Conservatism of RADTRAN Line-Source Model for Estimating Worker Exposures*

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Introduction

Concern about the risks posed to people who live along spent nuclear fuel transportation routes has led to demands for redundant inspections of the transported spent fuel. Several states appear to be considering mandatory state inspections. In actual practice, for example, research reactor spent fuel returned to the United States by sea may receive five redundant inspections (Neuhauser and Weiner, 1991) before leaving the dock area where it has been offloaded. It would be prudent to examine the radiological risk to the inspectors themselves before state or federal regulations are promulgated which require redundant inspections.

Federal regulations (10 CFR 71 and 49 CFR 173-178) require that the radiation dose rate at 1 meter from any accessible external surface of a radioactive materials package not exceed 0.1 mSv/hr (10 mrem/hr) except for packages shipped by exclusive-use vehicles (e.g., spent fuel casks). In the latter case, the maximum dose rate at any point 2 m from the vertical planes projected by the outer lateral surfaces of a closed vehicle or by the outer edges of an open vehicle may not exceed 0.1 mSv/hr. Important steps in the preparation of any radioactive materials shipment are measurement of the package dose rate at the point of origin and recording this dose rate on the shipping papers. To obtain these measurements, an individual must be 2 or 3 meters from the package surface for at least several minutes. Some state inspections take much longer: 30 to 45 minutes (Hostick, et al., 1992).

Other workers may also come close to a spent fuel cask during normal operations, even though the casks are actually lifted and moved with heavy cranes. For example, five handlers (one at each corner fitting, plus a spotter) are needed to load a containerized cask of spent fuel onto a truck with a crane (Neuhauser and Weiner, 1992). They align the corner fittings while the cask is suspended from the crane, and then secure the fittings after the cask has been lowered into place. These individuals spend several minutes within a few meters of the cask. Still another individual may inspect and tag the fittings after the cask is secured to the truck. The drivers of the truck also inspect the fittings, handle shipping papers, and so on, and have been observed to spend up to ten minutes a few meters from the cask.

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The dose rate to which these inspectors and handlers are exposed is higher than the dose rate to which any other group is exposed during incident-free truck transportation (other groups include occupants of other vehicles on the route, persons residing near the route, others who might share the rights-of-way with trucks carrying the spent fuel, and persons at stops), and higher than the dose rate to the drivers when they are in the truck cab. For most radioactive materials shipped in the United States there are only two handlings: one at the origin and one at the destination. The number of handlers does not vary greatly from one shipment to another of the same type. However, the number of inspections a given shipment might experience en route cannot be predicted with confidence because it can vary with changing state regulations, since there is no regulatory limit on the number of inspections that might occur. The potential population dose and risk associated with redundant inspections of spent fuel shipments should be evaluated carefully in the context of ALARA. That is the focus of this study.

Two different methods were used to estimate gamma doses to inspectors for a representative fuel shipment. These methods were compared, and the results of the dose calculations were compared to other components of incident-free dose. Comparison is also made to a measured dose rate mapped in another investigation (Hostick, et al., 1992).

Basic Parameters

In this study inspection time was estimated at 10 minutes. A typical inspection takes about 7.5 minutes (Neuhauser and Weiner, 1992), so that 10 minutes per inspection was considered a conservative estimate for these calculations. Doses to the public from incident-free transportation (D_{IF}) were calculated for three routes of increasing length (817 km, 1732 km, and 4363 km, respectively). For this analysis all three routes were assigned the same fractions of travel in each of the population density zones as those representative of interstate truck routes in the populous eastern United States. These fractions and the population densities used for each are given in Table 1.

Table 1. Population Densities and Fractions of Travel .

Population Density Zone	Population Density:persons/km^2	Percent of Route
Rural	6	88
Suburban	719	10
Urban	3861	2

The source considered was spent fuel in a current-design cask similar to those used with the Taiwan research reactor fuel offloaded at the port of Hampton Roads, VA, in 1991 and earlier (Neuhauser and Weiner, 1991).

