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INGESTION DOSE MODEL FOR TRANSPORTATION RISK ASSESSMENT

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ABSTRACT

Risks of transporting radioactive materials can be estimated using the program and code RADTRAN (Neuhauser, et al., 2000; Weiner, et al., 2009). Potential radiation doses to various receptors are calculated by RADTRAN, including doses from routine, incident-free transportation and from transportation accidents. If radioactive material is released from a transportation vehicle in an accident, agricultural products in the plume footprint could be contaminated. This paper discusses a method for calculating radiation doses from ingestion of such radioactively contaminated food stuffs. Transportation of radioactive materials occurs throughout the United States, so that agricultural products along many transportation corridors could be affected. This paper discusses a method for calculating radiation doses from ingestion of such radioactively contaminated food stuffs. However doses from ingesting agricultural crops contaminated from a traffic accident would be very small compared to natural background radiation.

INTRODUCTION

Risks of transporting radioactive materials can be estimated using the program and code RADTRAN (Neuhauser, et al., 2000; Weiner, et al., 2009). Potential radiation doses to various receptors are calculated by RADTRAN, including doses from routine, incident-free transportation and from transportation accidents. Although packaging of radioactive materials for transportation is robust (10 CFR 71.71 and 71.73), accidents in which radioactive material is released are possible, particularly with transportation packages that are built to withstand the rigors of routine transportation but not transportation accidents. If released radioactive material is deposited on any crop that is eaten by either people or animals, radioactive material can be ingested. Exposure to ingested radioactive material is proportional to the following parameters.

(1) the quantity of radioactive material taken up by the agricultural commodity ingested; e.g., 1.2 percent of ^{137}Cs deposited on grass could be transferred to cow's milk (Saricks, et al, 1989),
(2) the chemical form and activity of ingested radioactive material in any particular organ or tissue (the ingestion dose conversion factor); for example, the bone surface dose from dissolved ^{137}Cs is 1.4×10^{-8} Sv/Bq[i] (ICRP, 1996),

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(3) the type and energy of ionizing radiation ingested (e.g. see ICRP, 1983), and
(4) the extent to which a target organ is saturated with stable (non-radioactive) isotopes of the radionuclide in question (Moeller, et al., 2005).

This paper develops a method for determining the quantity of radioactive material taken up in food and available for ingestion, and the resulting ingestion dose, from radioactive material released in an accident. The ingestion dose model assumes that every radioactive atom is ingested by someone and therefore contributes to a collective, societal dose.
Only one accident will occur on any transportation route, so that the ingestion dose depends on the agricultural production of the local political jurisdiction (state, province) in which the accident occurs and not on the total agricultural production along the route. For the United States, the State is the political jurisdiction used in this study, because vehicle accident rates and similar validated statistics are available for each state but not for smaller jurisdisctions.

DERIVATION OF THE INGESTION DOSE EQUATIONS

Equation (1) is an expression of the collective ingestion dose potentially resulting from ingestion of radioactively contaminated food. The ingestion dose is a function of the radioactivity in food, and the equations in this and the succeeding sections reflect the pathway from release of radioactivity in the air to dose. The dose is collective, or "societal" because it is assumed that every radionuclide is ingested by some individual.

$$D_{ingest} = \sum_i^{Radionuclides}(INGEST_{i,j}\ x\ Clvl_{i,j,k}\ x\ Area_k) \qquad (1)$$

D_{ingest} = the total ingestion dose: units are Sv. The only summation is over the radionuclides (subscript i).
$INGEST_{i,j}$= ingestion dose due to ground contamination by radionuclide i in State j; units are $Sv/Bq_{deposited}$;
$Clvl_{i,j,k,}$ = deposited activity of radionuclide i in area k in State j: units are $Bq_{deposited}/m^2$;
$Area_k$ = area of k^{th} dispersion isopleth: units are m^2; for this calculation, 99.9% of the radioactive material is deposited in this area

The ingestion dose, $INGEST_{i,j}$, is given by Equation (2)

$$INGEST_{i,j} = ft_{i,j}(DCF_{Ing,i}) \qquad (2)$$

$ft_{i,j}$, = the total food transfer factor for each radionuclide i deposited in State j,
DCF_{Ing}, = the ingestion dose conversion factor, DCF_{Ing}, for each radionuclide i. The ingestion DCF is the effective ingestion DCF for adults listed in ICRP 72 (ICRP, 1996). Units are Sv/Bq.

<u>Calculation of the Total Food Transfer Factor</u>

Radioactive material released to the environment either falls to the ground or becomes airborne and is dispersed. Material that is airborne does not enter the food chain; it can be inhaled and the inhalation and cloudshine doses are calculated separately in RADTRAN (Neuhauser, et al, 2000; Weiner, et al, 2009). Material deposited on the ground can enter the food chain only if it is deposited on agricultural crops; other deposited material either remains on the surface or is resuspended and is weathered, covered, or dispersed with the passage of time. Deposited radioactive material that enters the food chain is taken up in vegetation by three mechanisms: direct deposition from the initial passing plume, deposition onto the vegetation from resuspended contaminants, and retention by root uptake. Contaminated vegetation can then enter the human food chain either directly, in the case of vegetable crops, or indirectly in milk or meat.

U.S. Nuclear Regulatory Commission (NRC) Regulatory Guide 1.109 (NRC, 1977) divides doses into sources from animal products (milk and meat) and crops. Appendix D of USDOE (2002) associates each of the potential uptake sources (crops, milk, meat) with physical modes of uptake: direct deposition, resuspension, and root uptake. The total food transfer factor in Equation (2), $ft_{i,j}$ is the fraction of the radioactive material i deposited in State j that is retained in foodstuff and available for human consumption. No crop interdiction (such as burial of contaminated food) or other treatment (such as washing) before consumption is assumed.

