A Comparison of the RADTRAN 5 and RISKIND 1.11 Incident-Free Dose Models

R.L. Steinman* and K.J. Kearfott

Department of Nuclear Engineering and Radiological Sciences
University of Michigan, Ann Arbor, MI

ABSTRACT

The potential for a certain activity to cause harm is usually discussed in terms of numerical risk. Two codes are frequently used to evaluate the radiological risks associated with the transport of radioactive material. The RADTRAN code, developed at Sandia National Laboratories (SNL), is designed primarily for the assessment of collective, or population-averaged, route-specific dose consequences and risks. The RISKIND code, developed at Argonne National Laboratory (ANL), uses a similar methodology, although slightly different models, to estimate consequences and risks to individuals or small groups of individuals at a specific location. In the past these two codes have been reviewed in terms of qualitative features such as user friendliness or compatibility with other computer generated data. This paper, however, will focus specifically on the mathematical representations used to model the routine, incident-free dose consequences associated with transporting radioactive material. Similarities in methodology and differences in specific models will be highlighted throughout the paper to enable users to understand variation in code output for similar input scenarios. Finally, a preliminary set of transient dose rate measurements will be compared to their respective RADTRAN and RISKIND estimates.

INTRODUCTION

In the late sixties and early seventies, people began realize the potentially serious consequences associated with the uncontrolled use of the earth's resources. Many of the industrial practices of the time were recognized as having an unacceptable impact on the environment. In response, the federal government set new rules, outlined in the National Environmental Policy Act (NEPA), to protect the environment from future degradation. Within NEPA there is a requirement to assess the environmental impact of every federal action or legislation that might "significantly affect the quality of the human environment." It is this requirement for an environmental impact statement (EIS) and the enforcement of the NEPA goals and policies, often in response to lawsuits filed by private citizens and environmental groups, that has forced federal agencies to focus on potential environmental effects.

Radioactive materials play an important role in the fields of medicine, defense, power production, research, and industry. Most radioactive materials are not used where they are manufactured, nor are they typically disposed of at the site where they are used. Instead, these materials must be transported between various processing, use, storage, consolidation, and disposal facilities. Millions of shipments of radioactive material occur over our nations highways, railways, waterways, and in the air each year. Yet, despite an excellent safety record for these shipments, there remains a significant level of public concern over the transportation of radioactive materials. To date, these concerns have been addressed in terms of numerically estimated risk in the form of numerous environmental assessments (EAs) and environmental impact statements (EISs).

There are two main computational tools used specifically to address transportation risk analyses in EAs and EISs. RADTRAN [1,2,3,4] was first developed at Sandia National Laboratories in 1975 in conjunction with the preparation of NUREG-0170 [5]. It is used to evaluate the collective radiological consequences of routine, or incident-free, shipments of radioactive materials, as well as risks from potential accidents that might occur during transport activities. RISKIND developed at Argonne National Laboratory in 1993 focuses on local, scenario-specific consequences and risk. It is used primarily for the evaluation of the maximally exposed individual and specific 'what if' scenarios [6].

References to both RADTRAN and RISKIND can be found throughout the literature. EAs and EISs focus on the application of the transportation risk assessment codes to a particular situation. In some cases, these applications have been questioned by outside groups or individuals [7, 8, 9]. Although many individual EAs or EISs have been criticized or even taken to court, very few critical reviews or comparisons of the actual models used in the RADTRAN and RISKIND codes have been published in open literature. Previous “reviews” of the transportation risk analysis codes have focused primarily on subjective observations of user friendliness and compatibility with auxiliary codes [10] or validation studies that show that the software properly performs the calculations it was designed to perform [11]. This paper, however, provides an in-depth evaluation and comparison of each code’s mathematical models for incident-free dose consequence calculations. In addition, the two off-link dose models are compared to preliminary experimental measurements of the transient off-link dose. Since RADTRAN 5 and RISKIND 1.11 are the most recent versions of these codes, they will be referred to simply as RADTRAN and RISKIND throughout the remainder of this manuscript.

COMPARISON OF THE MATHEMATICAL MODELS

The term incident-free, or routine, dose consequence collectively refers to the external dose experienced by a person or group of people near an intact radioactive materials package or a vehicle carrying such a package. The radiation emanating from the package may be composed of both gamma and neutron radiation, but alpha and beta emissions do not contribute to the external radiation field since the package and vehicle attenuates these particles. The dose rate at the receptor’s position in conjunction with the exposure time determines the dose consequence associated with being exposed to the radiation field surrounding the packaged radioactive material. The following sections will describe the various models used by the RADTRAN and RISKIND transportation risk analysis codes. Since many of the mathematical model descriptions use identical nomenclature, all of the symbols used in the equations discussed in this section are summarized in Appendix A rather than after each individual equation.

