A Parametric Analysis of Factors Affecting Calculations of Estimated Dose Rates from Spent Nuclear Fuel Shipments[1] - 16458

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ABSTRACT

Planning for transportation of SNF requires estimation of the radiation dose to the members of the public associated with the transportation. This dose is expected to be very low compared to natural background radiation because dose rates and exposure durations are minimal. A preliminary investigation was performed to estimate the dose rate from a SNF transportation package as a function of distance and evaluate factors affecting the estimated dose rate, such as local environment modeling. Effects on the dose rate are determined for changes in temperature and relative humidity of the air surrounding a transportation package and for different compositions of the ground underneath it. The impact of different vapor content in air was evaluated to be small, within the statistical uncertainty of the dose rate estimates. The neutron dose rate contributions from scattering interactions within different soil/pavement materials were from approximately 20% to 70% at 25 cm from the ground and from approximately 10% to 40% at 175 cm from the ground. The effect of photon scattering interactions within different soil/pavement materials was an increase in photon dose rate of less than 20% at 25 cm from the ground and less than 10% at 175 cm from the ground. The impact of different ground materials on the total dose rate would depend on the relative contributions of photon and neutron dose rates to the total dose rate.

INTRODUCTION

DOE's Nuclear Fuels Storage and Transportation Planning Project was established to lay the groundwork for implementing interim storage of SNF, including associated transportation from commercial nuclear power plant sites to an interim storage facility. Transportation planning requires an understanding of the radiation dose to

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members of the public associated with SNF transportation. This dose is expected to be very low compared to natural background radiation because dose rates and exposure durations will be minimal. Dose limits for individual members of the public are established in 10 CFR Part 20 [1]. The total effective dose equivalent to individual members of the public from activities conducted under NRC licenses is limited to 1 millisievert (mSv) in one year, and the dose in any unrestricted area from external sources is limited to 0.02 mSv in one hour (10 CFR 20.1301).

Dose rate limits for a transportation package are provided in 10 CFR Part 71 [2] (e.g., 0.1 mSv/h at 2 m from the outside edge of the vehicle transporting the cask under normal conditions of transport). Dose rate decreases as a function of distance from the radiation source and is expected to reach very low values at large distances from the transportation package. Assessment of the dose to members of the public has historically used idealized analytical models of dose rate as a function of distance from a transportation package [3,4]. The analytical models use isotropic point or line source approximations to represent the transportation package and incorporate adjustment factors to account for the actual geometry of the package. Different analytical models were developed for neutron and photon dose rates. Fitting coefficients were derived from either one-dimensional discrete ordinates calculations (neutron dose rate only in Ref. [3]) or Monte Carlo calculations [4]. The simplified point source approximations have been shown to produce conservative dose rate values at large distances from a transportation package (e.g., beyond 100 m) [3,5]. However, the effects of the environment (e.g., air, ground, buildings, and vegetation) on dose rate from a transportation package have not been rigorously evaluated and incorporated in the analytical dose rate models.

A detailed 3-dimensional (3-D) transportation package model and detailed simulation of the interactions that radiation undergoes within the media provide a capability for more accurate dose rate calculations. This paper presents dose rate calculations for a representative SNF transportation package using a Monte Carlo radiation transport code and evaluates the impact of variations in the atmospheric and ground compositions on dose rate.

CALCULATION METHOD

Computer Code

The dose rate as a function of distance from a transportation package was calculated with MAVRIC [6], the SCALE [7] Monte Carlo radiation transport sequence with automated variance reduction capabilities. *Variance reduction* refers to methods and techniques that significantly increase the efficiency of Monte Carlo radiation transport calculations. A variance reduction method referred to as *forward-weighted consistent adjoint driven importance sampling* (FW-CADIS) [8,9] was used in the MAVRIC calculations to obtain dose rate estimates with good statistical accuracy outside a transport package. This method requires both forward and adjoint discrete ordinates calculations with Denovo [10]. The adjoint calculation solution identifies the spatial regions and energy ranges of the source that make important contributions to dose rate within a geometry region of interest. Dose rate within mesh tally voxels was calculated with the track length estimator. The ANS/ANSI-6.1.1-1977 flux-to-dose factors [11] were used in the dose rate calculation.