Local agricultural productivity, agricultural land use, and agricultural yield differ from state to state. The total food transfer factor for radionuclide *i* in State *j*, $ft_{i,j}$, is obtained by summing the three food chain pathways for that State.

$$\mathrm{ft}_{i,j} = Agric_j\big((Crop_j)(fc_i) + (Milk_j)(fm_i) + (Meat_j)(fb_i)\big) \qquad (3)$$

$Agric_j$ = fraction of land in State j that is agricultural (unitless).
$Crop_j$ = local annual crop yield in State j; the unit is kg/km^2-yr;
fc_i = food transfer factor for crops for radionuclide i; the unit is km^2-yr/ kg;
$Milk_j$ = local annual milk production in State j; the unit is liters/ km^2-yr;
fm_i = food transfer factor for milk for radionuclide i; the unit is km^2-yr/ liter;
$Meat_j$ = local annual meat production in State j; the unit is kg/ km^2-yr ;
fb_i = food transfer factor for meat for radionuclide i: the unit is km^2-yr/ kg

Crop, meat, and milk production are estimated on a yearly basis in order to account for seasonal variation. The state specificity accounts for different growing seasons and conditions in different states. Fractions of land in agricultural production and local crop yields (Saricks, et al, 1989) are presented in Table 1 for the 48 contiguous States. The original source of these data is the U.S. Department of Agriculture (USDA, 2012).

Table 1. State Dependent Food Transfer Factors; Equation 1 (Saricks 1989)

State	Agric	Crop	Milk	Meat
		kg/km^2-yr	liters/km^2-yr	kg/km^2-yr
AL	0.31	1.76×10^4	2.00×10^3	7.19×10^3
AZ	0.52	4.15×10^3	1.85×10^3	6.36×10^2
AR	0.44	3.58×10^4	2.78×10^3	9.77×10^3
CA	0.32	4.29×10^4	1.63×10^4	3.41×10^3
CO	0.51	2.52×10^4	1.64×10^3	2.24×10^3
CT	0.14	4.36×10^3	2.32×10^4	5.97×10^3
DE	0.53	1.45×10^5	1.24×10^4	4.98×10^4
FL	0.37	5.94×10^4	6.82×10^3	3.47×10^3
GA	0.33	3.15×10^4	4.26×10^3	8.84×10^3
IA	0.91	3.17×10^5	1.25×10^4	1.74×10^4
ID	0.26	5.37×10^4	4.79×10^3	1.22×10^3
IL	0.81	3.29×10^5	8.36×10^3	6.70×10^3
IN	0.71	2.54×10^5	1.14×10^4	1.00×10^4
KS	0.90	9.40×10^4	2.90×10^3	6.01×10^3
KY	0.56	5.05×10^4	1.04×10^4	3.14×10^3
LA	0.31	2.17×10^4	3.84×10^3	1.98×10^3
MA	0.12	4.55×10^3	1.35×10^4	1.57×10^3
MD	0.41	8.79×10^4	2.81×10^4	1.59×10^4
ME	0.74	1.51×10^4	4.11×10^3	1.62×10^3
MI	0.30	7.84×10^4	1.62×10^4	2.24×10^3
MN	0.54	1.46×10^5	2.28×10^4	5.83×10^3
MO	0.66	6.76×10^4	7.38×10^3	5.56×10^3
MS	0.41	2.70×10^4	3.34×10^3	4.65×10^3
MT	0.65	1.84×10^4	4.11×10^2	8.39×10^2
NC	0.33	4.65×10^4	6.05×10^3	9.51×10^3
ND	0.91	9.23×10^4	2.58×10^3	1.14×10^3
NE	0.92	1.31×10^5	3.06×10^3	7.51×10^3
NH	0.82	1.04×10^3	7.11×10^3	6.62×10^2
NJ	0.19	3.23×10^4	1.15×10^4	1.59×10^3
NM	0.61	2.60×10^3	1.17×10^3	6.61×10^2
NV	0.14	1.03×10^3	3.59×10^2	1.58×10^2
NY	0.30	2.72×10^4	4.10×10^4	2.07×10^3
OH	0.59	1.49×10^5	1.94×10^4	5.55×10^3
OK	0.74	3.10×10^4	2.97×10^3	3.87×10^3
OR	0.29	1.47×10^4	2.37×10^3	9.18×10^2
PA	0.29	3.62×10^4	3.61×10^4	6.13×10^3
RI	0.093	1.28×10^4	7.64×10^3	2.06×10^3
SC	0.29	2.78×10^4	3.29×10^3	3.22×10^3
SD	0.90	5.04×10^4	4.06×10^3	3.20×10^3

Table 2. State Dependent Food Transfer Factors; Equation 1 - continued

State	Agric	Crop kg/km^2-yr	Milk liters/km^2-yr	Meat kg/km^2-yr
TN	0.47	3.34×10^4	9.90×10^3	3.72×10^3
TX	0.78	2.19×10^4	2.53×10^3	3.26×10^3
UT	0.19	2.66×10^3	2.48×10^3	5.72×10^2
VA	0.37	2.75×10^4	9.08×10^3	4.61×10^3
VT	0.27	2.48×10^3	4.50×10^4	1.27×10^3
WA	0.39	5.13×10^4	8.48×10^3	1.71×10^3
WV	0.23	5.41×10^3	2.53×10^3	1.62×10^3
WI	0.50	7.53×10^4	7.47×10^4	4.20×10^3
WY	0.54	5.77×10^3	2.47×10^2	6.39×10^2
US AVERAGE	0.44	5.58×10^4	6.71×10^3	3.07×10^3

Calculation of Food Transfer Coefficients[ii]

Radionuclide food transfer coefficients are the radionuclide-specific fractions of deposited radioactivity that are transferred from soil to plant to animal product and become available for human consumption. Food transfer coefficients are presented in Table 2, and the calculation is outlined in equations (4) through (11). Time-integrated concentrations in Equations (4), (5), and (6) are from Saricks, et al (1989). Ground deposition of each radionuclide is calculated by RADTRAN and presented in RADTRAN output.