Albedo Dose

The albedo dose is the contribution to total dose from scattering from nearby surfaces. Albedo dose rates for scattering from the ground surface and from the back of a semi-tractor cab were calculated from the equations given by Selph (Selph, 1968). The ground surface was assumed to scatter like concrete; the cab was assumed to scatter like a metal building. In calculating albedo dose, only scattering of 0.4 MeV to 0.9 MeV gammas was considered. Almost 98% of the cask surface gamma are within this range for spent fuel shipments (Sandquist, et al., 1985). The calculation was performed in order to determine whether scattering from the back of the cab was a potentially significant contributor to inspector dose rate at any distance from the cask. Table 2 summarizes the results of these calculations. The perpendicular distance of the receptor from the cask was 2 meters, in order to remain consistent with the PATHRAE analysis (Sandquist, et al., 1985); perpendicular distances from the scattering surfaces are given in Table 2. As may be seen from Table 2, scattering from surfaces other than the truck and the ground beneath accounted for 8% of the 0.4MeV gamma dose and 6% of the 0.9 MeV gamma dose.

Scattering from the ground surface at all distances is explicitly considered in the equations from the PATHRAE computer code, which also models the radiation field around a spent fuel cask explicitly (Sandquist, et al., 1985). In contrast, the RADTRAN computer code uses a line-source approximation (i.e., a model in which the dose rate is a function of 1/r where r is the minimum perpendicular distance to the source) to estimate the dose to persons close to a radioactive materials shipment (the near-field dose) (Neuhauser and Kanipe, 1991). Any distance within about 10 meters of a spent fuel cask is considered "close." Albedo dose is not explicitly evaluated in RADTRAN. In this report the two methods are compared to determine whether the tendency to overestimate dose in the RADTRAN model is sufficient to account for the albedo dose.

As may be seen from the table, scattering from the ground constitutes the only significant contribution of albedo dose to the radiation dose, and only to the dose received by persons within a few meters of the cask (e.g., inspectors and handlers). Contribution to the albedo dose from scattering from the back of the truck cab was negligible compared to ground scatter. The total incremental albedo dose was about 28% of the direct gamma dose for 0.4MeV gamma radiation and about 15% of the direct gamma dose for 0.9 MeV gamma radiation.

Table 2. Results of Albedo Calculations.

Scattering Surface	Perpendicular Distance from Scattering Surface	Fraction of Dose from Albedo	
		0.4MeV Gamma	0.9MeV Gamma
Ground	1.6 m.	0.1983	0.0883
Truck cab	9.3 m.	0.05	0.05
Backscatter of ground albedo from truck cab	9.3 m.	0.0297	0.0132
Total albedo		0.2780	0.1515

Inspection Doses

Doses to inspectors were compared to the doses to the public from incident-free transportation of radioactive material. The inspector dose (D_{insp}) was calculated for inspectors located 2 meters from a cask for 10 minutes per inspection. Doses to the public from incident-free transportation (D_{IF}) were calculated for the three routes described above. Since the total population dose to the public in incident-free transportation is a function of the total distance traveled by the shipment when population densities are held constant, the comparison may be expressed in terms of incremental dose per inspection per kilometer of travel, or as the ratio of total inspection dose to total dose to the public during incident-free transportation.

The ratio of these two doses was examined, rather than the absolute doses themselves, to remove dependence on actual cask dose rates. The dose rate used for the RADTRAN and PATHRAE calculations was 13.68 mrem/hr (the dose rate at 1 m from the surface in the RADTRAN spent fuel example). The inspection dose was calculated using the RADTRAN equations for handler/inspector dose; and dose to the public was calculated using the RADTRAN equations for the incident-free transportation dose to the public for typical routes (Neuhauser and Kanipe, 1991). This, in turn, allows the ratio D_{insp}/D_{IF} to be expressed in terms of population dose (person-sievert) per hour of inspection per kilometer of travel, or as person-sievert of inspection dose per person-sievert of public dose.

RADTRAN is based on a conception of the field around the source which has a simpler geometry than the actual field. Differences between the modeled and measured fields tend to be greater close to the field source than further away. The near-field dose calculated by RADTRAN was therefore compared both to that obtained by another more detailed model and to a dose map obtained by measurements made around a spent fuel cask (Hoskins, et al., 1992). For these comparisons, near-field doses were calculated using the equations of the PATHRAE model (Sandquist, et al., 1985). The dose per unit source strength was examined in order to eliminate any factor due to a difference in sources. The PATHRAE expression is

$$H_P=\left(\frac{1}{2\pi r}\right)\left(1.21+\mu\sqrt{r^2+(L/2+z)^2}\right)\left(\arctan\frac{L}{2r}\right) \quad \textbf{(1)}$$

where H_P = dose per unit source strength in PATHRAE
r = radial position from the center of the line source (Figure 1)
z = axial position from the center of the line source
μ = effective photon attenuation coefficient for air
L = one-half of the effective source length = 2.56 m.