Transportation Package Model

The calculation model is a SCALE representation of a high-capacity SNF transportation package at normal conditions of transport. The model consists of the HI-STAR 100 cask [12] containing 24 Trojan plant design basis SNF assemblies with an initial ^{235}U enrichment of 3.09 wt%, a burnup value of 42,000 MWd/MTU, and a 16-year cooling time. This fuel assembly contains gamma and neutron sources in the active fuel region and ^{60}Co activation sources in fuel assembly hardware regions. For this transportation package model, the calculated dose rate at two meters from the personnel barrier assuming infinite air medium is approximately 0.1 mSv/h. The transportation package, surrounded by air, is represented in horizontal orientation with its longitudinal axis located at 3 m from the ground. The ground was modeled to 1 m in depth to account for radiation scattering, absorption, and secondary radiation production in the ground/pavement material. The rail car, impact limiters, and personnel barrier were not explicitly represented in the model, so the dose rate results presented in this paper are slightly conservative. However, the dimensions of the impact limiters and rail car were considered when establishing the distance between the package's longitudinal axis and the ground. A cross section view of the representative transportation package model is illustrated in Fig. 1. The dose rate was calculated for distances up to 250 m from the transportation package (Fig. 6) to ensure dose rate estimates with low statistical uncertainties.

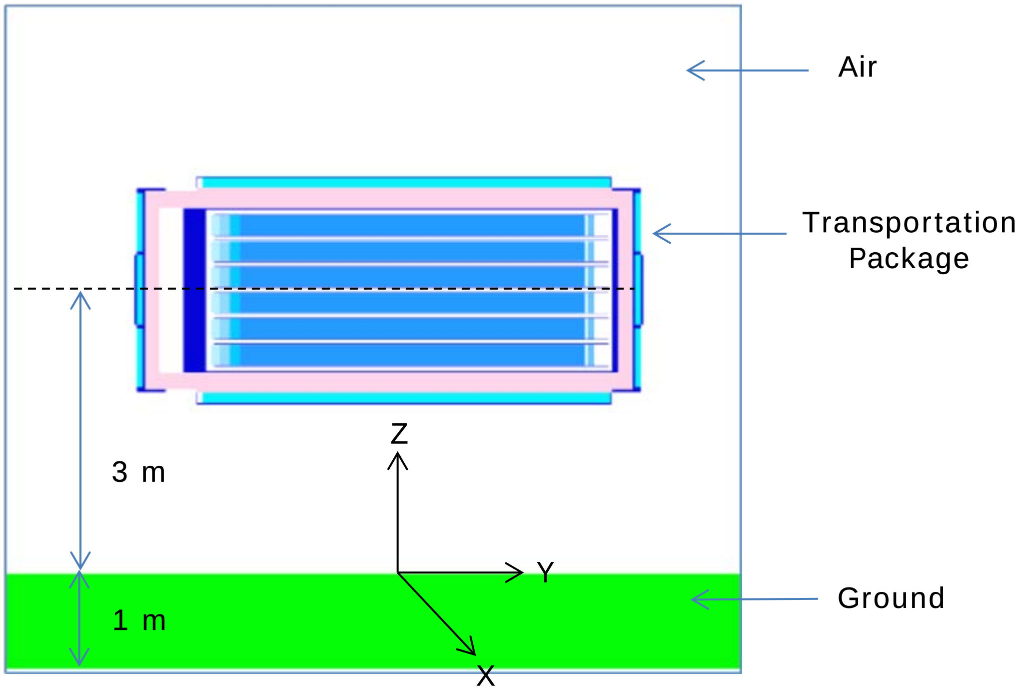


Fig. 1. Cross Section View of the Transportation Cask Model.