External Dose Rate Model

The incident-free dose consequence model used in RADTRAN is essentially the same as the model used in RISKIND. The primary distinction between the two codes is the mathematical representation of the external dose rate, DR, as a function of the source-to-receptor distance, r. Each code models both the gamma and neutron components of the radiation field as two independent co-located sources that are simply added together, as shown in EQ. (1). The effects of package geometry and interactions between the radiation field and the environment, however, are represented differently.

$$\mathrm{DR(r)} = \mathrm{DR}_{\gamma}\mathrm{(r)} + \mathrm{DR}_{n}\mathrm{(r)} \qquad \text{EQ. (1)}$$

RADTRAN uses an external dose rate model that provides for computational simplicity as well as applicability to a large variety of package shapes and sizes. Essentially, the RADTRAN model, shown in EQ. (2), transforms the actual radiation field into an isotropic point- or line-source through the use of a shape factor, k^{o} or k_{o}’, such that the dose rate at a distance of 1 meter plus half the effective characteristic package dimension (d_e) is equal to the actual package transport index (TI) [4]. Either the measured TI or the regulatory maximum [12] can be used as the variable $DR_{PKG,i}$ in EQ. (2). All transient packages, regardless of their actual geometry and external radiation field, are represented using an isotropic point-source model. Stationary packages are approximated as line-sources in the near field, but as isotropic point-sources outside this region (See EQ. (2) below).

$$DR_i(r) = f_i \cdot DR_{PKG,i} \cdot e^{-m_i r}(1 + a_{1i}r + a_{2i}r^2 + a_{3i}r^3 + a_{4i}r^4)\left[\frac{(1+0.5d_e)}{r}\right]^n$$

$$\text{where} \quad \mathrm{n = 1 \, for \, r < 2d_e \; (line\, source) and \, n = 2 \, for \, r \geq 2d_e \; (point\, source) and} \qquad \text{EQ. (2)}$$

$$\mathrm{d_e} = \begin{Bmatrix} d_p(or\ CPD) & \text{if } \mathrm{d_p < 4m} \\ \mathrm{2(1+0.5d_p)^{3/4} - 0.55} & \mathrm{for\, d_p \geq 4m} \end{Bmatrix}$$

The RADTRAN model neglects reflection and absorption from the ground and does not account for any energy distribution related effects. Reflection (albedo) is negligible, but some studies have shown that accounting for groundscatter can increase the near field neutron dose rate by 35% and the gamma dose rate by 15% [13]. Gamma attenuation and build-up in air are assumed to be approximately equal to one for all energies of interest in transient dose calculations; however, both properties are accounted for in certain stationary situations. Neutron attenuation and build-up in air are always accounted for [4].

The RISKIND external dose model, which is based on a spent nuclear fuel cask, uses a 3-D Monte Carlo based dose approximation [6]. The dose rate expression used in RISKIND is an empirical fit to the results of a MORSE-SGC/S [14, 15] calculation that includes the effects of both ground and air scattering, as well as energy dependant attenuation and build-up [13]. The MORSE-SGC/S calculation provided the dose rate at perpendicular mid-plane distances between 1 and 1000 meters for a horizontally oriented uranium and water shielded spent fuel cask 56 cm in radius and 5.46 m in length located 1 m above the ground surface [6,13]. An empirical fit to the resultant dose curve produced EQ. (3). The coefficients, $A_{j,i}$, are normalized such that the dose rate at 2 meters from the edge of the cask is equal to the regulatory limit of 10 mrem/hr. The numerical values for $A_{j,i}$ can be found in Table 2.1 of the RISKIND user guide [6].

$$\begin{aligned} \log[DR_i(r)] = {} & A_{0i} + A_{1i}[\log r] + A_{2i}[\log r]^2 + A_{3i}[\log r]^3 + A_{4i}[\log r]^4 \\ & + A_{5i}[\log r]^5 + A_{6i}[\log r]^6 + A_{7i}[\log r]^7 \end{aligned} \qquad \text{EQ. (3)}$$

To model a package other than the reference cask, RISKIND uses a cylindrical surface-source derived transformation factor to adjust the dose rate from EQ. (3) to any user-defined cylindrical dimensions. Biwer, et al. provides comparisons of the RISKIND external dose rate model to Microshield 4 and MCNP generated gamma and neutron dose curves. In addition, RISKIND was run using the NUREG-0170 dose curve and the calculated distance dependent dose rates were compared to the NUREG-0170 results [16]. In general, Biwer et. al showed that the RISKIND model predicts approximately the same dose rate as other codes for distances between 1 and 800 meters.

Transient Dose Rate Models

The external dose model is the kernel upon which all other incident-free models are built. Since the physical situation does not change, the overall mathematical models applied to the transient and stationary dose situations are identical in each code. Minor differences in the models arise when one considers population distribution, median width, and other characteristics of the transport route.

