An Independent Analysis of External Radiation Dose Fields in an Underground Facility at the Potential High-Level Waste Geologic Repository at Yucca Mountain, Nevada

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Abstract—*Radioactive waste handling operations at a potential high-level radioactive waste (HLW) geologic repository at Yucca Mountain, Nevada, would involve receiving, processing, aging, and emplacing HLW equivalent to 70,000 metric tons of heavy metal over a period of several decades. During this period, external radiation dose could be a dominant fraction of the collective annual personnel dose at the repository surface and underground facilities. This paper presents results of an independent analysis of the external radiation dose fields for various designs at a potential repository underground facility, performed at the Center for Nuclear Waste Regulatory Analyses (CNWRA). In order to analyze external dose fields, radiation source terms have been developed for commercial spent nuclear fuel (SNF) assemblies. Full scale three-dimensional models of waste packages and underground repository drifts were used in the Monte Carlo radiation transport simulations. Radiation dose rates along the drifts have been evaluated for multiple waste packages for SNF-emitted photons, neutrons, and Co-60 photons. Analysis shows that SNF photons contribute more than 68 percent, Co-60 photons contribute less than 30 percent, and neutrons contribute less than 2 percent to the total dose rates. The contribution of photons scattered off the drift walls is less than 10 percent of the total dose rates. For a single waste package loaded with average SNF, total dose rates drop from 50 rem/hr [500 mSv/hr] at 1 m [3.3 ft] from waste package surface to about 4 mrem/hr [40 mSv/hr] at 100 m [109 yd] from the waste package and to about 1 mrem/hr [0.01 mSv/hr] at a 600-m [656 yd] distance. The drift elbow significantly blocks direct radiation shine and reduces scattered dose rates at the junction of turnout and main access drifts where workers could be present. The waste packages themselves block radiation from waste packages placed behind them.*

I. INTRODUCTION

In the United States, the Yucca Mountain site in Nevada has been selected as a potential geologic repository for high-level waste (HLW), consisting of spent nuclear fuel (SNF) and solidified waste, equivalent to 70,000 metric tons of heavy metal. The period before the permanent closure of the repository (referred to as the preclosure period) would include when waste is transported to the site, prepared for disposal, and emplaced underground. During these waste handling operations, workers at the Geologic Repository Operations Area (GROA) could be exposed to external radiation emitted from HLW. In its potential license application for a HLW repository at Yucca Mountain, Nevada, the U.S. Department of Energy (DOE) would have to demonstrate that exposures to personnel at GROA during normal operations would be below the occupational exposure limits as required by the

U.S. Nuclear Regulatory Commission (NRC) in 10 CFR Part 63. The repository would consist of a network of underground access and horizontal emplacement drifts (also referred to as tunnels).

Approximately 70 miles [113 km] of tunnels would be excavated within Yucca Mountain for this network, with 40 miles [64 km] of the tunnels designed as emplacement drifts. After emplacement operations begin in prepared portions of the repository (also referred to as panels), workers could be present in the main access drifts. Waste packages are not designed to provide radiation shielding from HLW; therefore, emplaced waste packages may present a direct radiation hazard to workers in the main access drifts. In 1997, DOE reported some preliminary results of its radiological evaluation of a repository underground facility [1]. The evaluation was based on the current DOE design for the waste package and repository, source term estimates, and emplacement concepts. These designs, estimates, and concepts have changed significantly since then; therefore, the results presented by DOE [1] may not be applicable to the current repository design. Based on preliminary DOE analyses [2], external radiation dose is expected to be a dominant fraction of collective annual worker dose at the repository facilities. As part of the preparation for reviewing the potential DOE license application for a geologic repository at Yucca Mountain, the CNWRA staff have conducted an independent radiological analyses of the repository underground facility based on DOE information on the proposed as currently designed underground facility [2].

This paper presents the ongoing analyses of external radiation dose fields. Focus is on the external radiation dose fields at the underground repository drifts during preclosure waste handling operations under normal operating conditions. Section III.A presents results of the generation of average and bounding source terms used in the radiological evaluations. Section III.B presents results for evaluated dose fields within emplacement and access drifts. Section III.C presents results for radiation dose fields within an elbow-shaped access drift turnout serving as a junction between emplacement and main access drifts. Results from limited parametric studies were conducted using varying source term composition. The number of waste packages, and drift geometry are also presented.