Table 2. Radionuclide Food Transfer Coefficients

ATOMIC NUMBER	ELEMENT	TRANSFER COEFFICIENTS SOIL-TO-PLANT	GRASS-TO-MEAT(d/kg)	GRASS-TO-MILK(d/liter)
1	Hydrogen	4.8	1.20×10^{-02}	1.00×10^{-02}
2	Helium	0	0	0
3	Lithium	8.30×10^{-04}	1.00×10^{-02}	5.00×10^{-02}
4	Beryllium	4.20×10^{-04}	1.00×10^{-03}	1.00×10^{-04}
5	Boron	1.20×10^{-01}	8.00×10^{-04}	2.70×10^{-03}
6	Carbon	5.5	3.10×10^{-02}	1.20×10^{-02}
7	Nitrogen	7.5	7.70×10^{-02}	2.20×10^{-02}
8	Oxygen	1.6	1.60×10^{-02}	2.00×10^{-02}
9	Fluorine	6.50×10^{-04}	1.50×10^{-01}	1.40×10^{-02}
10	Neon	0	0	0
11	Sodium	5.20×10^{-02}	3.00×10^{-02}	4.00×10^{-02}
12	Magnesium	1.30×10^{-01}	5.00×10^{-03}	1.00×10^{-02}
13	Aluminum	1.80×10^{-04}	1.50×10^{-03}	5.00×10^{-04}

Table 2. Radionuclide Food Transfer Coefficients -- continued

ATOMIC NUMBER	ELEMENT	TRANSFER COEFFICIENTS		
		SOIL-TO-PLANT	GRASS-TO-MEAT(d/kg)	GRASS-TO-MILK(d/liter)
14	Silicon	$1.50x10^{-04}$	$4.00x10^{-05}$	$1.00x10^{-04}$
15	Phosphorus	1.1	$4.60x10^{-02}$	$2.50x10^{-02}$
16	Sulfur	$5.90x10^{-01}$	$1.00x10^{-01}$	$1.80x10^{-02}$
17	Chlorine	5	$8.00x10^{-02}$	$5.00x10^{-02}$
18	Argon	0	0	0
19	Potassium	$3.70x10^{-01}$	$1.20x10^{-02}$	$1.00x10^{-02}$
20	Calcium	$3.60x10^{-02}$	$4.00x10^{-03}$	$8.00x10^{-03}$
21	Scandium	$1.10x10^{-03}$	$1.60x10^{-02}$	$5.00x10^{-06}$
22	Titanium	$5.40x10^{-05}$	$3.10x10^{-02}$	$5.00x10^{-06}$
23	Vanadium	$1.30x10^{-03}$	$2.30x10^{-03}$	$1.00x10^{-03}$
24	Chromium	$2.50x10^{-04}$	$2.40x10^{-03}$	$2.20x10^{-03}$
25	Manganese	$2.90x10^{-02}$	$8.00x10^{-04}$	$2.50x10^{-04}$
26	Iron	$6.60x10^{-04}$	$4.00x10^{-02}$	$1.20x10^{-03}$
27	Cobalt	$9.40x10^{-03}$	$1.30x10^{-02}$	$1.00x10^{-03}$
28	Nickel	$1.90x10^{-02}$	$5.30x10^{-03}$	$6.70x10^{-03}$
29	Copper	$1.20x10^{-01}$	$8.00x10^{-03}$	$1.40x10^{-02}$
30	Zinc	$4.00x10^{-01}$	$3.00x10^{-02}$	$3.90x10^{-02}$
31	Gallium	$2.50x10^{-04}$	$5.00x10^{-04}$	$5.00x10^{-05}$
32	Germanium	$1.00x10^{-01}$	$1.00x10^{-01}$	$5.00x10^{-04}$
33	Arsenic	$1.00x10^{-02}$	$2.00x10^{-03}$	$6.00x10^{-03}$
34	Selenium	$2.50x10^{-02}$	$1.50x10^{-02}$	$4.50x10^{-03}$
35	Bromine	$7.60x10^{-01}$	$2.60x10^{-02}$	$5.00x10^{-02}$
37	Rubidium	$1.30x10^{-01}$	$3.10x10^{-02}$	$3.00x10^{-02}$
38	Strontium	$1.70x10^{-02}$	$6.00x10^{-04}$	$8.00x10^{-04}$
40	Zirconium	$1.70x10^{-04}$	$3.40x10^{-02}$	$5.00x10^{-06}$
41	Niobium	$9.40x10^{-03}$	$2.80x10^{-01}$	$2.50x10^{-03}$
42	Molybdenum	$1.20x10^{-01}$	$8.00x10^{-03}$	$7.50x10^{-03}$
43	Technetium	$2.50x10^{-01}$	$4.00x10^{-01}$	$2.50x10^{-02}$
44	Ruthenium	$5.00x10^{-02}$	$4.00x10^{-01}$	$1.00x10^{-06}$
45	Rhodium	1.30	$1.50x10^{-03}$	$1.00x10^{-02}$
46	Palladium	$1.50x10^{-01}$	$4.00x10^{-03}$	$1.00x10^{-02}$
47	Silver	$1.50x10^{-01}$	$1.70x10^{-02}$	$5.00x10^{-02}$
48	Cadmium	$3.00x10^{-01}$	$5.30x10^{-04}$	$1.20x10^{-04}$
49	Indium	$2.50x10^{-01}$	$8.00x10^{-03}$	$1.00x10^{-04}$
50	Tin	$2.50x10^{-03}$	$8.00x10^{-02}$	$2.50x10^{-03}$