The dose to persons who reside along side the transport route, called the off-link population, is calculated using the same basic equation in both RADTRAN and RISKIND. RADTRAN uses EQ. (4) for truck transportation, where $PDR*Y_1$ represents the pedestrian population fraction and $SF*Y_2$ represents the shielded indoor population fraction. The RADTRAN equation for the off-link dose using rail transport is the same as for truck transport except that the pedestrian related factor, $PDR*Y_{1,}$ equals zero. The limits of integration ("$\min_m$" and "$\max_m$") are user-determined [4].

$$D = \frac{4Q \cdot PPS \cdot SPY \cdot DIST \cdot k_0 \cdot DR_{PKG} \cdot PD}{V}\left[PDR \cdot Y_1 + SF \cdot Y_2\right]$$

$$\text{where } \mathrm{Y_m} = FG \cdot \int_{\min_m}^{\max_m}\int_x^{\infty} \frac{\mathrm{e}^{-m_g r} B(r)}{r\sqrt{r^2 - x^2}}\,dr\,dx + FN \cdot \int_{\min_m}^{\max_m}\int_x^{\infty} \frac{\mathrm{e}^{-m_n r} B(r)}{r\sqrt{r^2 - x^2}}\,dr\,dx \qquad \text{EQ. (4)}$$

$$\mathrm{m} = 1 \text{ for the pedestrian and } \mathrm{m} = 2 \text{ for the indoor population}$$

The RISKIND equation, given in EQ. (5), is the same regardless of the transport mode. In this equation, $SF*F_{in}$ represents the shielded indoor population and $(1\text{-}F_{in})$ represents the population exposed while outdoors [6]. A review of EQ. (4) and (5) reveals that the equations share essentially the same factors. Noted differences between EQ. (4) and (5) include

(1) RADTRAN accounts for population on both sides of the road [factor of 2 in EQ. (4) that is not in EQ. (5)] and
(2) RISKIND uses the same integration width for both the pedestrian and indoor populations. [RADTRAN allows the user to define the limits of integration separately for the pedestrian and indoor populations.]

$$D = [SF \cdot F_{in} + (1 - F_{in})] \cdot PD \cdot DIST \cdot Q \cdot \frac{2}{V} \int_{\min}^{\max} \int_{x}^{\infty} DR(r) \frac{r}{\sqrt{r^2 - x^2}} dr\, dx \qquad \text{EQ. (5)}$$

The dose to people in vehicles that share the transport route is called the on-link population dose. EQ. (6) is the mathematical representation of the link specific on-link dose model used for truck transport in RADTRAN. The rail transport equation is the same except that the second integral and the 1/X̲ terms both equal zero. The total on-link dose is the sum of all the individual segment specific on-link dose calculations [4], i.e. EQ. (6) is summed over all route segments, or links.

$$D = \frac{2Q \cdot PPS \cdot SPY \cdot k_o \cdot DR_{PKG} \cdot DIST \cdot PPV \cdot TD}{V^2} \left\{ \frac{1}{\underline{X}} + \sum_{i=1}^{2} f_i \left[\int_{x}^{\infty} \frac{e^{-m_i r} B_i(r)}{r\sqrt{r^2 - x^2}} dr + \frac{1}{2} \int_{2V}^{\infty} \frac{e^{-m_i r} B_i(r)}{r^2} dr \right] \right\} \qquad \text{EQ. (6)}$$

RISKIND uses a similar mathematical on-link dose model except that the RISKIND model specifically accounts for user defined road median widths and integrates an average uniform route population over the appropriate portion of the travel route [6]. The RISKIND on-link expression is given in EQ. (7) is the same regardless of the transport mode.

$$D = \frac{2Q \cdot DIST \cdot PPV \cdot TD}{V^2 \cdot w_L} \left[w_L \int_{2}^{\infty} DR(r) dr + \sum_{j=1}^{2} \int_{\min_j}^{\max_j} \int_{x}^{\infty} DR(r) \frac{r}{\sqrt{r^2 - x^2}} dr\, dx \right] \qquad \text{EQ. (7)}$$

where $\min_1$ = 1 m
$\max_1 = \min_1$ + (NUMLANE-1)RDWTH for adjacent lanes

$\min_2$ = [1 + (NUMLANES-1)RDWTH + MEDWTH] and
$\max_2 = \min_2$ + NUMLANES(RDWTH) for opposite lanes

Stationary Dose Rate Models

RISKIND takes a simple approach to stationary dose consequence models. There is one model, EQ. (8), for individual exposures and another model, EQ. (9), for exposures to an annular uniformly distributed population [6]. Multiple individuals or sub-populations may be summed externally to obtain total occupational or stop dose values as appropriate.

$$D(r) = [DR_g(r) + DR_n(r)] SF \cdot T \qquad \text{EQ. (8)}$$

$$D(r) = 2\left[\frac{P}{r_2^2 - r_1^2}\right] N \cdot T \int_{r_1}^{r_2} DR(r)\, r\, dr \qquad \text{EQ. (9)}$$