NEAR-FIELD ANALYSIS

Radiation escaping from the transportation package may penetrate the ground and undergo multiple scattering interactions with the nuclei or electrons of the medium. The incident radiation that reemerges into the air as a result of scattering within the ground/pavement is referred to as *groundshine*. The dose rate in the air regions near the ground includes contributions from the direct radiation and the groundshine because scattering within the surrounding air would have negligible contributions to the near-field dose rate [13]. Hence, an infinite air medium approximation without taking into account groundshine would underestimate dose rate in the regions above the ground. The near-field analysis of dose rate in this paper evaluates the groundshine effects of different soil/pavement materials.

Soil/pavement materials have different effects on neutron and photon radiation; groundshine dose rate contribution is more important for neutrons than for photon radiation. Fast neutrons escaping from the cask are slowed down primarily by multiple elastic scattering interactions with the nuclei within the surrounding media. Neutron interaction with hydrogen nuclei most effectively degrades the neutron energy to very low values. Thermalized neutrons may be captured by nuclei in the interacting medium producing energetic photons. Therefore, media with large hydrogen content are expected to produce smaller groundshine effects than media with little or no hydrogen content. Hydrogen content in soil depends on the type of soil and its water content. Acidic soils contain greater concentrations of hydrogen than alkaline soils. Water content depends on water availability and soil porosity, which varies from approximately 40% for sandy soils to 52–64% for loamy soils [14]. Pavement materials such as concrete or asphalt also contain hydrogen. Photons escaping from the transportation package have relatively high energies and are predominantly attenuated by Compton scattering interactions with the electrons of the atoms. High energy photons are predominantly scattered in the forward direction (i.e., the attenuating medium does not have significant backscattering effects for the energetic photons escaping from the transportation package). Secondary gamma rays may be generated as a result of neutron slowing down and capture in the ground/pavement material.

The dose rate was evaluated within a height of 2 m from the ground and 40 m from the center of the cask in the radial direction. The extent of the tally mesh was 40 m along the x axis, 0.5 m along the y axis, and 2 m along the z axis (Fig. 1), and the dose rate values were estimated within mesh tally voxels of approximately 0.5 m × 0.5 m × 0.5 m. Dose rate values assuming infinite air medium are used as reference values to evaluate the groundshine effects of different ground/pavement materials because scattering within surrounding air produces negligible contributions to the near-field dose rate.

Ground/Pavement Materials

Five materials were evaluated for groundshine effects: soil without hydrogen content (i.e., dry soil), soil with water content (i.e., wet soil), ordinary concrete, a concrete type with a large content of iron (i.e., iron-Portland concrete), and asphalt. These materials have differing mass densities and elemental compositions and concentrations [7,15]. Their mass densities vary from 1.52 g/cm^3 for dry soil to 5.9 g/cm^3 for the iron-Portland concrete. Except for the dry soil, the materials contain different concentrations of hydrogen, ranging from 0.33% in the iron-Portland concrete to 3.50% in wet soil.

Neutron Dose Rate

Neutron dose rate variation as a function of distance for infinite air medium and for the different pavement/soil materials considered in the analysis is illustrated in Fig. 2. The dose rate values in the figure, estimated with a maximum relative error of 1%, are shown at 175 cm from the ground. The statistical uncertainty associated with the dose rate estimates is illustrated by the error bars representing ± 2 standard deviations. As seen in the figure, ground/pavement materials have clear neutron groundshine effects that can be distinguished from the dose rate assuming infinite air medium. The increase in the neutron dose rate in the air region above the ground was between approximately 10–70%, depending on the soil/pavement material and the distance from ground, as shown in Fig. 3. As expected, the soil with water content had the smallest groundshine effect, and the soil without any hydrogen content had the largest groundshine effect. The neutron energy spectrum is important because harmful biological effects increase with increasing neutron energy [11]. The effects of the scattering medium on the neutron energy spectra within a mesh tally voxel can be observed in Fig. 4. Compared to dry soil or infinite air medium, wet soil has pronounced moderating effects on neutrons, primarily from neutron interactions with the hydrogen nuclei, as illustrated by the low energy region of the neutron spectra. Compared to wet soil or infinite air medium, dry soil produces more energetic backscattered neutrons as illustrated by the high-energy region of the neutron spectra due to significantly smaller neutron energy loss from elastic scattering interactions.