Table 2. Radionuclide Food Transfer Coefficients -- continued

Atomic Number	Element	Transfer Coefficients		
		Soil-to-Plant	Grass-to-Meat(d/kg)	Grass-to-Milk(d/liter)
51	Antimony	1.10×10^{-02}	4.00×10^{-03}	1.50×10^{-03}
52	Tellurium	1.30	7.70×10^{-02}	1.00×10^{-03}
53	Iodine	2.00×10^{-02}	2.90×10^{-03}	6.00×10^{-03}
54	Xenon	0	0	0
55	Cesium	1.00×10^{-02}	4.00×10^{-03}	1.20×10^{-02}
56	Barium	5.00×10^{-03}	3.20×10^{-03}	4.00×10^{-04}
57	Lanthanum	2.50×10^{-03}	2.00×10^{-04}	5.00×10^{-06}
58	Cerium	2.50×10^{-03}	1.20×10^{-03}	6.00×10^{-04}
59	Praseodymium	2.50×10^{-03}	4.70×10^{-03}	5.00×10^{-06}
60	Neodymium	2.40×10^{-03}	3.30×10^{-03}	5.00×10^{-06}
61	Promethium	2.50×10^{-03}	4.80×10^{-03}	5.00×10^{-06}
62	Samarium	2.50×10^{-03}	5.00×10^{-03}	5.00×10^{-06}
63	Europium	2.50×10^{-03}	4.80×10^{-03}	5.00×10^{-06}
64	Gadolinium	2.60×10^{-03}	3.60×10^{-03}	5.00×10^{-06}
65	Terbium	2.60×10^{-03}	4.40×10^{-03}	5.00×10^{-06}
66	Dysprosium	2.50×10^{-03}	5.30×10^{-03}	5.00×10^{-06}
67	Holmium	2.60×10^{-03}	4.40×10^{-03}	5.00×10^{-06}
68	Erbium	2.50×10^{-03}	4.00×10^{-03}	5.00×10^{-06}
70	Ytterbium	2.50×10^{-03}	4.00×10^{-03}	5.00×10^{-06}
71	Lutetium	2.60×10^{-03}	4.40×10^{-03}	5.00×10^{-06}
72	Hafnium	1.70×10^{-04}	4.00×10^{-01}	5.00×10^{-06}
73	Tantalum	6.30×10^{-03}	6.00×10^{-04}	2.50×10^{-02}
74	Tungsten	1.80×10^{-02}	1.30×10^{-03}	5.00×10^{-04}
75	Rhenium	2.50×10^{-01}	8.00×10^{-03}	2.50×10^{-02}
76	Osmium	5.00×10^{-02}	4.00×10^{-01}	5.00×10^{-03}
77	Iridium	5.50×10^{-02}	1.50×10^{-03}	5.00×10^{-03}
78	Platinum	5.00×10^{-01}	4.00×10^{-03}	5.00×10^{-03}
79	Gold	2.50×10^{-03}	8.00×10^{-03}	5.00×10^{-03}
80	Mercury	3.80×10^{-01}	2.60×10^{-01}	3.80×10^{-02}
81	Thallium	2.50×10^{-01}	4.00×10^{-02}	2.20×10^{-02}
82	Lead	6.80×10^{-02}	2.90×10^{-04}	6.20×10^{-04}
83	Bismuth	1.50×10^{-01}	1.30×10^{-02}	5.00×10^{-04}
84	Polonium	1.50×10^{-01}	1.20×10^{-02}	3.00×10^{-04}
85	Astatine	2.50×10^{-01}	3.00×10^{-04}	5.00×10^{-02}
86	Radon	0	0	0

Table 2. Radionuclide Food Transfer Coefficients -- continued

Atomic Number	Element	Transfer Coefficients		
		Soil-to-Plant	Grass-to-Meat(d/kg)	Grass-to-Milk(d/liter)
87	Francium	$1.00x10^{-02}$	$2.00x10^{-02}$	$5.00x10^{-02}$
88	Radium	$3.10x10^{-04}$	$3.40x10^{-02}$	$8.00x10^{-03}$
89	Actinium	$2.50x10^{-03}$	$6.00x10^{-02}$	$5.00x10^{-06}$
90	Thorium	$4.20x10^{-03}$	$2.00x10^{-04}$	$5.00x10^{-06}$
91	Protactinium	$2.50x10^{-03}$	$1.00x10^{-05}$	$5.00x10^{-06}$
92	Uranium	$2.50x10^{-03}$	$3.40x10^{-04}$	$5.00x10^{-04}$
93	Neptunium	$2.50x10^{-03}$	$2.00x10^{-04}$	$5.00x10^{-06}$
94	Plutonium	$2.50x10^{-04}$	$1.40x10^{-05}$	$2.00x10^{-06}$
95	Americium	$2.50x10^{-04}$	$2.00x10^{-04}$	$5.00x10^{-06}$
96	Curium	$2.50x10^{-03}$	$2.00x10^{-04}$	$5.00x10^{-06}$
97	Berkelium	$2.50x10^{-03}$	$2.00x10^{-04}$	$5.00x10^{-06}$
98	Californium	$2.50x10^{-03}$	$2.00x10^{-04}$	$5.00x10^{-06}$
99	Einsteinium	$2.50x10^{-03}$	$2.00x10^{-04}$	$5.00x10^{-06}$
100	Fermium	$2.50x10^{-03}$	$2.00x10^{-04}$	$5.00x10^{-06}$

The food transfer coefficient for crops, fc_i is the fraction of the radioactivity deposited on the crop area that is transferred to crops that are eventually consumed. DOE (2002) presents the food transfer coefficients in units of m^2-yr /kg; units (e.g., m^2 and km^2) are reconciled in the calculation. The transfer coefficient is:

$$\mathrm{fc_i} = \frac{<\mathrm{C_i^c}>}{\mathrm{G_{i0}}} \qquad (4)$$

fc_i = food transfer coefficient via crops: units are m^2-yr/ kg;
$<C_i^c> = <C^c_{di}> + <C^c_{si}> + <C^c_{ri}>$, the total time-integrated concentration of radionuclide i in crops via direct deposition, resuspension, and the root uptake pathways: units are Bq-yr/ kg;
G_{i0} = initial ground deposition of radionuclide i: units are Bq/m^2.