II. METHOD

The analyses of the radiation dose fields within drifts are separated into two parts: (i) the generation of the radiation source terms to represent the SNF at the appropriate burnup and cooling time and (ii) the radiation transport Monte Carlo simulations to calculate the dose rates along the drifts. Resulting particle fluxes at locations of interest are converted into dose rates.

External radiation source terms are necessary elements of external radiation field analysis. Various types of HLW would be put in the repository emplacement drifts. The focus of this study is on commercial pressurized water reactor (PWR) SNF assemblies that are treated as repository representative wasteform. Other repository wasteforms are expected by DOE to be bounded by this analysis. DOE has identified two levels of source terms for its analyses: (i) average and (ii) bounding [3]. CNWRA generated source terms for these levels using two modules of SCALE Version 4.4A [4] code system: SAS2H [5] and ORIGEN-S [6]. The SNF assemblies and reactor core characteristics and assembly operational history in the reactor were used as input. The SAS2H module uses a one-dimensional neutron transport model. The ORIGEN-S module conducts isotope point-depletion/generation computations.

The repository dose field analyses presented below use SNF assembly neutron and photon source strengths and spectra information generated by the SAS2H and ORIGEN-S calculations.

Radiation dose rate calculations use the average and bounding radiation source terms as inputs. The dose rates are calculated using the Monte Carlo N-Particle Version 5 code (MCNP5) [7]. The MCNP5 code is capable of three-dimensional neutron-gamma coupled radiation transport and shielding analysis involving such processes as radiation streaming, scattering, and secondary radiation generation within complex structures of various material compositions. The code uses continuous energy cross sections in full three-dimensional geometry. In addition to the source terms, the MCNP5 input included three-dimensional models of the waste packages and emplacement and access drifts. The dose rate analyses for underground drifts were carried out assuming 21 PWR SNF assemblies placed within a waste package (21-PWR waste package configuration). Figure 1 presents a graphical representation of a 21-PWR waste package as modeled in this study (side walls were made semi-transparent in order to show internals). The representation corresponds to the DOE preliminary design [8,9]. The waste package consists of outer and inner containers designed to function as corrosion resistant barrier and structural support, respectively. The waste package does not have a design function to shield personnel from radiation. For these analyses, components of SNF assemblies and waste package internals have been homogenized inside the waste package within three separate regions: (i) fuel region, (ii) assemblies upper, and (iii) lower end fittings. The fuel region contains SNF photons, neutrons and Co-60, and end fittings regions contain only Co-60 as radiation source terms. Radiation dose rate calculations have been conducted for single and multiple waste packages in an emplacement drift. Resulting particle fluxes are converted to dose rates using flux-to-dose-rate conversion factors from the American National Standards Institute and American Nuclear Society [10].

III. RESULTS

Results are presented in terms of external radiation dose rates at various distances from the waste packages emplaced in an underground drift and for scattered radiation dose rates in access drift turnout (e.g., in a drift elbow or turnout drift). Two drifts are considered in the analyses: (i) a 600-m long [656-yd long] cylindrical drift representing repository emplacement and access drifts and (ii) a turnout drift (also referred to as access drift turnout) representing the junction of the repository main access drift with access and emplacement drifts.