RADTRAN specifically models stop, crew, and storage dose for each transport mode. Unlike the transient dose models, the stop and crew/worker dose calculations account for the attenuation and build-up for both the gamma and neutron components, as shown in EQ. (10).

$$\begin{aligned} TR_g &= e^{-m_g r}[1 + a_{1g} r + a_{2g} r^2 + a_{3g} r^3 + a_{4g} r^4] \\ TR_n &= e^{-m_n r}[1 + a_{1n} r + a_{2n} r^2 + a_{3n} r^3 + a_{4n} r^4] \end{aligned} \qquad \text{EQ. (10)}$$

The stop dose model can be based on either the exposed population density in an annular area or the actual number of people being exposed at an average distance from the package. EQ. (11) describes the stop dose model as described in the RADTRAN 5 Tech Manual [2]. EQ. (11) describes the number of people exposed at an average distance from the package. The equation for the annular stop dose model was missing from the manual at this time.

$$D = Q \cdot PPS \cdot SPY \cdot k_o \cdot DR_{PKG} \cdot T_{stop} \cdot P_{stop} \cdot SF_{stop} \left[FG \cdot TR_g + FN \cdot TR_n\right] \begin{Bmatrix} \dfrac{k_o}{r^2} \\ \dfrac{k_0^{'}}{r} \end{Bmatrix} \qquad \text{EQ. (11)}$$

The truck crew dose is estimated using EQ. (12). At first glance the crew dose appears to be modeled as a transient situation, however, this dose is truly a stationary model since the crew is moving in the same frame of reference as the transient vehicle. The travel velocity and total travel distance are included in EQ. (12) since they are used to estimate the crew exposure time. In addition, EQ. (12) includes factors that modify the shape factor for calculating the crew dose since the crew is normally exposed to the end of a package instead of the longest dimension.

$$D = Q \cdot PPS \cdot SPY \cdot N_{crew} \cdot DR_{PKG} \cdot \frac{1}{V_L} \cdot DIST_L \cdot SF_v \left[FG \cdot TR_g + FN \cdot TR_n\right] \left\{ \frac{k_{o,end}}{r_{end}^{\;2}} \right\} \qquad \text{EQ.(12)}$$

For the purpose of occupational dose estimates, RADTRAN assumes that rail workers are primarily rail car inspectors and classifiers who must get close to the package. The rail worker dose per classification or inspection, given in EQ. (13), uses a line-source approximation since the workers remain close to the package. The remaining train crew is so far away and so well shielded from any package of radioactive material that the dose is vanishingly small so these crew members are excluded from the rail worker calculation [2].

$$D = Q \cdot PPS \cdot SPY \cdot DR_{PKG} \left[FG \cdot TR_g + FN \cdot TR_n\right] \left\{ \frac{k_o^{'}}{r} \right\} \qquad \text{EQ. (13)}$$

The RADTRAN storage dose is a simple point-source approximation that is a function of dose rate, exposure time, and distance. The storage dose model is given in EQ. (14) [4]. The storage dose is not modeled specifically in RISKIND since the code is designed for scenario specific evaluations rather than campaign (or shipment) level dose calculations.

$$D = Q \cdot k_o \cdot DR_{PKG} \cdot PPS \cdot SPY \cdot P \cdot \frac{T}{r^2} \qquad \text{EQ. (14)}$$

PRELIMINARY RADTRAN BENCHMARKING EFFORTS

Risk assessment has become an increasingly important tool in the support of federal decisions concerning the handling, storage, disposal and transportation of spent nuclear fuel (SNF) and high-level waste (HLW). As concerned citizens and environmental groups have become increasingly involved in the decision-making process many aspects of the essential risk assessment tools have been criticized [7, 8, 9]

Both RADTRAN and RISKIND have been verified and evaluated by various groups over the past 15 years. Brumburgh and Alesso critiqued subjective aspects of earlier versions of the codes such as user friendliness and the ability to read data generated by other programs [10]. Maheras and Pippen validated several transportation codes by comparing code output to either hand calculations or output from other software designed to perform similar calculations to ensure that the results remained within an acceptable range of variability [11]. In addition, RADTRAN and RISKIND code authors have provided verification at various intervals throughout the development of subsequent code revisions [16, 17, 18]. Although RISKIND has been compared to RADTRAN and benchmarked against Microshield [19] and MCNP [20] calculations, neither code has been benchmarked against experimentally measured values. The following section describes the results of the first attempt to experimentally verify that the RADTRAN off-link dose model reflects the actual dose situation realized by the exposed population.