The food transfer coefficient for milk, fm_i, is the fraction of deposited radioactive material that is transferred from animal feed and pasture grass to milk that then becomes available for human consumption. In the course of a year, the milk cow would feed on pasture grass half of the time and on stored feed half of the time (DOE, 2002). The transfer coefficient is:

$$\mathrm{fm_i} = \frac{<\mathrm{C_i^p}>+<\mathrm{C_i^s}>}{2\mathrm{G_{i0}}}\mathrm{Fm_i}Q_f \qquad (5)$$

fm_i = food transfer coefficient for milk via pasture grass and feed: units are m^2-yr/ liter;
$<C_i^p> = <C^p_{di}> + <C^p_{si}> + <C^p_{ri}>$, the time-integrated concentration of radionuclide i in pasture grass via direct deposition, resuspension, and the root uptake pathways: units are Bq-yr/kg;
$<C_i^s>$ = the time-integrated concentration of radionuclide i in stored feeds. The feed is assumed to be the pasture grass that has decayed for 90 days, $<C_i^p>e^{-90\lambda i}$ (DOE, 2002).

$\lambda = \ln 2/t_{1/2}$; $t_{1/2}$ = radiological half life
G_{i0} = initial ground deposition concentration of radionuclide i: units are Bq/m^2;
Fm_i = transfer coefficient from feed to milk for radionuclide i: units are Bq-day/liter$^-$ Bq from Table 2;
Q_f = total pasture grass and stored feed consumed by animal (assumed as 50 kg/day) (DOE, 2002)

The food transfer coefficient for meat, fb_i is the fraction of deposited radioactivity retained in animal feed and pasture grass and becomes available for human consumption as meat. In the course of a year, the beef cattle would feed on pasture grass half of the time and on stored feed half of the time (DOE, 2002). The transfer coefficient is:

$$fb_i = \frac{<C_i^p> + <C_i^s>}{2 * G_{i0}} Fb_i Q_f \qquad (6)$$

fb_i = food transfer coefficient for beef via pasture grass and feed.
$<C_i^p> = <C^p_{di}> + <C^p_{si}> + <C^p_{ri}>$, the time-integrated concentration of radionuclide i in pasture grass via direct deposition, resuspension, and the root uptake pathways: units are Bq-yr/kg;
Fb_i = transfer coefficient from feed to animal flesh for radionuclide i: units are Bq-day/kg-Bq from Table 2.

A few of the food transfer coefficients, primarily Fb_i, have been modified, based on the results from Kennedy & Strenge (1992). In general the transfer coefficient from Kennedy and Strenge (1992) is several orders of magnitude smaller and is more in line with coefficients for the transition elements, lanthanides, and actinides.

<u>Food Pathway Calculations</u>

Equations (7) through (14) provide algorithms for uptake by vegetation through direct deposition onto the vegetation, deposition of material resuspended in the air, and uptake by the plant roots. For the direct deposition from the initial plume, the amount of radioactive material retained on the vegetation is:

$$Cd_i = < x_i > V_d \frac{Pr}{Y_v} \exp[-(\lambda_{ei} t_e + \lambda_i t_h)] \qquad (7)$$

Cd_i = concentration of radionuclide i retained in vegetation: units are Bq/kg;
$<x_i>$ = time-integrated air concentration of radionuclide i in the initial passing plume: units are $Bq\text{-}yrm^{-3}$;
V_d = deposition velocity[iii] 0.01 m/sec (Weiner, et al., 2009);
r = fraction of deposited activity intercepted and retained by the edible portion of the crop (dimensionless, assumed as 0.25) (DOE, 2002);
P = probability that an accident will occur during the growing season (assumed as 0.5, an approximate average of U.S. growing seasons);
Y_v = standing crop biomass of edible portion of vegetation at harvest, assumed to be 2 kg/m^2 for crops and 0.72 kg m^{-2} for pasture grass (DOE, 2002);

$\lambda_{\varepsilon\iota}$ = effective decay constant for removal of the radionuclide deposited on vegetation where $\lambda_{ei} = \lambda_i + \ln 2/t_w$, t_w = 0.0383 yr (14 days) (DOE, 2002);
t_e = time period of aboveground crop exposure to contamination during the growing season, assumed to be 0.165 yr (60 days) for crops and 0.082 yr (30 days) for pasture grass (DOE, 2002);
λ_i = radioactive decay constant ($\ln 2/t_{1/2}$) of radionuclide (units are yr^{-1}); and
t_h = time period between harvest of vegetation and consumption, assumed to be 0.038 yr (14 days) for crops by human consumption and zero for pasture grass for animals (DOE, 2002) .

Equation (7) (DOE, 2002, Section D.1.1) is the result of integrating over time, while Equation (8) is an integral over the resuspension time. The deposited concentration Cd_i depends on the plume spread over the potentially affected area, which is assumed to occur relatively quickly, and results in the time-integrated concentration $<x_i>$ in Equation (7). The exponential term in Equation (7) could have been written as appropriate integrals. However, DOE (2002) Section D.1.1 presents the length of the growing season and the time to consumption as constants.

Radioactivity initially deposited from the airborne plume can be resuspended and become available for deposition onto the vegetation. The concentration of resuspended material is expressed as an integral because resuspension of deposited material and integration of this material with already resuspended material is time-dependent process. The integrand of Equation (8) combines Equation (7) with a resuspension factor (Equation (9)). The time-integrated concentration of radionuclide i retained in vegetation from resuspension is thus:

$$< C_{si} > = \int_0^{\infty} x_{Ri}(t)\, V_d \,\frac{r(1-e^{-\lambda_{ei} t_e})}{Y_v \lambda_{ei}} \exp(-\lambda_i t_h)\, dt \qquad (8)$$

$< C_{si}>$ = time-integrated concentration of radionuclide i in vegetation due to resuspension: units are Bq-yr/kg, and
$x_{Ri}(t)$ resuspended air concentration of radionuclide i at time t: units are Bq/m^3.