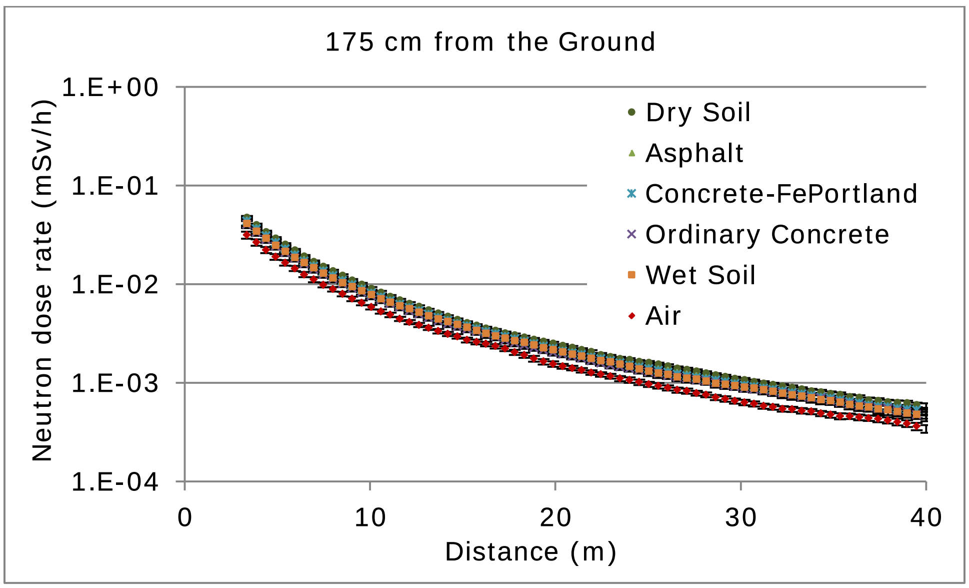
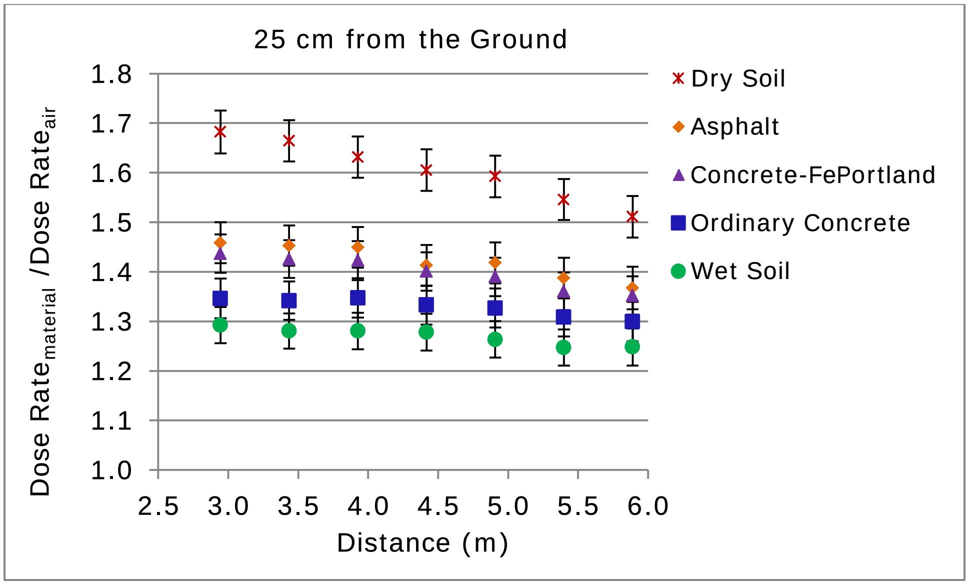
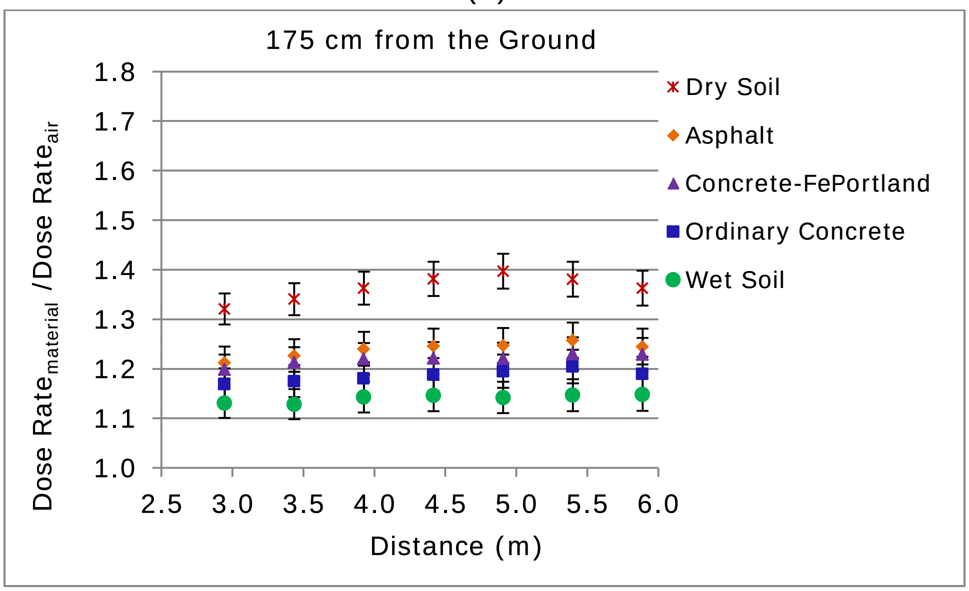


