namely: long-lived waste package, slow release of radionuclides from the engineered barriers, and slow migration of radionuclides in the geosphere. These attributes promote waste isolation by delaying and/or reducing releases of radionuclides to the compliance location. Performance assessment calculations can be used to evaluate the effectiveness of individual barriers to isolate waste. For example, delay times can be calculated for barriers that principally act to delay the onset of releases or the movement of radionuclides (e.g., waste package lifetime, transport time to move through the geosphere) whereas release rates would be a more appropriate for barriers that limit, rather than delay, releases (e.g., solubility limits, limited water contact with waste, spent fuel degradation rates).

Table II provides this type of general perspective on the capabilities of the site and design attributes for isolating the radionuclides considered in the ground-water pathway. The site and design attributes are divided into three categories affecting waste isolation, namely: delay for the onset of initial release, release rates from the engineered barrier system (principally the waste package and waste form), and transport in the geosphere. The effectiveness of each barrier associated with the attributes of waste isolation is indicated by the letter "D" or "L," which is used to represent three levels of effectiveness by the number of letters present. When the design or site attribute delays the onset of release or transport in the geosphere, the level of effectiveness was determined according to delays no less than 10,000 years (DDD), 1,000 years (DD), and 100 years (D). For the release rate, where the attribute of a barrier is not a delay but rather limits the magnitude of the release, the level of effectiveness was determined by whether the magnitude of release, if instantly released to the biosphere, would result in a potential dose of 10,000 (LLL), 1000(LL), and 100 (L) times less than 0.15 mSv (15 mrem). Table II offers a general explanation for the risk currently estimated for the proposed repository; namely, the variety and number of design and site attributes results in a very limited amount of the high-level waste inventory being transported by ground water to the compliance location. Additionally, from a defense-in-depth perspective, the importance of any one barrier is generally diminished as the number of relatively independent barriers increases - i.e., poor performance of one barrier does not cause a significant increase in the estimated risk, thus, confidence in the overall safety of the repository system is significantly enhanced when there are multiple and effective barriers.

Table II Representation of effectiveness of the attributes of waste isolation. [D denotes delay time of at least 10,000 (DDD); 1,000 (DD); 100 (D) years; and L denotes limit on release of 10,000 (LLL); 1,000 (LL); 100(L) times less than 0.15 mSv (15 mrem)]

Inventory	**Attributes of Waste Isolation**						
	Onset of Release	Release Rate			Geosphere Transport		
	Waste Package	Waste Form	Solubility Limits	Solubility & limited water	Unsat. Zone	Saturated Zone Tuff	Saturated Zone Alluvium
Am 241	DDD				DDD	DDD	DDD
Pu 240	DDD			L	DDD	DD	DDD
Pu 239	DDD			L	DDD	DD	DDD
Am 243	DDD			L	DDD	DD	DDD
Tc 99	DDD	LL			D	D	D
U 234	DDD			L	DDD	D	DDD
Ni 59	DDD	LLL	L	LL	DDD	D	DDD
C 14	DDD	LLL			D	D	D
Np 237	DDD			L	DDD	D	DDD
Nb 94	DDD	LL	LLL	LLL	D	DD	DDD
Cs 135	DDD	LL			DDD	DDD	DDD
Se 79	DDD	LL			DD	D	DD
Cm 245	DDD				D	DD	DDD
U 238	DDD	L	LLL	LLL	DDD	D	DDD
Cm 246	DDD	L			D	DD	DDD
I 129	DDD	LL			D	D	D
Th 230	DDD	LL	L	LL	DDD	DD	DDD
Cl 36	DDD	LL			DDD	DDD	DDD
Ra 226	DDD	LL		L	DDD	DD	DDD
Pb 210	DDD	LL	L	LL	DDD	DD	DDD

CONCLUSIONS

The NRC uses a "risk-informed" approach to regulatory decision-making, a philosophy whereby risk insights are considered together with other factors to establish requirements that better focus licensee and regulatory attention on design and operational issues commensurate with their importance to public health and safety. As part of this approach to use risk information in its regulatory activities, the NRC's high-level radioactive waste (HLW) program continues to improve its documentation of related risk information and synthesis of the information to better support a risk-informed regulatory program. Table 2 provides risk insights that clarify the elements of defense-in-depth by quantifying and presenting the capabilities of the safety attributes of the repository site and design. Quantification of overall system behavior, as depicted in Table II, provides a useful approach for representing and communicating the understanding of the performance of a potential repository. This approach quantifies the effectiveness of individual barriers which contribute to waste isolation, and provides a depiction of the effectiveness of the repository system through the depiction of the key attributes of the overall system. This information on risk insights serves as a common reference for staff to use in risk-informing the Agency's HLW program, as it continues through pre-licensing regulatory activities and prepares to review a license application that may be submitted by the U.S. Department of Energy for a HLW repository at Yucca Mountain, Nevada.

ACKNOWLEDGMENT

The NRC staff and CNWRA staff views expressed herein are preliminary and do not constitute a final judgment or determination of the matters addressed or of the acceptability for a geologic repository at Yucca Mountain.

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