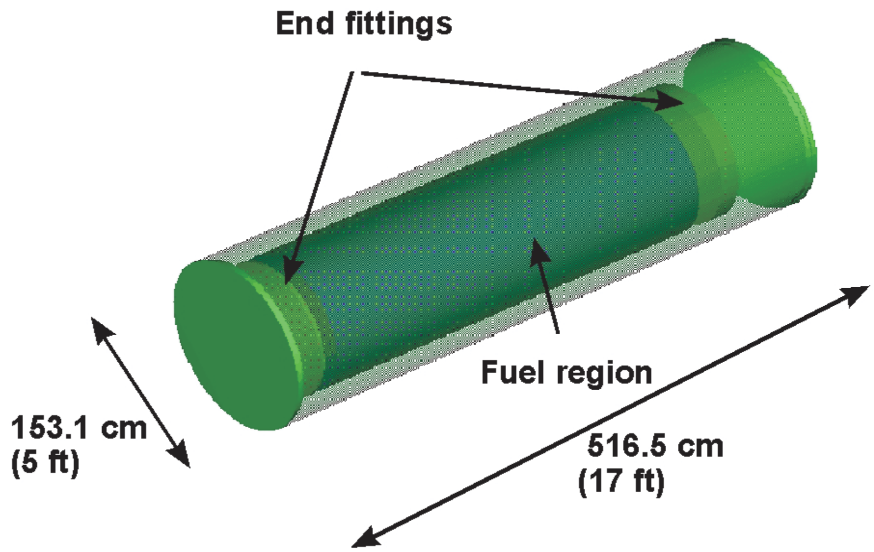

Figure 1. Locations of Radiation Sources Within 21-PWR Waste Package. Waste Package Side Walls Are Semi-Transparent.

Access and emplacement drifts have 7.62-m [8.33-yd] and 5.5-m [6.02-yd] internal diameters, respectively. Drift walls are modeled as a 10-cm [3.9-inch] inner concrete lining and 15-cm [5.9-inch] outer volcanic tuff layer. The photon and neutron fluxes are calculated at certain points along the drift axis in case of the 600-m [656-yd] long cylindrical drift and as the average particle flux values across drift cross-sectional planes in the turnout drift.

III.A. Average and Bounding Source Terms

The characteristics of SNF assemblies and the parameters of their operational history in the reactor, used as input for the source-term generation, are presented in Table I. These characteristics and parameters are based on the design basis of source term analyses conducted by DOE [1,3]. The cobalt content corresponds to zircaloy cladding for the average assembly and to stainless steel cladding for the bounding assembly [3]. The generated photon and neutron source terms in Table I are described in terms of the source strength and energy spectra (not shown).

III.B. Dose Fields in 600-m Long Cylindrical Drift

Dose rates are evaluated separately for (i) SNF photons without Co-60 contribution, (ii) neutrons, and (iii) Co-60 photons. Results for the first 150-m [164-yd] drift section adjacent to a single emplaced waste package loaded with average SNF are presented in Figure 2. Farther away from the waste package along the drift, dose rates drop significantly to about 60-μrem/hr [0.6-μSv/hr] level at 300 m [328 yd] from the waste package and to about 1 μrem/hr [0.01 μSv/hr] at a 600 m [656 yd] distance. The contribution of SNF photons to the dose rates, without accounting for Co-60 contribution, is on the order of 70–73 percent of the total dose rates. The Co-60 contribution to the total dose rate is on the order of 25–29 percent and the contribution of neutrons is on the order of 0–2 percent for various distances along the drift axis. Photons scattered off the drift walls contribute less than 10 percent to the total dose rates along the drift as presented in Figure 3. Results for the effect of adding more waste packages on photon dose rates are presented in

Table I. Characteristics of SNF Assemblies Used in Source-Term Derivation and Resulted Source-Term Strength

	Average SNF	**Bounding SNF**	**Ratio of Bounding to Average SNF**
Assembly Type	PWR 15 × 15	PWR 15 × 15	N/A
Initial Uranium Enrichment, Percent	4	5	1.25
Initial Uranium Loading, Kg/assembly [lb/assembly]	475 [1,047]	475 [1,047]	1
Cobalt Content, g/assembly [lb/assembly]	50 [0.11]	160 [0.353]	3.2
Burnup, GWD/MTU	48	80	1.7
Cooling Time, years	25	5	0.2
Total Photon Emission, photons/sec/assembly	1.6×10^{15}	8.9×10^{15}	5.6
Co-60 Photon Emission, photons/sec/assembly	2.3×10^{13}	1.4×10^{15}	58
Total Neutron Emission, neutrons/sec/assembly	2.1×10^{8}	1.4×10^{9}	6.7

