# CALCULATION OF POPULATION DOSES WITH RADTRAN FOR ROUTE SEGMENTS THAT HAVE AN UNPOPULATED NEAR-FIELD REGION

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## SUMMARY

A way to perform RADTRAN calculations, that allows an unpopulated near-field region along a transportation link to be approximately modeled, is described, validated, and then illustratively applied to a coastal sailing route.

## INTRODUCTION

The RADTRAN code (Neuhauser and Kanipe, 1994) models the radiological consequences of the transportation of radioactive materials, both the exposures that will occur if the transport occurs without incident, and the exposures that may occur should the transport vehicle be involved in an accident while en route. Because accidents might occur at any point along a transportation route, RADTRAN divides the route into segments (links) and uses a uniform population density and constant meteorological conditions (windspeed and atmospheric stability) to represent the population and weather characteristics of each route segment. When a route segment has a near-field region that is devoid of population, as is the case when a ship is sailing a coastal route at a distance of several tens of miles from shore, the use of a uniform population distribution moves population located away from the route to positions closer to the route, which artificially increases estimates of population dose and radiation induced cancer fatalities.

This paper describes and validates a way to use RADTRAN to model a route segment that has an unpopulated near-field region, and then illustratively applies the method to the transport of spent power reactor fuel from New London, CT, to Charleston, SC. The effects of a near-field region that is devoid of population are approximated by differencing the results of two RADTRAN calculations. The transportation scenario examined to validate this approach was the maritime shipment of spent fuel along the East Coast of the United States on a freighter sailing at a distance of 48 km from the coastline. To capture the effect of the 48-km-wide, near-field region of open ocean that is devoid of

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population, two RADTRAN calculations were performed, one 0-to-80 km calculation, and one 0-to-48 km calculation, and their results were differenced, thereby obtaining the results from 48-to-80 km. The results of this computational procedure were compared to the results of a MACCS calculation, because the MACCS site-specific consequence code (Chanin et al.1990, Jow et al. 1990) uses a population distribution that is specified on a polar-coordinate grid that can have grid cells that are unpopulated.

## SOURCE TERMS

The magnitude, $M_{ST}$, of the accident source terms used in the validation and application calculations was calculated using the equation, $\mathbf{M_{ST} = \sum_i M_{STi} = \sum_i I_i F_{mci} F_{cei}}$. Here, $M_{STi}$ is the amount of radionuclide i that is released from the RAM transport cask to the environment as a result of the accident, $I_i$ is the inventory of radionuclide i in the cask, $F_{mci}$ is the release fraction for radionuclide i from the radioactive material, here spent fuel, to the cask interior, and $F_{cei}$ is the release fraction for radionuclide i from the cask interior to the environment.

The calculations assumed that the spent fuel was transported in a Transnuclear TN-125 cask. Table 1 presents the radioactive inventory calculated by the ORIGEN code (Croff 1980) for a TN-125 cask fully loaded with spent fuel that has cooled for three years.

**Table 1. TN-125 Cask Inventory**

| Radionuclide | Inventory (Bq) | Radionuclide | Inventory (Bq) | Radionuclide | Inventory (Bq) |
|---|---|---|---|---|---|
| CO-58 | 3.64E+10 | RU-106 | 1.60E+16 | CE-144 | 2.02E+16 |
| CO-60 | 1.71E+15 | TE-127 | 3.54E+12 | PU-238 | 5.47E+14 |
| KR-85 | 1.73E+15 | TE-127M | 3.62E+12 | PU-239 | 6.81E+13 |
| SR-89 | 6.89E+10 | TE-129 | 1.28E+06 | PU-240 | 1.03E+14 |
| SR-90 | 1.52E+16 | TE-129M | 1.96E+06 | PU-241 | 2.24E+16 |
| Y-91 | 7.07E+11 | CS-134 | 1.35E+16 | AM-241 | 1.34E+14 |
| ZR-95 | 2.99E+12 | CS-137 | 2.12E+16 | CM-242 | 6.97E+13 |
| NB-95 | 6.65E+12 | BA-140 | 7.33E-09 | CM-244 | 4.03E+14 |
| RU-103 | 1.69E+09 | CE-141 | 3.11E+07 | | |