Measurement Results

The experimental transient dose rate data was collected using the General Electric Reuter-Stokes RSS-112 PIC Portable Environmental Radiation Monitor, which consists of a high-pressure ion chamber (IC) and the RSS-112 data acquisition hardware [21]. The high-pressure ion chamber is filled with ultra-high purity argon gas pressurized to 25 atmospheres (absolute). It has a 7.2 L (7.6 qt) spherical ion chamber that gives an omni directional response when used in the 0-1 mSv/hr (1-100 mrem/hr) range. The detector was mounted on a tripod and then the detector, battery power supply, and electronic microcomputer console (RSS-112) were secured to the bed of a pick-up truck as shown in Fig. 1. Spatial restrictions dictated that the transient dose rate be measured by driving the detector system past the staged shipment, rather than making multiple shipment passes by a staged detector. The collected data are averaged over a 5-second time interval and written to a memory cartridge for later retrieval and external integration.

Figure 1. The RSS-112 PIC Portable Environmental Radiation Monitor Setup

Two sets of transient dose rate data were collected in April and July 1999 [22]. The April data measured a shipment of twelve 55-gallon drums arranged in a 6 by 2 array on a standard flatbed truck. Only eleven of the drums actually contained waste materials, the twelfth drum was empty and used solely to maintain a rectangular array configuration. The July data measured three drums aligned in a column along the edge of a truck bed. Additional non-radioactive drums were transported with the shipment, but these additional drums did not obscure the line of sight since the transient measurements were made parallel to the radioactive drum array. Potential scattering off the non-radioactive drums was assumed to be negligible.

Table I lists the detector travel velocity and perpendicular distance pairs used for each transient dose rate measurement. The RADTRAN and RISKIND estimated individual integrated off-link doses are also listed in Table I. Since RADTRAN accounts for population on both sides of the road and RISKIND does not the values in Table I are one half of the values reported in the actual RADTRAN output file.

Table I. Data for Code Generated and Measured Individual Off-Link Doses

Perpendicular Distance (m)	Travel Velocity (km/hr)	RADTRAN (mrem)	RISKIND (mrem)	Measured Dose (mrem)
April 1, 1999 55-Gallon Drum Array (3.5 m long, 1.2 m wide, 87.5 cm tall) *TI = 7 mrem/hr*				
12	16.1	1.53×10^{-3}	3.76×10^{-4}	8.00×10^{-4}
12	32.2	7.35×10^{-4}	1.88×10^{-4}	4.20×10^{-4}
12	48.3	4.94×10^{-4}	1.25×10^{-4}	2.60×10^{-4}
17	16.1	1.01×10^{-3}	2.46×10^{-4}	5.00×10^{-4}
17	32.2	5.25×10^{-4}	1.23×10^{-4}	2.40×10^{-4}
7	16.1	2.56×10^{-3}	6.63×10^{-4}	1.20×10^{-3}
4	8	3.10×10^{-3}	NA	2.10×10^{-3}
24	16.1	2.78×10^{-4}	NA	1.50×10^{-4}
July 1, 1999 55-Gallon Drum Array (1.83 m long, 61 cm wide, 88.9 cm tall) *TI = 7. 17 mrem/hr*				
3.05	16.1	9.40×10^{-3}	1.03×10^{-3}	6.43×10^{-4}
3.05	16.1	9.40×10^{-3}	1.03×10^{-3}	6.67×10^{-4}
4.88	16.1	4.86×10^{-3}	6.97×10^{-4}	3.84×10^{-4}
4.88	32.2	2.43×10^{-3}	3.49×10^{-4}	2.34×10^{-4}
4.88	32.2	2.43×10^{-3}	3.49×10^{-4}	2.30×10^{-4}
7.16	16.1	3.99×10^{-3}	5.01×10^{-4}	2.38×10^{-4}
8.23	16.1	3.62×10^{-3}	4.49×10^{-4}	2.13×10^{-4}
8.23	16.1	3.61×10^{-3}	4.11×10^{-4}	1.93×10^{-4}
8.23	32.2	1.80×10^{-3}	2.06×10^{-4}	1.18×10^{-4}
8.23	32.2	1.80×10^{-3}	2.06×10^{-4}	1.29×10^{-4}

DISCUSSION

RADTRAN and RISKIND were designed to calculate similar dose quantities for two distinctly different situations. RADTRAN was designed for collective population, route-averaged dose consequence and risk estimates. Thus, many of the RADTRAN equations discussed above include parameters such as the number of packages per shipment (PPS) and the number of shipments per year (SPY). RISKIND was designed to estimate scenario specific dose consequences and risks. Thus, RISKIND does not include equations to calculate the crew/worker dose or doses that are incurred while a package is temporarily stored during transit.