The resuspended air concentration in Equation (8) is calculated by the following (Momeni, et al, 1979):

$$x_{Ri}(t) = G_i(t)R(t) \qquad (9)$$

$G_i(t)$ = deposited ground concentration of radionuclide i at time t
$R(t)$ = resuspension coefficient at time t.

$$G_i(t) = G_{io}\exp\left[-\left(\lambda_g + \lambda_i\right)t\right] \qquad (10)$$

G_{io} = <xi>Vd, = initial deposition of radionuclide i (units are Bq/m^2),
λg = ln2/ tg
tg = ground removal half-life, assumed to be 50 yr (Momeni. et al., 1979)

$$R(t) = \begin{Bmatrix} F_I e^{-\lambda_w t}, & 0 \le t \le t_s \\ F_E, & t_s \le t \end{Bmatrix} \qquad (11)$$

$F_I =$ initial resuspension factor (10^{-5}/m),
$F_E =$ final resuspension factor (10^{-9}/m),
$\lambda_w =$ ln2/tw,
tw = 0.1368 yr (50 d) (Momeni. et al., 1979)
t_s = 1.823 yr. (Momeni. et al., 1979)

The expressions for the resuspension factors and the resuspension decay constant, equations (9) through (11), were derived from experimental measurements (Volchok, 1971; Anspaugh, 1973; Phelps, et al., 1974; NRC, 1974) and are consistent with measured resuspension times in locations as different as the Nevada Test Site, the African bush, and a sheep farm (Anspaugh, et al., 2002).

By using Equations (9) through (11), the time-integrated concentration for Equation (8) becomes

$$< C_{si} >= \mathrm{G_{io}} < \mathrm{T_i} > \mathrm{V_d} \frac{\mathrm{r}(1-\mathrm{e}^{-\lambda_{ei} t_e})}{\mathrm{Y_v} \lambda_{ei}} \exp(-\lambda_i t_h) \qquad (12)$$

$$< \mathrm{T_i} > = \frac{\mathrm{F_I}}{(\lambda_g+\lambda_i+\lambda_w)} \{1 - \exp[-(\lambda_g + \lambda_i + \lambda_w) t_s]\} + \frac{\mathrm{F_E}}{(\lambda_g+\lambda_i)} \exp[-(\lambda_g + \lambda_i) t_s] \quad (13)$$

The time-integrated concentration of radioactivity in vegetation via root uptake is calculated by:

$$< \mathrm{C_{ri}} > = \int_0^{\infty} \mathrm{G_i(t)} \frac{\mathrm{B_v(i)}}{\rho} \exp(-\lambda_i t_h)\, dt = \mathrm{G_{i0}} \frac{\mathrm{B_v(i)}}{\rho(\lambda_g+\lambda_i)} \exp(-\lambda_i t_h) \qquad (14)$$

<Cri> = time-integrated radioactivity concentration in vegetation from root uptake: units are Bq-yr kg^{-1};
Gi(t) = ground concentration at time t, given in Equation (10);
Bv(i) = concentration ratio for the transfer of the element to the edible portion of a crop from dry soil: units are Bq/kg-plant per Bq/kg-soil from Table 2;
ρ = density for the effective root zone in dry soil, assumed to be 240 kg/m (Momeni. et al., 1979)

CALCULATION OF INGESTION DOSE

The following example illustrates the application of food transfer factors and coefficients in a RADTRAN risk analysis:

> A truck carries transuranic waste in a RH-72B cask from Argonne National Laboratory to the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico. The truck transits rural areas in Illinois, Missouri, Oklahoma, Texas, and New Mexico. An accident involving a release is assumed to take place in one of the states transited, but not in more than one. The accident is modeled in each state transited. The resulting ingestion dose is calculated for each of the modeled accidents.

Table 3 shows the radionuclide inventory and the activity of the radioactive material potentially released in a severe accident (Dunagan and Weiner, 2008), which could occur in any of the states transited. Table 3 also shows the ingestion dose conversion factors (ICRP,1996), and the fraction of the radionuclide inventory that would be released in a severe accident (NRC, 2012, Chapter 5 and Appendix 5, Sprung, et al, 2000, Chapter 7).

Table 3. Radionuclides potentially released from a RH-72B cask in an accident.

Nuclide	Bq	Fraction Released	Bq Released	Ingestion DCF: Sv/Bq
^{137}Cs	9.77×10^{12}	7.68×10^{-5}	7.50×10^{8}	2.50×10^{-11}
^{60}Co	4.96×10^{11}	9.30×10^{-6}	4.61×10^{6}	3.40×10^{-9}
^{90}Sr	9.77×10^{12}	9.30×10^{-6}	9.08×10^{7}	2.80×10^{-8}
^{238}Pu	1.99×10^{14}	9.30×10^{-6}	1.85×10^{9}	2.30×10^{-7}
^{239}Pu	4.00×10^{12}	9.30×10^{-6}	3.71×10^{7}	2.50×10^{-7}
^{240}Pu	1.99×10^{12}	9.30×10^{-6}	1.85×10^{7}	2.50×10^{-7}
^{241}Am	2.39×10^{12}	9.30×10^{-6}	2.22×10^{7}	2.00×10^{-7}
^{241}Pu	1.99×10^{12}	9.30×10^{-6}	1.85×10^{7}	4.80×10^{-9}
^{233}U	5.96×10^{9}	9.30×10^{-6}	5.54×10^{4}	5.10×10^{-8}
^{235}U	2.19×10^{8}	9.30×10^{-6}	2.04×10^{3}	4.70×10^{-8}
^{238}U	1.41×10^{7}	9.30×10^{-6}	1.31×10^{2}	4.50×10^{-8}

1 Ci = 3.7×10^{10} Bq
1 rem = 0.01 Sv

Using the Gaussian air dispersion model in RADTRAN, the air concentration and ground deposition of radioactive material are calculated, yielding the results shown in Table 4. The total deposition is 0.00111 Bq/m^2 per Bq released. The plume footprint can be modeled to 120 km downwind. However, Table 4 shows results only to 476 meters downwind, because the difference in total Bq/m^2 per Bq released is less than one percent.

Applying the appropriate agriculture-specific food transfer factors from Table 1, as shown in Table 5 and the radionuclide-specific food transfer coefficients from Table 2, Equation (3) yields the total food transfer factor for each state in which an accident could take place. This is shown in Tables 6a and 6b.

Table 4. Air concentration and ground deposition of radioactive material.