Fig. 2. Neutron Dose Rate at 175 cm from the Ground as a Function of Distance from the Transportation Package.



(a)



(b)

Fig. 3. Groundshine Effects on Neutron Dose Rate as a Function of Distance from the Transportation Package at (a) 25 cm and (b) 175 cm from the Ground.

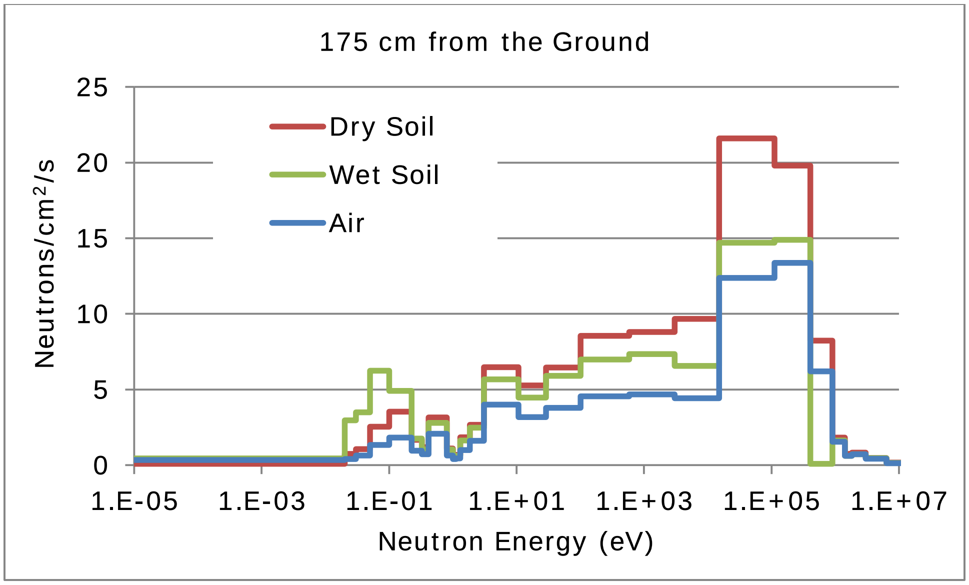


Fig. 4. Neutron Energy Spectra in Air
Assuming Different Ground Materials.