The main difference between the RADTRAN and RISKIND computer codes lies within the mathematical model used to represent the radiation field surrounding an intact package of radioactive material. Figure 2 graphically depicts the dose rate as a function of the source-to-receptor distance for the RADTRAN and RISKIND dose models. Unfortunately, time restraints associated with the nature of the preliminary measured shipments prevented multiple stationary dose rate measurements as a function of source-to-detector distance. Thus, Figure 2 only demonstrates the comparison between the RADTRAN and RISKIND models, rather than with respect to measured dose rate data. The comparison example was computed assuming the same representative spent fuel cask dimensions described in Yaun et al. for determining the RISKIND reference dose rates [6]. An external radiation dose field of 10 mrem/hr at 2 meters from the package surface composed of 70% gamma and 30% neutron radiation was assumed.

Section 4.2.1 of the RADTRAN Technical Manual states that in general the line-source approximation applies in the near field ($r < 2d_e$, which in this case is ~10 m) and that the point-source approximation applies at distances outside the near field region [2]. This general rule applies to the equations used to describe the stationary handler dose; however, the equations for transient radioactive shipments (found in sections 4.4 and 4.12 of the manual) were written assuming that the exposed population was always located outside of the near field region.

RADTRAN always predicts a larger dose rate than RISKIND, which makes sense considering that RADTRAN does not account for any type of radiation reduction processes such as scatter or attenuation. The difference between the output values increased with source-to-receptor distance primarily due to the impact of neglecting gamma attenuation and build-up in the RADTRAN model. Although, it is possible that poor statistics at large distances in the MORSE-SGC/S also effect the drop off in RIKSIND predicted dose rate between 800 and 1000 m. Thus, Figure 2 shows that RADTRAN should always produce larger, and presumably more conservative, estimates of the dose received from passing shipments of radioactive material. Unfortunately, these calculations do not indicate how well either of the models reflects the real external dose situation.

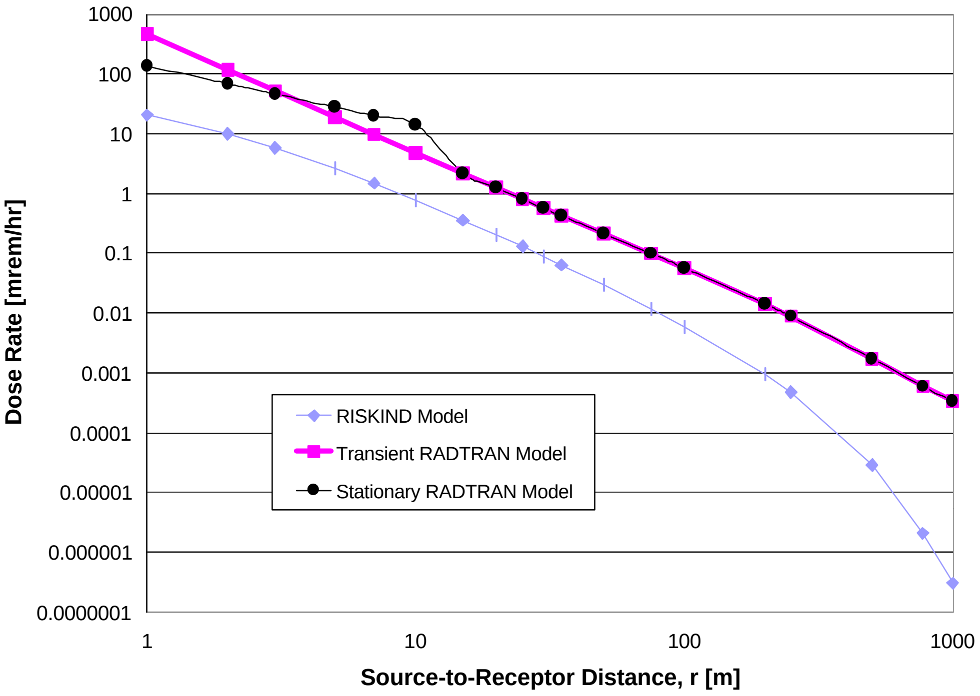

Figure 2. Graphical Comparison of the RISKIND and RADTRAN External Dose Models

The preliminary transient dose results given in Table I show that RADTRAN over-predicts the off-link dose, which is expected considering the restrictions of the dose rate model previously discussed. RISKIND is shown to under-predict the April data, but caution should be exercised when drawing conclusions since the shipment level TI of 7.0 mrem/hr was not measured, but instead an estimated average of the individual drums within the shipment. It is assumed that this average value is conservative since it did not account for placement of the highest (22 mrem/hr) and lowest (0.5 mrem/hr) drums within the array or any type of drum self shielding.

In general, we observe an inverse trend between dose rate and shipment travel velocity. The RADTRAN data exactly follow this trend for the July data, but for reasons unknown at this time the April data is off by approximately 4%. All the RISKIND values follow this trend except for the 8.23 m data. Measured values approximate the 1/v trend but do not follow it exactly since the travel velocities were known to vary by a few kilometers per hour (16.1 ± 1.6 kph and 32.2 ± 3.2 kph). Additional uncertainties in the data include the fact that RADTRAN suggests using the longest internal diagonal (3.82 m and 2.12 m, respectively) for a rectangular array, whereas RISKIND approximated the array using a cylinder of the same length as the array. Thus, we have shown that although these data provide some insight into the relative difference between the actual and estimated dose situations, more experimental results, under a controlled environment, are necessary.