The elements in this inventory were assigned to five chemical element classes. Eighteen of the elements were assigned to the **Particulate** chemical element class because during a severe transportation accident they would each be released as constituents of fuel fines. One other element, Co, would also be released as a constituent of particles. However, because these particles would be formed by spallation of the chemical deposits that form on the surface of fuel rods during reactor operation, they are assigned to a separate chemical element class, termed **CRUD** (Sandoval et al. 1991). One element in the inventory, Kr, will always transport as a gas and therefore is assigned to the **Noble Gases** chemical element class. Finally, two elements in the inventory, Cs and Ru, may be released from spent fuel as vapors during fire accident scenarios that heat the fuel to temperatures above 800 C. At these temperatures, Cs may be released from fuel pellets as $CsOH(g)$ or, if the fuel contains iodine, as $CsI(g)$. In addition, if the fuel is exposed to air while hot, involatile $RuO_2$ could be oxidized to and thus be released and transport as $RuO_4$ vapor. Thus, because Cs and Ru have unique high- temperature chemistries, they were each assigned to a separate chemical element classes, Cs to the **Cesium** and Ru to the **Ruthenium** chemical element classes.

Release fractions were estimated for two severe accident scenarios, a ship collision that leads to a small failure of the cask seal but not to a fire, and an extremely severe collision that initiates a fire and also causes a double failure of the cask. For the collision-only scenario, a seal failure with a crosssectional area of 2 $mm^2$ is assumed. For the collision-plus-fire scenario, two cask failures are assumed, a 2 $mm^2$ seal failure plus a puncture or shear failure of the cask body.

Values of $F_{mci}$ for the collision-only scenario were taken from Wilmot (1984). For collision-plus-fire scenario, values of $F_{mci}$ for Cs and Ru were taken from Sprung et al. (1996). Values of $F_{mci}$ for CRUD were based on estimates of CRUD spallation under accident conditions developed by Sandoval et al. (1991). For the collision-plus-fire scenario, uneven heating of the cask is assumed to cause combustion gases, that contain enough air to oxidize involatile $RuO_2$ to volatile $RuO_4$, to flow through the failed cask. Therefore, for this scenario, $F_{cei} = 1.0$ for all species, because the flow of combustion gases is assumed to carry all species released to the cask interior out to the environment. Table 2 summarizes these release fraction values.

**Table 2. Release Fractions**

| Chemical Element Class | | Scenario | | | | | |
|---|---|---|---|---|---|---|---|
| Name | Symbol | Collision-Only (1 hole) | | | Collision-plus-Fire (2 holes) | | |
| | | $F_{mci}$ | $F_{cei}$ | $F_i$ | $F_{mci}$ | $F_{cei}$ | $F_i$ |
| **Noble Gases** | Kr | 0.2 | 0.8 | 0.16 | 0.2 | 1.0 | 0.2 |
| **CRUD** | Co | 0.3 | $1 \times 10^{-2}$ | $3 \times 10^{-3}$ | 0.3 | 1.0 | 0.3 |
| **Cesium** | Cs | $2 \times 10^{-6}$ | $1 \times 10^{-2}$ | $2 \times 10^{-8}$ | $1.6 \times 10^{-3}$ | 1.0 | $1.6 \times 10^{-3}$ |
| **Ruthenium** | Ru | $2 \times 10^{-6}$ | $1 \times 10^{-2}$ | $2 \times 10^{-8}$ | $1.6 \times 10^{-6}$ | 1.0 | $1.6 \times 10^{-6}$ |
| **Particulates** | Part | $2 \times 10^{-6}$ | $1 \times 10^{-2}$ | $2 \times 10^{-8}$ | $2 \times 10^{-6}$ | 1.0 | $2 \times 10^{-6}$ |

## PLUME DISPERSION

The RADTRAN code does not contain a plume dispersion model. Instead plume isopleth areas, calculated externally using a dispersion model and weather conditions typical of the hypothetical accident location, are input to the code. The RADTRAN calculations described here used isopleths calculated by a Gaussian plume model. Each isopleth has the shape of an elongated tear drop. As a group, the isopleths form a set of nested tear drops that have the pointed tops of each drop centered on the release point of the radioactive plume, that is on the location of the hypothesized transportation accident. RADTRAN can use either one set of isopleths calculated using average weather, or six sets, one for each of the six Pasquill-Gifford atmospheric stability classes. When six sets are used, the consequences calculated using each set of isopleths are summed, weighting the individual results by the frequency of occurrence of each Pasquill-Gifford atmospheric stability class in the region where the hypothetical accident is assumed to occur.