Photon Dose Rate

The groundshine contributed 10% to 20% of the total photon dose rate near the ground and less than 10% of the total photon dose rate at 175 cm from the ground. Photon dose rate variation as a function of distance for the different soil/pavement materials is illustrated in Fig. 5. The dose rate values in the graph, which were evaluated at 175 cm from the ground, are shown with error bars representing ±2 standard deviations. As shown in the graph, the different media have small backscattering effects on photons, which are approximately within the statistical uncertainty of the dose rate estimates based on infinite air medium.

Total Dose Rate

The groundshine effect on the total dose rate would depend on the relative contributions of the photon and neutron dose rates to the total dose rate. Groundshine would have relatively small effects on a total dose rate that is dominated by gamma dose rate. For the cask evaluated in this paper, the gamma dose rate of which represents approximately two thirds of the total dose rate, the groundshine contribution to the total dose rate at 175 cm from the ground would be approximately 10 to 20% depending on the ground composition.

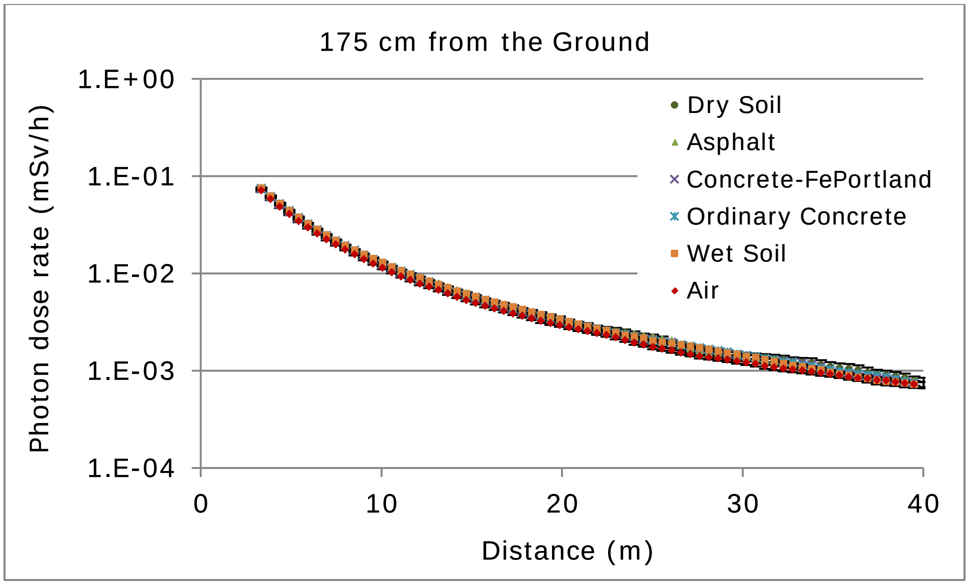


Fig. 5. Photon Dose Rate at 175 cm from the Ground as a Function of Distance from the Transportation Package.

FAR-FIELD ANALYSIS

Surrounding air has scattering effects on radiation, a phenomenon known as *skyshine*. For an SNF storage cask, skyshine has been shown to have a larger effect on the neutron dose rate than on the photon dose rate, and the skyshine neutron dose rate becomes a significant component of the total dose rate at distances greater than approximately 100 m from the cask [13]. The far-field analysis evaluated the effects of air at different conditions of humidity and temperature—ranging from dry air to air with a relative humidity of 100% and a temperature of 40°C—on the dose rate within 250 m from the transportation package. Dry air has a mass density of approximately 1.2 kg/m^3 and contains approximately 78% nitrogen, 21% oxygen, and 1% other gasses. The water vapor and dry air in one metric cube of air with a relative humidity of 100% and a temperature of 40°C weigh approximately 51 g and 1.05 kg, respectively.

The dose rate above the ground was evaluated as a function of distance within 2 m from the ground and 250 m from a plane through the longitudinal axis of the transportation package. A 2-D cross section view of the geometry model in the x-z plane (see Fig. 1) is illustrated in Fig. 6. The volume of air considered in the model was 750 m × 500 m × 500 m. The ground was modeled at 1 m in depth, and the soil composition with water content was used in the model. The dose rate values were calculated with a maximum relative error of 5% within 2m × 1m × 2m tally mesh voxels.