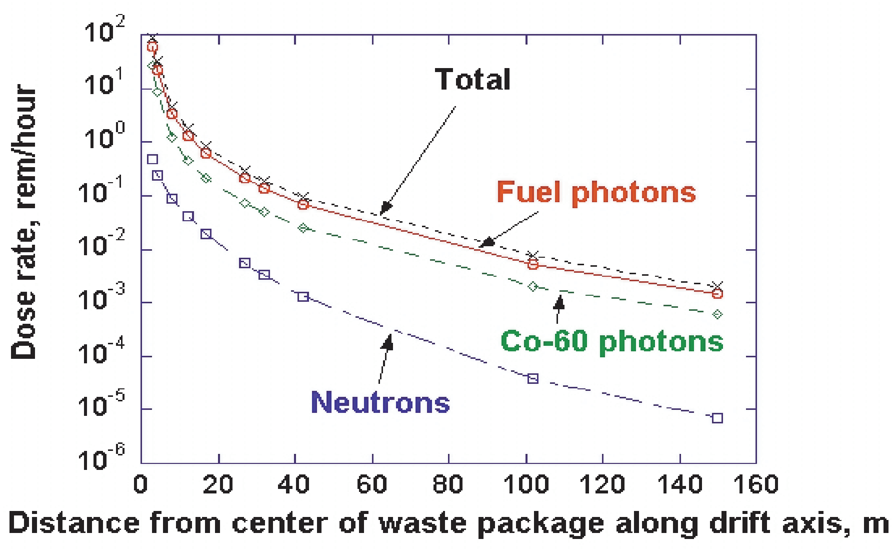

Figure 2. Drift Axial Dose Rates From a Single Waste Package For an Average Source Term.

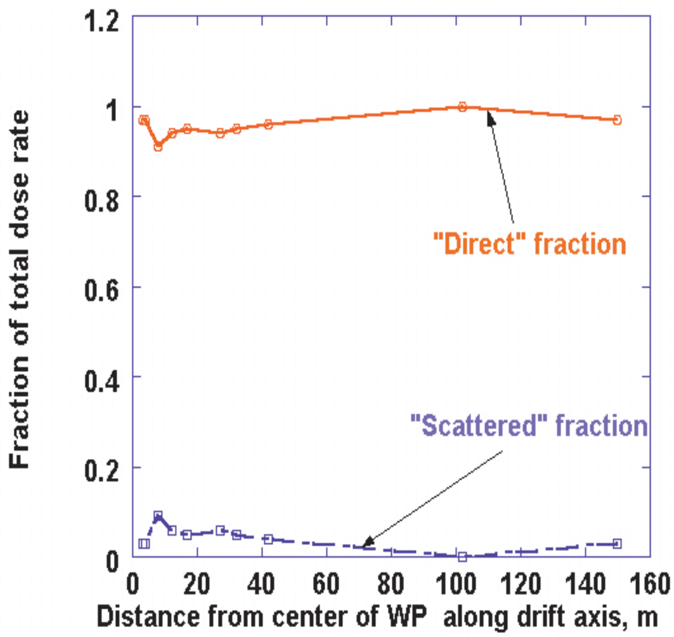

Figure 3. Contributions of "Direct" and "Scattered" Photons to the Total Photon Dose Rate Along 150-m [164-yd] Drift Centerline From Single Waste Package. "Scattered" Refers to Photons Emitted from the Waste Packages That Scatter off the Drift Walls.

Figure 4. It was found that dose rates for the bounding source term are 14–19 times higher than for the average source term.

III.C. Dose Fields in the Turnout Drifts

Workers may not be present in emplacement drifts during and after waste package emplacement. Direct radiation shine from waste packages already in emplacement drifts may pose a radiation hazard to workers in main access drifts. The portion between the emplacement drift and main access drift is called the access drift. There would be no waste packages emplaced within the access drift. The junction between the access drifts and the main access drift is called the turnout drift, which is shaped as an elbow, as depicted in Figure 5 (configuration B). The turnout drift has been designed in such a shape so that its curvature (composed of rock) would block direct radiation shine to the main access drift from waste packages in the emplacement drift. Radiation scattered off the turnout drift walls potentially may reach the main access drift and may pose a radiation hazard to repository personnel. Photon radiation scattering within the turnout drift has been investigated in this study. The turnout drift design details, including its shape, are not yet known. The shape of the turnout drift may affect the scattering and, consequently, dose rates in the main access drift. The effect of the turnout drift shape on radiation fields has been investigated for turnout drifts of two shapes: (i) angled, as in Figure 5 (configuration A) and (ii) toroidal, as in Figure 5 (configuration B).