The expression derived from the RADTRAN equation (Neuhauser and Kanipe, 1991, Section 4.8), taking into account the package shape factor in RADTRAN, is

$$H_R=e^{-\mu r}\left(1.21+\mu\sqrt{r^2+(L/2+z)^2}\right)\left(.725+(1+L/2)^{.75}\right) \quad \textbf{(2)}$$

where H_R = dose per unit source strength in RADTRAN

Figures 1 and 2 compare the calculated RADTRAN dose rate and PATHRAE dose rate at various distances from the surface of the cask. In the calculations, "z" is the distance from the center of the cask along the cask's long axis; "r" is the distance perpendicular to the long axis of the cask. Recall that PATHRAE includes ground-surface albedo explicitly, while RADTRAN uses a line source approximation which is independent of "z." The normalized dose rate as modeled by PATHRAE is less than the dose rate modeled by RADTRAN at all distances from the cask for which the 1/r approximation for RADTRAN is appropriate. Hostick, et al., (Hostick, et al., 1992) mapped the near-field dose around a TN-8L cask having the same dimensions as the cask in the RADTRAN and PATHRAE calculations, and qualified their measured values with the statement that 72% of the measured dose rate around the cask is from background radiation. The figures show the measured values taken from Hostick, et al., normalized for source strength (dose rate at 1 m from the surface), both with and without correction for background.

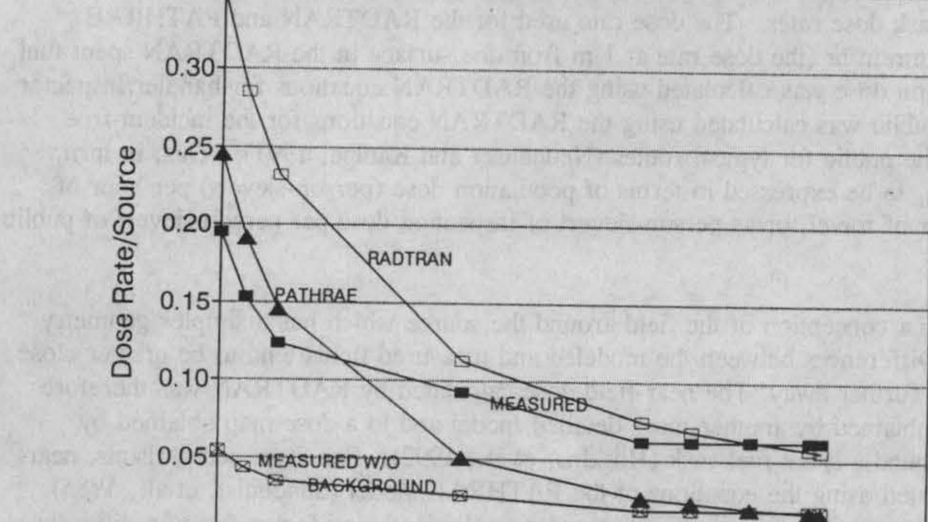

Figure 1. **Dose Rate Per Unit Source Strength at z=0.**

The average dose to an inspector per inspection of a spent fuel shipment, as calculated by RADTRAN, in 2.17 mSv (217 mrem). An individual who inspects 23 shipments a year (fewer than one every other week) will have received his or her annual allowed occupational dose of .05 Sv (5 rem) (10 CFR 20.1201). By comparison, the average annual external gamma dose to workers in all aspects of the nuclear industry during the period 1943-1985 was 0.0506 mSv (5.06 mrem) (Upton, 1991), or about 2.3% of the calculated dose per inspection. It should be noted that the inspection (handler) dose calculated by RADTRAN for the present study is based on the maximum package dose rate (DR_p) allowed by regulation (49 CFR 173.941). DR_p is the dose rate in mrem/hour at 1 meter from the surface of the package. If the measured DR_p is less than the maximum allowed by regulation, as it usually is, the inspection dose will also be less.