CONCLUSIONS

The incident-free dose models used in RADTRAN 5 and RISKIND 1.11 are quite similar. The fundamental difference lies primarily in the external dose rate model used within each code. Figure 1 showed that for the reference cask used, RADTRAN predicted an order of magnitude higher dose rate than RISKIND for distances between 5 and 100 meters. At distances closer than 5 meters the RADTRAN predicted dose rate rose more quickly than the RISKIND predicted dose rate. For distances between 100 and 1000 meters, the RISKIND dose rate fell more quickly than the RADTRAN predicted dose rate.

Both computer codes provide off-link and on-link dose predictions. Although the equations for on-link dose look different, they calculate essentially the same quantity using similar parameters. There are two differences between the models used to predict the off-link dose. The first difference is in the fact that RADTRAN uses separate integration widths for pedestrian and indoor populations. The other difference is the fact that RADTRAN assumes exposed populations on both sides of the route and RISKIND does not. The preliminary measurements show that RADTRAN always over-predicts the off-link dose by about an order of magnitude. In one case RISKIND produced predictions of the off-link dose rate that were of the same order of magnitude as the measured integrated dose. In the other case, RISKIND under-predicted the results by about an order of magnitude. Further investigation will be necessary to really quantify to how closely the codes model reality.

REFERENCES

1. K.S. NEUHAUSER AND F.L. KANIPE, “RADTRAN 5 User Guide”, Sandia National Laboratories: Albuquerque, NM, in press (1998).

2. K.S. NEUHAUSER AND F.L. KANIPE, “RADTRAN 5 Technical Manual”, Sandia National Laboratories: Albuquerque, NM, in press (1999).

3. K.S. NEUHAUSER AND F.L. KANIPE, “RADTRAN 4 Volume III: User Guide”, SAND89-2370, Sandia National Laboratories: Albuquerque, NM (1992).

4. K.S. NEUHAUSER AND F.L. KANIPE, “RADTRAN 4 Volume II: Technical Manual”, SAND89-2370, Sandia National Laboratories: Albuquerque, NM (1992).

5. U.S. Nuclear Regulatory Commission, “Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes”, NUREG-0170, USNRC: Washington, D.C. (1977).

6. Y.C. YAUN, S.Y. CHEN, B.M. BIWER, AND D.J. LEPOIRE, “RISKIND - A Computer Program for Calculating Radiological Consequences and Health Risks from Transportation of Spent Nuclear Fuel”, ANL/EAD-1, Argonne National Laboratory: Argonne, IL (1995).

7. M. RESNIKOFF, “Probabilistic Risk Assessment and Nuclear Waste Transportation: A Case Study of the Use of RADTRAN in the 1986 Environmental Assessment of Yucca Mountain”, NWPO-TN-006-90, Nevada Nuclear Waste Projects Office: Las Vegas, NV (1990).

8. R.M. JEFFERSON, “Transporting Spent Nuclear Fuel Allegations and Responses”, SAND82-2778, Sandia National Laboratories: Albuquerque, NM (1983).

9. M.L. RESINKOFF, L. BIRNBAUM, and L. AUDIN, “The Latest Dilemma: Waste Shipment Peril Explored”, CEP Publication N 82-1, Council on Economic Priorities: New York, NY (1982).

10. GREGG P. BRUMBURGH AND H. PETER ALESSO, “A Comparison of RISKIND and RADTRAN 4”, UCRL-ID-115618, Lawrence Livermore National Laboratory: Livermore, CA (1993).

11. STEVEN J. MAHERAS AND HOWARD K. PIPPEN, "Validation of the Transportation Computer Codes HIGHWAY, INTERLINE, RADTRAN 4, and RISKIND", DOE/ID-10511, Science Applications International Corporation: Idaho Falls, ID (1995).

12. U.S. NRC, Title 10, Code of Federal Regulations, Chapter 1, Part 71.4, "Definitions", U.S. Nuclear Regulatory Commission: Washington, D.C. (1999).

13. S.Y. CHEN AND Y.C. YAUN, "Calculation of Radiation Dose Rates from a Spent Nuclear Fuel Shipping Cask", Transactions of the American Nuclear Society **56**:110-112 (1988).

14. M. B. EMMETT, "The MORSE Monte Carlo Radiation Transport Code System," ORNL-4972R2, Oak Ridge National Laboratory: Oak Ridge, TN (1984).

15. "SCALE-3, A Modular Code System for Performing Standardized Computer Analysis for Licensing Evaluation", Oak Ridge National Laboratory, Oak Ridge, TN (1986).