Dose rate results for both turnout drift configurations and for one waste package in the emplacement drift are presented in Table II. Dose point 1 is located on the drift cross plane inside turnout drift about 18 m [19.7 yd] from the main access drift (about halfway between the main drift and the line

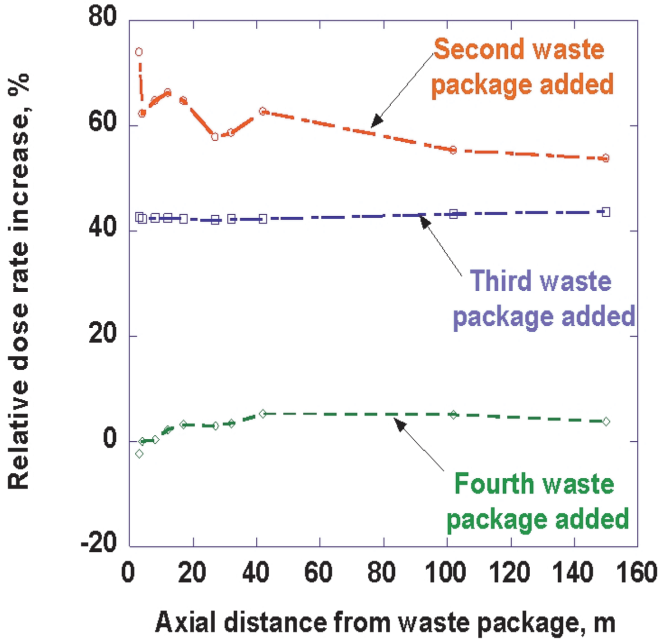

Figure 4. Effect of the Addition of More Waste Packages on Photon Dose Rates Along the Drift Centerline

of direct radiation shine). Dose point 2 is located at the junction of the turnout and main access drifts. There is no direct radiation shine from emplaced waste packages at either point. The turnout drift shape has a greater effect on dose rate at point 1 and a lesser effect at point 2. The dose rate ratios are about 7.3 and 1.6 (for Configuration B compared to the Configuration A) for dose points 1 and 2, respectively.