The impact of different vapor content in air was evaluated to be small, within the statistical uncertainty (± 10%) of the dose rate estimates based on dry air. That is the dose rate within 250 m from the transportation package was not sensitive to the vapor content of air. This finding is consistent with previous observations that water in gaseous or condensed form, including heavy rain and heavy sea fog, does not contribute to air scattering to any appreciable content [16].

Neutron, photon, and total dose rate variations as a function of distance—assuming air with a 50% relative humidity at 20°C outside the transportation package—are presented in the graph shown in Fig. 7. The total dose rate values at 50, 100, 150, 200, and 250 m from the transportation package in the radial direction were approximately 8×10^{-4}, 1.5×10^{-4}, 5×10^{-5}, 2×10^{-5}, and 1×10^{-5} mSv/h, respectively. For comparison, the dose rate corresponding to average background radiation exposure in the US is approximately 4.1×10^{-4} mSv/h [17].

A comparison to a common radiation source other than natural background, one which people may be exposed to intermittently, may also be helpful. Air travel exposes members of the public to low doses of radiation for the duration of the flight. The dose rate to air travelers varies by altitude and latitude; a summary article [18] states that at the equator, the dose rate at 40,000 feet averages 2.71×10^{-3} mSv/h, while at 70° north latitude, the dose rate at 40,000 feet ranges from 4.89×10^{-3} to 8.87×10^{-3} mSv/h. The same reference [18] also lists dose rates for 32 different flights, ranging from 2.0×10^{-4} to 6.0×10^{-3} mSv/h for the duration of flights lasting from 0.6 to 13.4 hours.

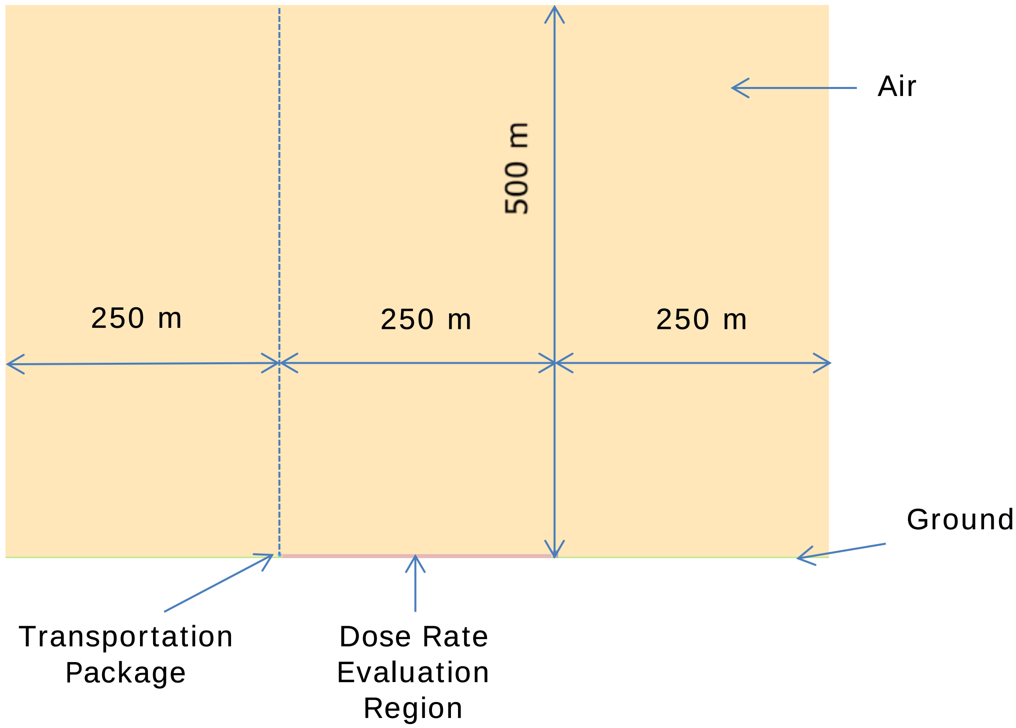


Fig. 6. Cross Section View of the Geometry Configuration for Skyshine Calculations.