Downwind Distance (m)	Plume Footprint Area (m^2)	Dilution ($Bq\text{-}sec/m^3\text{-}Bq$-released)	Deposition ($Bq\text{-}sec/m^2\text{-}Bq$-released)
22	5	0.03580	3.58×10^{-4}
27	27	0.02780	2.78×10^{-4}
35	82	0.01990	1.99×10^{-4}
50	244	0.01190	1.19×10^{-4}
65	471	0.00795	7.95×10^{-5}
99	1210	0.00398	3.98×10^{-5}
145	2750	0.00199	1.99×10^{-5}
235	7400	7.95×10^{-4}	7.95×10^{-6}
335	15100	3.98×10^{-4}	3.98×10^{-6}
476	30100	1.99×10^{-4}	1.99×10^{-6}

Table 5. Parameter values for Equation (3).

	Illinois	Missouri	Oklahoma	Texas	New Mexico
Fraction of state land in agriculture	0.81	0.66	0.74	0.78	0.61
Crop yield (kg/m^2-day)	3.29×10^{-4}	6.76×10^{-5}	3.10×10^{-5}	2.19×10^{-5}	2.60×10^{-6}
Milk yield (liters /m^2-day)	8.36×10^{-6}	7.38×10^{-6}	2.97×10^{-6}	2.53×10^{-6}	1.17×10^{-6}
Meat yield (kg /m^2-day)	6.70×10^{-6}	5.56×10^{-6}	3.87×10^{-6}	3.26×10^{-6}	6.61×10^{-7}

Table 6a. Food transfer factors.

	Food transfer coefficients (Table 2)		
	to plant	to milk	to meat
^{137}Cs	0.0010	0.012	0.0040
^{60}Co	0.0094	0.0010	0.0013
^{90}Sr	0.0170	$8.00x10^{-4}$	$6.00x10^{-4}$
^{238}Pu	$2.5x10^{-4}$	$2.00x10^{-6}$	$1.40x10^{-5}$
^{239}Pu	$2.5x10^{-4}$	$2.00x10^{-6}$	$1.40x10^{-5}$
^{240}Pu	$2.5x10^{-4}$	$2.00x10^{-6}$	$1.40x10^{-5}$
^{241}Am	$2.5x10^{-4}$	$5.00x10^{-6}$	$2.00x10^{-4}$
^{241}Pu	$2.5x10^{-4}$	$2.00x10^{-6}$	$1.40x10^{-5}$
^{233}U	0.0025	$5.00x10^{-4}$	$3.40x10^{-4}$
^{235}U	0.0025	$5.00x10^{-4}$	$3.40x10^{-4}$
^{238}U	0.0025	$5.00x10^{-4}$	$3.40x10^{-4}$

Table 6b. Food transfer factors.

	Total food transfer factor, $ft_{i,j}$ (Equation 3)				
	Illinois	Missouri	Oklahoma	Texas	New Mexico
^{137}Cs	$3.69x10^{-7}$	$1.18x10^{-7}$	$6.08 x10^{-8}$	$5.09 x10^{-8}$	$1.18 x10^{-8}$
^{60}Co	$2.52x10^{-6}$	$4.29x10^{-7}$	$2.22x10^{-7}$	$1.66x10^{-7}$	$1.61x10^{-8}$
^{90}Sr	$4.54x10^{-6}$	$7.65x10^{-7}$	$3.93x10^{-7}$	$2.93x10^{-7}$	$2.78x10^{-8}$
^{238}Pu	$6.67x10^{-8}$	$1.12x10^{-8}$	$5.78x10^{-9}$	$4.31x10^{-9}$	$4.04x10^{-7}$
^{239}Pu	$6.67x10^{-8}$	$1.12x10^{-8}$	$5.78x10^{-9}$	$4.31x10^{-9}$	$4.04x10^{-7}$
^{240}Pu	$6.67x10^{-8}$	$1.12x10^{-8}$	$5.78x10^{-9}$	$4.31x10^{-9}$	$4.04x10^{-7}$
^{241}Am	$6.77x10^{-8}$	$1.19x10^{-8}$	$6.32x10^{-9}$	$4.79x10^{-9}$	$4.81x10^{-7}$
^{241}Pu	$6.67x10^{-8}$	$1.12x10^{-8}$	$5.78x10^{-9}$	$4.31x10^{-9}$	$4.04x10^{-7}$
^{233}U	$6.71x10^{-7}$	$1.15x10^{-7}$	$5.94x10^{-8}$	$4.46x10^{-8}$	$4.46x10^{-9}$
^{235}U	$6.71x10^{-7}$	$1.15x10^{-7}$	$5.94x10^{-8}$	$4.46x10^{-8}$	$4.46x10^{-9}$
^{238}U	$6.71x10^{-7}$	$1.15x10^{-7}$	$5.94x10^{-8}$	$4.46x10^{-8}$	$4.46x10^{-9}$

The parameter INGEST (Equation (2)) can then be calculated for each radionuclide, and for each State transited, by multiplyi8ng the total food transfer factor (a unitless fraction) by the appropriate DCF (Sv/Bq). The results of the INGEST calculation are shown in Table 7. The ingestion dose shown in Table 8 is then calculated using Equation (1) and the appropriate RADTRAN output (the sum of the deposition values shown in Table 4.