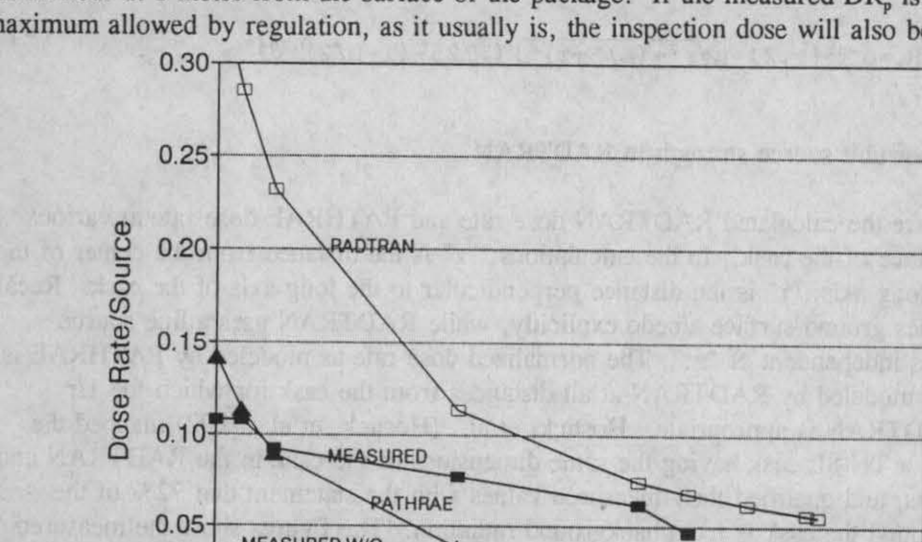

Figure 2. **Dose Rate Per Unit Source Strength at z=3 m.**

In another paper (Weiner and Neuhauser, 1992) the authors discussed the ratio of the inspection dose (D_{insp}) to the dose to the general public (D_{IF}). The D_{insp}/D_{IF} ratio for a typical cross-country route was found to be 1.72E+4/km/hour, where the "hour" in the denominator refers to hours of inspection and the "km" is the kilometers of incident-free transportation. This ratio is independent of cask dose rate. Table 2 illustrates the influence of trip length on D_{insp}/D_{IF} for a single 10-minute inspection. The contribution to total dose of each inspection is inversely proportional to trip length.

Table 3. Influence of Trip Length on D_{insp}/D_{IF}.

Trip Length (km)[a]	D_{insp}/D_{IF} Per Inspection
817	3.56
1732	1.68
4363	0.67

[a] Fractions of travel were held constant at 88% rural, 10% suburban, 2% urban.

Conclusions

Both RADTRAN and PATHRAE overestimate the dose to the population subgroup of handlers and inspectors, and anyone else very close to the container, to an extent that is may be overly conservative. It is not surprising that a model which is a simplified representation of a source field (a straight line in the case of RADTRAN and a rectangular area in the case of PATHRAE) represents that field less accurately the closer the receptor is to the source. Both RADTRAN and PATHRAE accommodate the inaccuracy by (1) accepting the conservatism and (2) introducing a factor for package shape and dimensions to improve the accuracy of the representation. Clearly, however, in RADTRAN the overestimate within a few meters of the package is large, in part because a field depending on 1/r goes to infinity as r becomes very small and in part because the RADTRAN model, by neglecting the cask diameter, places the receptor much closer to the source than he or she actually is. Alternative representations of the package shape factor and a refinement of the near-field model in RADTRAN are presently under study.

The total dose to inspectors per shipment is a function of total inspection time, i.e., the sum of all times during which the inspectors are within a few meters of the cask surface during a single trip from origin to destination. Since the RADTRAN calculation of inspector dose has been demonstrated to be conservative, the results presented here represent upper-bound estimates rather than actual expected values of inspector dose for ten-minute inspections. The estimated dose would, of course, increase for longer inspection times. The results suggest that superfluous inspections of radioactive materials shipments and long inspection times are not compatible with ALARA principles.

No need has been demonstrated for additional inspections beyond the radiological inspection at the point of origin (and possibly at a modal transfer point). There already are nonradiological operations performed at the point of origin and at modal transfer points (e.g., inspection of tie-downs, placarding of vehicle, etc.) that cannot be dispensed with and that require individuals to come into proximity with the shipment. Actual experience with the Taiwan shipments shows that the dose rates measured during Coast Guard inspections agreed with the values given on the shipping papers prepared at the point of origin in Taiwan. Since the shipments were inspected by International Atomic Energy Agency personnel before they left Taiwan, this is not surprising. Additional radiological inspections, which were performed by the state police and the shipping firm on the same day as the Coast Guard inspection, but with separate, independently calibrated instruments, were also in close agreement with the original values. A reasonable conclusion is that some of these inspections were unnecessary.

RADTRAN files used in these calculations are available to the public through the TRANSNET system (Neuhauser and Kanipe, 1992).

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