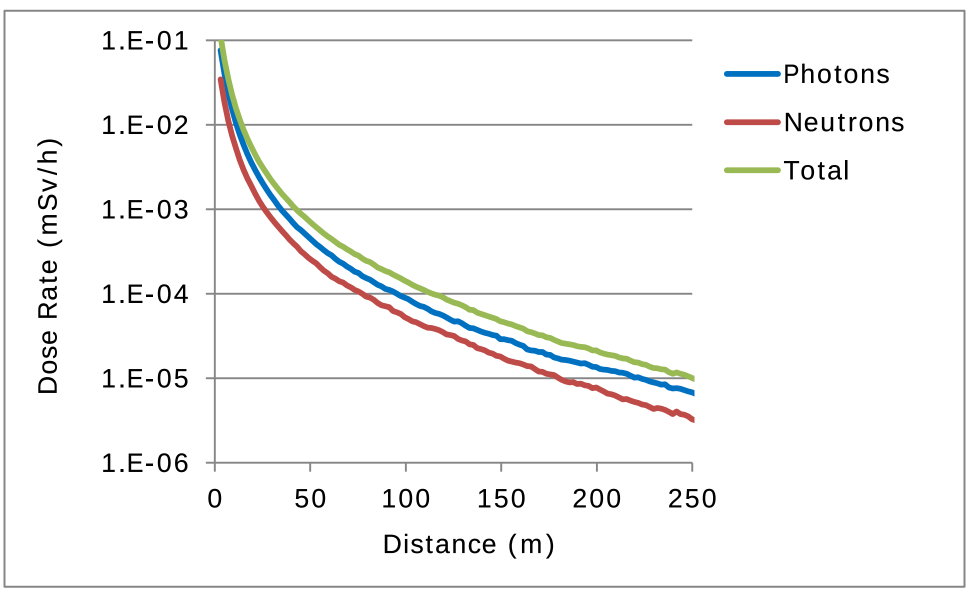


Fig. 7. Dose Rate Variation as a Function of Distance from the Transportation Package.

CONCLUSIONS

Estimated dose rate generated by a representative transportation package and factors affecting dose rate, including soil/pavement and surrounding air compositions, were evaluated within a height of 2 m from the ground and 250 m from the center of the cask in the radial direction. The groundshine effects of the evaluated soil/pavement materials, including asphalt and different types of soil and concrete, were determined by comparison to dose rate in infinite air medium. Neutron groundshine dose rate, which is sensitive to the hydrogen content of the interacting medium, increased the total neutron dose rate by 20–70% at 25 cm from the ground and by 10–40% at 175 cm from the ground. The groundshine contributed 10–20% of the total photon dose rate at 25 cm from the ground and less than 10% at 175 cm from the ground. The groundshine effect on the total dose rate would depend on the relative contributions of the photon and neutron dose rates to the total dose rate. Groundshine would have relatively small effects on a total dose rate that is dominated by gamma dose rate.

The effects on dose rate within 250 m from the transportation package were evaluated for air at different conditions of humidity and temperature. The dose rate variations due to different vapor contents were within the statistical uncertainty (± 10%) of the dose rate estimates based on dry air. Therefore, water vapor does not contribute to any significant air scattering within 250 m from the transportation package. This information will be helpful in understanding the differences in estimated dose rates received by members of the public along transportation routes. While dose rates may vary in regions due to the presence of wet or dry soil, the dose rates may not be appreciably affected by the temperature or humidity of the air.

The estimated total dose rate values at 50, 100, 150, 200, and 250 m from the center of the transportation package were approximately 8×10^{-4}, 1.5×10^{-4}, 5×10^{-5}, 2×10^{-5}, and 1×10^{-5} mSv/h, respectively. For comparison, the dose rate corresponding to average US background radiation is approximately 4.1×10^{-4} mSv/h.

This paper focuses on the estimated dose rate from a stationary transportation cask. During an actual SNF shipment under normal transport conditions, the members of the public along the transportation route would be exposed to the radiation for a very small period of time, on the order of tens of seconds.

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