Table 7. Calculation of INGEST (Equation 2)

	Illinois	Missouri	Oklahoma	Texas	New Mexico
^{137}Cs	9.2×10^{-18}	2.9×10^{-18}	1.5×10^{-18}	1.3×10^{-18}	2.9×10^{-19}
^{60}Co	8.6×10^{-15}	1.5×10^{-15}	7.5×10^{-16}	5.6×10^{-16}	5.5×10^{-17}
^{90}Sr	1.3×10^{-13}	2.1×10^{-14}	1.1×10^{-14}	8.2×10^{-15}	7.8×10^{-16}
^{238}Pu	1.5×10^{-14}	2.6×10^{-15}	1.3×10^{-15}	9.9×10^{-16}	9.3×10^{-17}
^{239}Pu	1.7×10^{-14}	2.8×10^{-15}	1.4×10^{-15}	1.1×10^{-15}	1.0×10^{-16}
^{240}Pu	1.7×10^{-14}	2.8×10^{-15}	1.4×10^{-15}	1.1×10^{-15}	1.0×10^{-16}
^{241}Am	1.4×10^{-14}	2.4×10^{-15}	1.3×10^{-15}	9.6×10^{-16}	9.6×10^{-17}
^{241}Pu	3.2×10^{-16}	5.4×10^{-17}	2.8×10^{-17}	2.1×10^{-17}	1.9×10^{-18}
^{233}U	3.4×10^{-14}	5.9×10^{-15}	3.0×10^{-15}	2.3×10^{-15}	2.3×10^{-16}
^{235}U	3.2×10^{-14}	5.4×10^{-15}	2.8×10^{-15}	2.1×10^{-15}	2.1×10^{-16}
^{238}U	3.0×10^{-14}	5.2×10^{-15}	2.7×10^{-15}	2.0×10^{-15}	2.0×10^{-16}

Table 8. Calculation of Ingestion Dose (Sv/radionuclide)

	Illinois	Missouri	Oklahoma	Texas	New Mexico
^{137}Cs	2.3×10^{-7}	7.4×10^{-8}	3.8×10^{-8}	3.2×10^{-8}	7.4×10^{-9}
^{60}Co	1.3×10^{-6}	2.2×10^{-7}	1.2×10^{-7}	8.7×10^{-8}	8.4×10^{-9}
^{90}Sr	3.9×10^{-4}	6.5×10^{-5}	3.3×10^{-5}	2.5×10^{-5}	2.4×10^{-6}
^{238}Pu	9.5×10^{-4}	1.6×10^{-4}	8.2×10^{-5}	6.1×10^{-5}	5.7×10^{-6}
^{239}Pu	2.1×10^{-5}	3.5×10^{-6}	1.8×10^{-6}	1.3×10^{-6}	1.3×10^{-7}
^{240}Pu	1.0×10^{-5}	1.7×10^{-6}	8.9×10^{-7}	6.7×10^{-7}	6.2×10^{-8}
^{241}Am	1.0×10^{-5}	1.8×10^{-6}	9.4×10^{-7}	7.1×10^{-7}	7.1×10^{-8}
^{241}Pu	2.0×10^{-7}	3.3×10^{-8}	1.7×10^{-8}	1.3×10^{-8}	1.2×10^{-9}
^{233}U	6.3×10^{-8}	1.1×10^{-8}	5.6×10^{-9}	4.2×10^{-9}	4.2×10^{-10}
^{235}U	2.1×10^{-9}	3.7×10^{-10}	1.9×10^{-10}	1.4×10^{-10}	1.4×10^{-11}
^{238}U	1.3×10^{-10}	2.3×10^{-11}	1.2×10^{-11}	8.8×10^{-12}	8.8×10^{-13}

RESULTS AND CONCLUSIONS

Table 9 shows the total ingestion dose from all of the radionuclides released, in both Standard International (SI) and historical units. This is the output of the ingestion dose model in RADTRAN 6.02.

Table 8. Ingestion dose from all radionuclides (person-Sv and person-rem)

Accident Location	Illinois	Missouri	Oklahoma	Texas	New Mexico
Societal Ingestion Dose					
Person-Sv	1.38×10^{-3}	2.31×10^{-4}	1.19×10^{-4}	8.90×10^{-5}	8.36×10^{-6}
Person-rem	1.38×10^{-1}	2.31×10^{-2}	1.19×10^{-2}	8.90×10^{-3}	8.36×10^{-4}

The ingestion dose is a societal dose, since food products are distributed throughout the United States. The radioactivity deposited because of the accident, however, is deposited within the footprint of the plume of material released in the accident. That footprint is located in one of the five states transited. If the accident occurs in, e.g., Illinois, the total societal ingestion dose would be 1.38×10^{-3} person-Sv (1.38 person-mSv or 138 person-mrem), whereas if the accident occurred in New Mexico, the total societal ingestion dose would be 8.36×10^{-6} person-Sv (8.36 person-μSv or 0.836 person-mrem). As Table 5 shows, New Mexico has less land in agriculture and all agricultural yields are less that the corresponding yields in Illinois. These results illustrate dramatically the dependence of the total ingestion dose on accident location. They are consistent with results obtained by other investigators (e.g., Abbott and Rood, 1993) whose model and algorithms are different from those presented here.

The radionuclides listed in Table 3 are typical of material that could be released in an accident involving a truck carrying a cask of spent nuclear fuel, like the accident described in NRC (2012), Chapter 5. The primary contributors to that dose are ^{137}Cs and ^{90}Sr, with half-lives of approximately 30 years, and ^{238}Pu, of which a moderately large amount is present in the spent fuel. The long-lived actinides in the mixture exhibit considerably lower activities. Most of the ^{60}Co fraction in spent fuel, which could be expected to contribute significantly, will have decayed away before the spent fuel is ever transported. The contribution of ^{137}Cs is probably exaggerated in the model because ^{137}Cs is assumed to behave like a semi-volatile substance when released while the other radionuclides are assumed to behave like particulate matter.

The implication of the calculated ingestion dose may be understood by comparison with a natural source of radioactivity. For example, the internal dose from ^{40}K and ^{14}C sustained by a 70 kg individual is about 2.8 mSv (Kramer, 2012). The radioactive material released in any of the sample accidents discussed would be deposited on a surface of about 30,100 m^2 (Table 4). If the crop is a leafy green like spinach, it would yield 330 one-cup (30 gm) servings of raw spinach (Table 5 and USDA, 2012). Each serving would deliver an average ingestion dose of about 4.2 μSv (0.42 mrem), about 0.15 percent of the naturally occurring internal dose from ^{40}K and ^{14}C.

The equations and variables defined in Appendix D of NRC (1974) were implemented in a Microsoft Excel spreadsheet which provides the state-specific food transfer factors for six radioisotopes in expanded detail, and allows the user to replace any of these six radionuclides to determine transfer factors or to change the states of the United States to locales of greater interest.

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