Table 3 presents the set of 18 isopleths that were used to calculate consequences for the illustrative New London, CT, to Charleston, SC coastal route. A similar set of isopleths was used for each of the six Pasquill-Gifford constant meteorology calculations that were performed to validate the differencing method. Table 3 shows that the eighteenth isopleth has a downwind length of 121 km. Thus, when all of these eighteen isopleths are used, RADTRAN will calculate radiation doses and consequences for an impact distance of 121 km. Results for shorter impact distances can be obtained by deleting from this table all isopleths that extend to downwind distances further than the desired impact distance. Because of the elongated shape of the isopleths, most but not all of the area that is neglected by removal of an isopleth lies beyond the downwind endpoint of the next longest remaining isopleth. Thus, performing a RADTRAN calculation using only the first fifteen isopleths in Table 3, would produce consequences that have an impact distance somewhat smaller than 40 km because removal of the last three isopleths deletes not only all area beyond 40 km but also all area inside of 40 km that lies between the outlines of the fifteenth and eighteenth isopleths.

Table 3. Isopleth Areas and Downwind Lengths for the Set of 18 Isopleths Calculated Using a Gaussian Plume Model and National Average US Weather

| Isopleth | Area (km$^2$) | Downwind Length (km) | Isopleth | Area (km$^2$) | Downwind Length (km) | Isopleth | Area (km$^2$) | Downwind Length (km) |
|---|---|---|---|---|---|---|---|---|
| 1 | $4.59 \times 10^{-4}$ | 0.0335 | 7 | $1.76 \times 10^{-1}$ | 1.02 | 13 | $2.16 \times 10^{1}$ | 13.1 |
| 2 | $1.53 \times 10^{-3}$ | 0.0681 | 8 | $4.45 \times 10^{-1}$ | 1.63 | 14 | $5.52 \times 10^{1}$ | 21.2 |
| 3 | $3.94 \times 10^{-3}$ | 0.105 | 9 | $8.59 \times 10^{-1}$ | 2.32 | 15 | $1.77 \times 10^{2}$ | 40.1 |
| 4 | $1.25 \times 10^{-2}$ | 0.245 | 10 | 2.55 | 4.27 | 16 | $4.89 \times 10^{2}$ | 70.0 |
| 5 | $3.04 \times 10^{-2}$ | 0.369 | 11 | 4.45 | 5.47 | 17 | $8.12 \times 10^{2}$ | 90.0 |
| 6 | $6.85 \times 10^{-2}$ | 0.562 | 12 | $1.03 \times 10^{1}$ | 11.1 | 18 | $1.35 \times 10^{3}$ | 121 |

## VALIDATION CALCULATIONS

To confirm that a near-field region devoid of population can be modeled by differencing two RADTRAN calculations, the results obtained by differencing two RADTRAN calculations were compared to the results of a MACCS calculation that directly used a population distribution that was empty from 0-to-48 km. Specifically, a MACCS calculation was performed that modeled the release of a radioactive source term from Buxton, NC. Buxton was selected as the hypothetical accident location because Buxton is located on the outer banks at a distance of 48 km from the North Carolina shoreline and because a MACCS meteorology file (one year of hourly readings of wind speed, rain rate, and atmospheric stability), constructed from National Weather Service data, was available for the Buxton site.

A MACCS polar-coordinate, compass-sector, population distribution centered on Buxton was constructed using SECPOP90 (Humphreys et al., 1997). This population distribution had ten downwind distance intervals which had the following outer radii: 1.6, 3.2, 4.8, 6.4, 8.0, 16, 32, 48, 64, and 80 km. Next, all populated intervals with outer radii of 48 km or less had their calculated populations set to zero. This removed the population of the outer banks from the population distribution and reduced the population in the distribution to the population located within 32 km of the North Carolina coastline. Table 4 presents this population distribution.