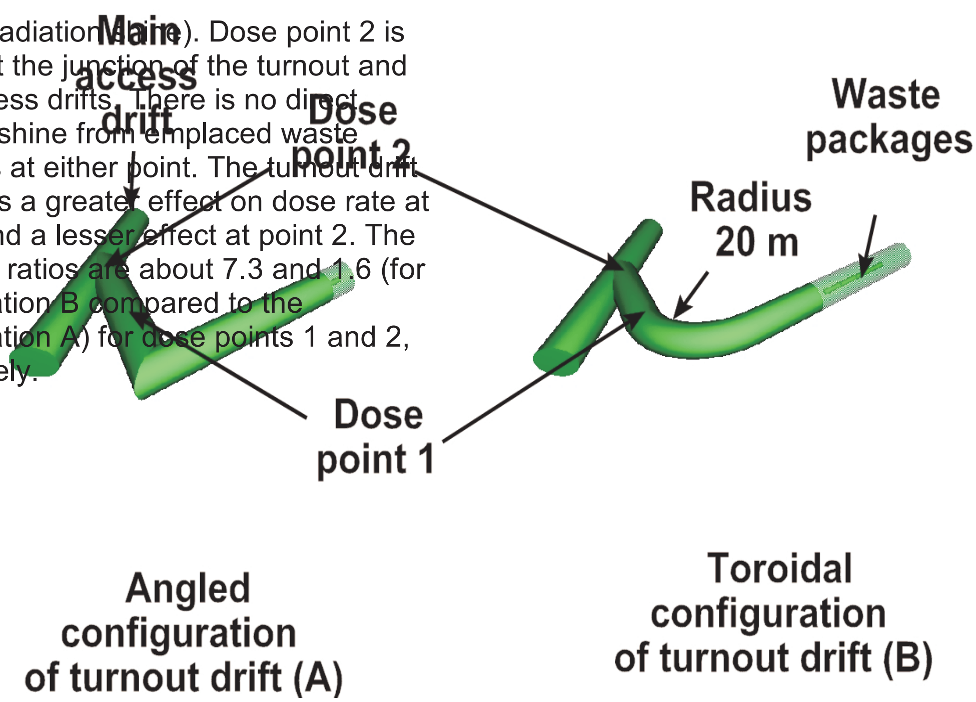

Figure 5. Two Configurations of Turnout Drift: Angled (A) and Toroidal (B). Dose Points 1 and 2 Are Located Inside the Drifts on the Drift Cross Planes.

Table II. Comparison of Gamma Dose Rates for Two Different Turnout Drift Configurations: A and B on Figure 5. Radiation is Emitted From a Single 21-PWR Waste Package Containing Average SNF Assemblies. Dose Rates Are in mrem/hr [10^{-5} Sv/hr].			
	Turnout Drift Configuration		Dose Rate Ratio, B/A
	A	B	
Dose Point 1 from Figure 5	0.15	1.1	7.3
Dose Point 2 from Figure 5	0.03	0.048	1.6

Results for gamma dose rates for turnout drift configuration B from one and four waste packages are presented in Table III. In both dose point locations, dose rates double in the case of four emplaced waste packages as compared to a single waste package. The factor of two increase in dose rate is attributed mainly to the self-blocking effect of front waste packages on radiations emitted from rear waste packages.

Dose rates for bounding SNF are found to be about 5 times higher in either point 1 or 2 in Figure 5 than those for average SNF for toroidal configuration B.

IV. CONCLUSIONS

Based on the radiation transport simulations presented above, some radiation protection assessments can be made for GROA workers in an underground facility. For normal geologic repository operations, based on DOE preliminary designs, in the case of four waste packages in an emplacement drift with average SNF, the in-drift radiation dose field would be 1 rem/hr [10 mSv/hr] at a 20-m [21.9-yd] distance from the closest waste package. The elbow-shaped turnout drift provides significant radiation shielding for the main access drift, reducing dose rate caused by scattered photons to levels under 1 mrem/hr [10 *m*Sv/hr] for up to four emplaced waste packages. This should make the main drift generally accessible to workers with appropriate monitoring and protection. However, it was found that the gamma dose rate rapidly increases within the elbow-shaped turnout drift from 0.1 mrem/hr [1 *m*Sv/hr] at the junction with the main drift to 2.6 mrem/hr [26 *m*Sv/hr] at around the midpoint distance from the junction to the line of direct radiation shine within the access drift. These calculations provide insights of radiation field characteristics in the proposed as currently designed underground facility. It was found that the neutron component of the total external dose rate for average SNF is below 1 percent. The Co-60 contribution to the dose rates along the access drift varies from 25 to 29 percent of the total external dose rates for average SNF. Photons scattered off the drift walls contribute less than 10 percent to the total dose rates along the drift. Dose rates from scattered photon radiation were found to be sensitive to the turnout drift shape, with greater sensitivity for locations closer to the emplacement drift.

As a result of this study, insights have been gained of potential radiation dose fields in an underground facility of the potential HLW geologic repository at Yucca Mountain, Nevada. These insights can be used to assess worker dose estimates, radiation protection features such as supplementary shielding and accessibility controls such as personnel barriers in an underground facility. Results of the analyses will assist the NRC and CNWRA staffs in evaluating compliance with occupational exposure requirements in conjunction with as low as reasonably achievable requirements and the DOE radiation protection program.

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Table III. Effect of Additional Emplaced Waste Package on Gamma Dose Rates in the Turnout Drift of Configuration B in Figure 5. Radiation Is Emitted From One or Four 21-PWR Waste Package Containing Average SNF Assemblies. Dose Rates Are in mrem/hr [10^{-5} Sv/hr].

	Number of Emplaced Waste Packages	
	1	4
Dose Point 1 From Figure 5	1.1	2.3
Dose Point 2 From Figure 5	0.048	0.1

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