16. B.M. BIWER, J.J. ARNISH, S. KAMBOJ, AND S.Y. CHEN, "RISKIND Verification and Benchmark Comparisons", ANL/EAD/TM-74, Argonne National Laboratory: Argonne, IL (1997).

17. K.L. KANIPE AND K.S. NEUHAUSER, "Verification Process for RADTRAN", *RAMTRANS*¸ **8**:2:95-98 (1997).

18. R.F. WEINER AND K.S. NEUHAUSER, "Conservatism of the RADTRAN Line Source Model for Estimating Worker Exposures", Proc. PATRAM '92, Yokohama, Japan, September 12-18, 1992.

19. C.A. NEGIN AND G. WORKU, "Microshield, Version 4, User's Manual", Grove 92-2, Grove Engineering, Inc.: Rockville, MD (1992).

20. J.F. BRIESMEISTER, ed., "MCNP – A General Monte Carlo N-Particle Transport Code, Version 4A", LA-12625-M, Los Alamos National Laboratory: Los Alamos, NM (1993).

21. Reuter-Stokes, "RSS-112 PIC Portable Environmental Radiation Monitor Operational Manual Version 1.9", Reuter-Stokes: Twinsburg, OH (1995).

22. McFADDEN, J.G., J.L. BOLES, R.L. STEINMAN, AND R.F. WEINER, "Final Progress Report for RADTRAN Benchmarking FY99", ENG-RPT-026 Rev. 0, Waste Management Federal Services, Inc., Northwest Operations: Richland, WA (1999).

* *This research was performed under appointment to the Nuclear Engineering/Health Physics Fellowship Program sponsored by the U.S. Department of Energy's Office of Nuclear Energy, Science and Technology*.

Appendix A: Definition of the Variables Presented in Text Equations

k	Index variable representing the number of tested cases
P_k	Predicted value for case k in the RRMSE calculation
O_k	Observed (measured) value for case k in the RRMSE calculation
i	Index variable used to denote gamma ($i=1=\gamma$) or neutron ($i=2=n$) radiation
f_i, FG, FN	Fraction of the radiation field composed of gamma (or neutron) radiation
$DR(r)$	Total dose rate as a function of distance, r [mrem/hr]
$DR_i(r)$	Gamma (or neutron) dose rate as a function of distance, r [mrem/hr]
DR_{PKG}	Dose rate at 1 meter from the external surface of the package [mrem/hr]
μ_i	Gamma (or neutron) air attenuation coefficient [m^{-1}]
r	Source-to-receptor distance [m]
x	Minimum distance of approach [m]
a_{ji}	RADTRAN geometric build-up approximation coefficients, $j = 1, 2, 3$, or 4 and $i = \gamma$ or n
d_e	Effective package dimension (defined in EQ. (2)) [m]
dp, CPD	Characteristic package dimension [m]
A_{ki}	RISKIND empirical fit coefficients, $k = 1, 2, 3, 4, 5, 6$, and 7
Q	Units conversion factor
PPS	Number of packages per shipment
SPY	Number of shipments per year
DIST	Total travel distance [km]
k_o	RADTRAN point-source package shape factor, $k_o = [\tfrac{1}{2}d_e + 1]^2$ [m]
k_o'	RADTRAN line-source package shape factor, $k_o' = \tfrac{1}{2}d_e + 1$ [m]
PD	Population density [person/km2]
V	Travel velocity, subscript L refers to link specific velocity [km/hr]
PDR	Pedestrian ratio
SF	Shielding transmission factor
m	Index denoting pedestrian ($m=1$) and indoor ($m=2$) populations
min_m, max_m	Minimum and maximum distances between which the population is distributed [m]
F_{in}	Fraction of the population that is indoors
$\underline{X}$	Minimum distance to an adjacent vehicle [m]
PPV	Number of people per vehicle
TD	Traffic density [vehicle/hr]
w_L	Lane width [m]
NUMLANE	Number of lanes in each direction for truck transport or number of parallel tracks for rail transport
RDWTH	Width of one lane for truck shipments [m]
MEDWTH	Width of the median dividing opposing lanes of traffic for truck transport or the distance between track centerlines for rail transport [m]

j	Index variable used to denote adjacent (j=1) or opposite (j=2) lane of travel
D	Integrated dose [mrem]
T	Exposure time [hr]
P_{stop}	Population exposed at the stop
$k_{o.}/r^2$	Factor used in the point source model, when the distance to the receptor is more than twice the largest package dimension (d_p)
k'_o/r	Factor used in the line source model, when the distance to the receptor is less than twice the largest package dimension (d_p)
N_{crew}	Number of crew members
$DIST_L$	Distance the crew travels along the link [km]
SF_v	Vehicle cab shielding factor
r_{end}	Distance between the end of the nearest package end and the crew compartment [km]
$k_{o,\ end}$	Point-source shape factor for package dimension as viewed from the crew compartment