Table 4. Compass Sector Distribution of Population on the North Carolina Coast Located within 80 km of Buxton, NC

| Distance | N | NNE | NE | ENE | E | ESE | SE | SSE | S | SSW | SW | WSW | W | WNW | NW | NNW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0-48 km | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 48-64 km | 851 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 70 | 1948 | 5 | 191 |
| 64-80 km | 4036 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 316 | 124 | 1394 | 361 | 3472 |

Next, the land areas of the eleven populated elements of this distribution were estimated. The average population density of the eleven populated elements was than calculated by dividing the total population of the eleven elements by the sum of their estimated areas. The resulting average population density was 2.6 people per square kilometer. Finally, the data in the MACCS meteorology file for Buxton was used to construct an annual wind rose for the Buxton site and the annual frequency of occurrence of the six Pasquill-Gifford atmospheric stability classes A through F. Tables 5 and 6 respectively present the wind rose and the frequencies of occurrence of Pasquill-Gifford stability classes developed by these analyses.

### Table 5. Annual Wind Rose for the Buxton, NC, Site (frequency with which the wind blows from the site toward the specified direction)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Direction** | **N** | **NNE** | **NE** | **ENE** | **E** | **ESE** | **SE** | **SSE** |
| **Frequency** | **0.0702** | **0.0999** | **0.1083** | **0.0607** | **0.0282** | **0.0200** | **0.0255** | **0.0201** |
| **Direction** | **S** | **SSW** | **SW** | **WSW** | **W** | **WNW** | **NW** | **NNW** |
| **Frequency** | **0.0650** | **0.0884** | **0.1152** | **0.0749** | **0.0421** | **0.0422** | **0.0458** | **0.0936** |

### Table 6. Annual Frequency of Occurrence of Pasquill-Gifford Atmospheric Stability Classes A Through F at Buxton, NC

| **Class** | **A** | **B** | **C** | **D** | **E** | **F** |
|---|---|---|---|---|---|---|
| **Frequency** | **0.0008** | **0.0352** | **0.1113** | **0.5906** | **0.1495** | **0.1126** |

Finally, one MACCS calculation and two RADTRAN calculations, one 0-to-48 km calculation and one 0-to-80 km calculation, were performed. Each calculation used the TN-125 cask inventory presented in Table 1. For these validation calculations, the radionuclides in this inventory were assigned to four chemical element groups, Noble Gases, Cesium, Ruthenium, and Particulates (CRUD release was neglected), which had the following release fractions for release from failed fuel rods to the environment: 0.1, 9.0x10$^{-4}$, 1.0x10$^{-6}$, and 5.0x10$^{-8}$, respectively.

The MACCS calculation used the population distribution presented in Table 4 and one year of hourly meteorological data recorded at the National Weather Service Station located at Buxton, NC. Results for single variable meteorology weather trials, that assumed the wind was blowing in a given compass direction, were summed using the wind rose frequencies presented in Table 6 as weights. MACCS usually calculates consequences only when the wind is blowing into a compass sector that contains population. However, because plumes can be broader than a single compass sector, MACCS will calculate consequences when the wind blows into a sector that is devoid of population, whenever that sector lies next to a sector that contains population. Inspection of Table 6 shows that the fraction of time when the wind blows from Buxton toward the six compass sectors that contain population (the WSW, W, WNW, NW, NNW, and N compass sectors) is 0.3688. Therefore, the fraction of MACCS single weather sequence trials that yielded consequences was about 0.37.

Each RADTRAN calculation consisted of six constant meteorology calculations, one for each of the six Pasquill-Gifford atmospheric stability classes. Both RADTRAN calculations assumed a downwind population density of 2.6 people km$^{-2}$. Each calculation produced an average annual result by summing the results for the six separate constant meteorology calculations using the annual frequencies of occurrence for the six Pasquill-Gifford atmospheric stability classes given in Table 5 as weights. By subtracting the 0-to-48 km results from the 0-to-80 km results, the 48-to-80 km results were obtained. Because RADTRAN uses a uniform population distribution that has no dependence on compass direction (doesn't reflect the presence of ocean), the 48-to-80 km RADTRAN results must be multiplied by 0.37 in order to obtain a result directly comparable to the MACCS results.

Table 7 compares the RADTRAN population dose for the 48-to-80 km distance interval multiplied by 0.37 to the population dose obtained by the MACCS calculation. Table 7 shows that the population dose calculated by MACCS, using a 0-to-80 km population distribution that is devoid of population from 0 to 48 km, is twice the population dose calculated by RADTRAN for the 48-to-80 km region after that result is multiplied by 0.37 in order to correct for compass sectors that contain only ocean and thus no population.

### Table 7. 50-Year Population Doses Calculated by RADTRAN and MACCS for a Hypothetical Ship Collision that Occurs While Sailing a Coastal Route along the North Carolina Coast 48 km Out to Sea

| Code | 48 to 80 km Population Dose (person-rem) |
|---|---|
| RADTRAN | 16.4 |
| MACCS | 32.0 |

Agreement of the RADTRAN and MACCS population doses to better than a factor of two was not expected (1) because the two codes use atmospheric dispersion data calculated using different Gaussian dispersion models, (2) because the 0.37 correction factor is too small since some MACCS weather trials where the wind is blowing into an unpopulated compass sector still yield population dose by exposing population in neighboring compass sectors to the radioactive plume, (3) because the codes do not use identical dosimetric models, and (4) because the precision of these consequence calculations is no better than a factor of two to three. Thus, the fact that MACCS predicts a population dose only twice that predicted by RADTRAN confirms that differencing two RADTRAN calculations yields a reasonable estimate of the dose to the population of a transportation route segment that contains a near-field region that is devoid of population.

## ILLUSTRATIVE CALCULATION

Modeling of a near-field region that is devoid of population by differencing two RADTRAN calculations was illustrated by estimating the consequences of two hypothetical transportation accidents that might occur while spent power reactor fuel is transported in a TN-125 cask from New London CT around Long Island and then down the east coast of the United States to Charleston SC on an ocean-going barge sailing at a distance of approximately 40 km from the coast. These calculations used three aggregate route segments (one urban, one suburban, and one rural segment), the inventory presented in Table 1, the release fractions presented in Table 2, and the isopleth areas presented in Table 3. The lengths and average population densities of these three aggregate route segments were calculated using the HIGHWAY code and the following coastal highway route: State Highway 27 from Montauk Point on Long Island to New York City; US 9 from New York City through Cape May, New Jersey, and Lewes, Deleware, to US 13; US 13 to Norfolk, Virginia; and US 17 from Norfolk, Virginia, to Charleston, South Carolina. Table 8 presents the lengths and population densities of the aggregate urban, suburban, and rural route segments used in these calculations.

### Table 8. Aggregate Route Segment Lengths and Population Densities

| Segment | Urban | Suburban | Rural |
|---|---|---|---|
| Length (km) | 133 | 415 | 902 |
| Population Density (people per km$^2$) | 2780 | 386 | 13.5 |

Results were developed for two hypothetical accident scenarios that bound the expected range of severe ship accidents, the one hole collision-only scenario and the two hole collision-plus-fire scenario described above. Results for each scenario were developed by differencing two RADTRAN calculations. The first calculation used the full set of isopleths presented in Table 3 and the second calculation deleted from that set of isopleths, isopleths sixteen, seventeen, and eighteen. Thus, the first calculation was a 0-to-121 km calculation and the second was a 0-to-40 km calculation. By differencing the results of these two calculations, the 40 km near-field open ocean region between the barge and the shoreline was subtracted from the results of the standard RADTRAN calculation, thereby obtaining an estimate of the consequences that occurred in the 40-to-121 km distance range, which comprises the first 81 km of land next to the shoreline.

Table 9 presents the results of these RADTRAN calculations. Specifically, Table 9 presents, for each source term and each distance range, the 50-year population dose estimated by RADTRAN for each of the three aggregate route segments used in these calculations. Finally, the table presents the results obtained for the 40-to-121 km distance range, i.e., for the onshore population along the sailing route, by differencing the results obtained for the 0-to-121 and 0-to-40 km distance ranges.

**Table 9. Fifty-Year Population Doses (Sv) Calculated by RADTRAN for Three Distance Ranges for the New London to Charleston Coastal Shipping Route**

| Source Term | Collision-Only (1 hole) | | | Collision-plus-Fire (2 holes) | | |
|---|---|---|---|---|---|---|
| **Route Segment** | **Urban** | **Suburban** | **Rural** | **Urban** | **Suburban** | **Rural** |
| **0-to-121 km** | **1110** | **255** | **8.9** | **106,000** | **24,400** | **855** |
| **0-to-40 km** | **795** | **183** | **6.4** | **72,900** | **16,700** | **586** |
| **40-to-121 km** | **315** | **72** | **2.5** | **33,100** | **7,700** | **269** |

Table 9 shows that deposition of radioactive materials, onto the surface of the 40 km wide region of ocean between the sailing route and the shoreline, reduces the estimated population dose by a factor of about three. Thus, correcting for the presence of a near-field region that is devoid of population produces a significant reduction in estimated population dose. Some of the radioactivity that deposits onto the ocean surface will eventually cause population dose via marine food pathways. Because contaminated seafoods reach individuals in the general population through the commercial food distribution system, the individual doses caused by consumption of these contaminated seafoods will always be very small, much smaller than normal background exposures, and thus of little significance.

Although the 50-year 33,100 Sv urban population dose calculated for the collision-plus-fire (2-hole) accident scenario seems to be very large, in fact it is below the background dose that the exposed population would accumulate during the 50 years that follow the hypothesized accident. Normal individual background doses are about $3.6\text{x}10^{-3}$ Sv per year. Tables 3 and 8 show that about $3.3\text{x}10^{6}$ people = (2780 people $\text{km}^{-2}$)(1350 $\text{km}^2$ – 177 $\text{km}^2$) might be exposed to radiation if the hypothesized accidents occur off of an urban region. Therefore, during the 50 years that follow the hypothesized accidents, the $3.3\text{x}10^{6}$ people exposed to radiation as a result of the accident would also accumulate background doses totaling about $5.9\text{x}10^{5}$ Sv = ($3.3\text{x}10^{6}$ people)( $3.6\text{x}10^{-3}$ Sv $\text{yr}^{-1}$)(50 yrs). Because this background dose is about 20 times larger than the accident dose predicted for the collision-plus-fire (2 holes) ship accident scenario, if that accident were to occur while sailing off of an urban area, any radiological effects caused by the accidental exposures would not be expected to be detected by even an unusually long epidemiological study of a large portion of the population exposed to radiation as a result of the hypothesized accident.

Finally, the population dose predicted for the collision-plus-fire ship accident scenario is not only small, it is also most improbable (Sprung et al. 1997). The urban portion of the New London to Charleston route has an aggregate length of 133 km = 71.8 nautical miles. The frequency of ship collisions while sailing in coastal water is $1.9\text{x}10^{-7}$ collisions per nautical mile sailed. In less than half of these collisions, the barge will be struck. Thus, the chance that the barge will be struck while sailing off of an urbanized shore is about $6.8\text{x}10^{-6}$ = (0.5)(71.8 nautical miles)($1.9\text{x}10^{-7}$ collisions per nautical mile sailed). For a small ship (a charter freighter with a loaded displacement of 1740tonnes), the probability that a collision will cause a double (2 hole) failure of the cask is about $6\text{x}10^{-3}$ = ($P_{\text{crush}}$)( $P_{\text{puncture/shear}}$) = (0.03)(0.2). Since the barge carries no fuel and no cargo other than the

RAM cask, the collision can lead to a large long-duration engulfing fire only if the striking ship is a loaded tanker and then only if the collision is severe enough to fail both the tanker's collision bulkhead and also its forward oil hold. Given that less than half of the ships in the world fleet are tankers or bulkers and that only a most severe collision of a tanker with a barge can fail the tanker's collision bulkhead (say 4 of every 100 collisions), and assuming that the world fleet contains roughly equal numbers of tankers and bulkers, then the probability that the collision leads to a long-lasting fire that engulfs the barge is something like $10^{-2} = (1/2)(1/2)(0.04)$. Accordingly, the probability that the barge is struck during the voyage from New London to Charleston, while sailing off of an urban area, and the collision leads to a double failure of the cask and also to a large long-duration fire, that engulfs the barge and thus the cask, is estimated to be $4 \times 10^{-10} = (6.8 \times 10^{-6})( 6 \times 10^{-3})(10^{-2})$. Thus, not only are the radiological consequences of this extremely severe collision-plus-fire accident unlikely to be capable of epidemiological detection, but also the probability that this accident will occur during a voyage from New London to Charleston is so small that it is almost not credible.

## CONCLUSION

Because the RADTRAN and MACCS calculations used the same uniform population density, source terms, and meteorological conditions, agreement within a factor of two of the population dose obtained by differencing two RADTRAN calculations with the population dose calculated by MACCS confirms that differencing two RADTRAN calculations is an appropriate way to model a transportation route segment with an unpopulated near-field region.

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