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ECONOMIC COSTS FROM A RADIOLOGICAL TRANSPORTATION ACCIDENT

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With the increased use of nuclear power and nuclear medicine, transportation of radioactive materials along highways and railways has become commonplace. In an accident involving a vehicle transporting radioactive materials, a release of radioactive materials may occur. Following such a release, a need exists to decontaminate the affected areas and to evacuate persons. It is useful to know the post-accident costs in order to project the economic impact of a radiological transportation accident. The radiological transportation risk & consequence program, RADTRAN, has recently added an updated economic costing model to it most recent version, RADTRAN 6.0. This paper discusses the analysis used in the RADTRAN economic model. An earlier version, RADTRAN 4.0, calculates a cost of post-accident cleanup, but the model was not scenario-specific. The paper is intended to better account for variations such as radioactive material cleanup level, type of cleanup, and land use.

I. INTRODUCTION

An accidental release of radionuclides during transportation could require evacuation of the population and decontamination of the affected area. The economic model in RADTRAN 6 estimates the cost of evacuation and decontamination.

The cost of decontamination depends on the size of the release, the number of people and land area affected by the release, the activity of the released material, and the "goal" cleanup level. The values of these input parameters are either defined by the analyst or default values in RADTRAN using user-defined inputs. Lower limit and upper limit values and average values, based on data and observations, are provided for many user-defined variables.

The categories of parameter values are:

- Building Cleanup
    - Residential
    - Commercial
    - Industrial
- Road Cleanup
- Soil Cleanup
- Agricultural Damage
    - Crops
    - Livestock
- Evacuation and Emergency

Post-accident costs considered are the cost of building and road cleanup, soil disposal, agricultural sequestration, and emergency evacuation, as financed by the federal government through the Federal Emergency Management Agency (FEMA) loans and grants[3]. Political, social, and psychological costs are not included.

Buildings and roads are decontaminated by washing deposited radioactive compounds from contaminated surfaces. The contaminated water is collected on adsorption resins, which are disposed as low-level radioactive waste. It is assumed that all roads and other horizontal surfaces are contaminated. Building sides, however, are vertical and the entire vertical surface would not be contaminated. Depending on the location of the release, orientation of the building(s), and height of the building(s), different fractions of the building's exposed surface area will be contaminated.

II. SCENARIO

There has been concern since the 1970's that a spent fuel shipment could be attacked using a High Energy Density Device (HEDD). Recent studies suggest that the affected contamination area could be 10 square kilometers (3.9 square miles) or more with costs ranging from $668 million to $10 billion for cleanup costs[1].

Using the assumption of 10 square kilometers for a contamination area, RADTRAN calculations were conducted using the default economic input values, and the following input data:

- The curie content of a PWR fuel assembly from the Yucca Mountain EIS[6] Table A-12 was adjusted according to the radionuclide's mass fraction to account for the total mass swept out of the cask due to a HEDD attack on a truck transportation cask.
- The HEDD swept mass was determined from Table 5-64 of the page 187 of the transportation health and safety calculation/analysis documentation[5].
- The swept mass per assembly was assumed to be the maximum, 9.6 kg.
- The number of assemblies penetrated was determined from Table 5-64[5] to be two.
- This analysis used the swept mass value 19.2 kg.

Table 1 lists the chemical/physical group, activity in curies, swept mass in grams, and mass fraction for each radionuclide for the 19.2 kg swept mass. The radionuclides in Table 1 are listed in order of decreasing mass fraction. The radionuclides Se-79 and Nb-93m were not included in this analysis since they are not in the RADTRAN internal radionuclide library. The radionuclide Ba-137m has been incorporated in the Cs-137 radionuclide in the RADTRAN radionuclide library.

TABLE 1: 19.2 kg Swept Mass Radionuclides List

Nuclide	**Chem./Phys. Group**	**Activity (Ci)**	**Mass (g)**	**Mass Fraction**
U-238	Particulate	6.22E-03	1.85E+04	9.64E-01
U-235	Particulate	3.91E-04	1.81E+02	9.42E-03
U-236	Particulate	8.44E-03	1.30E+02	6.79E-03
Pu-239	Particulate	7.99E+00	1.29E+02	6.70E-03
Pu-240	Particulate	1.38E+01	6.04E+01	3.14E-03
Cs-137	Volatile	2.31E+03	2.65E+01	1.38E-03
Tc-99	Particulate	4.04E-01	2.38E+01	1.24E-03
Am-241	Particulate	6.66E+01	1.94E+01	1.01E-03
Zr-93	Particulate	4.35E-02	1.73E+01	9.03E-04
Pu-242	Particulate	6.66E-02	1.70E+01	8.85E-04
Pu-241	Particulate	1.73E+03	1.68E+01	8.76E-04
Np-237	Particulate	1.11E-02	1.57E+01	8.20E-04
Cs-135	Volatile	1.69E-02	1.47E+01	7.64E-04
Sr-90	Particulate	1.60E+03	1.17E+01	6.08E-04
Pu-238	Particulate	1.15E+02	6.75E+00	3.52E-04
Pd-107	Particulate	3.46E-03	6.74E+00	3.51E-04
I-129	Iodine	9.77E-04	5.52E+00	2.87E-04
U-234	Particulate	2.98E-02	4.76E+00	2.48E-04
Am-243	Particulate	8.88E-01	4.46E+00	2.32E-04
Sn-126	Particulate	1.64E-02	1.34E+00	6.96E-05
Ni-59	Particulate	8.44E-02	1.04E+00	5.43E-05
Cm-244	Particulate	7.99E+01	9.88E-01	5.15E-05
Sm-151	Particulate	1.07E+01	4.05E-01	2.11E-05
Eu-154	Particulate	6.66E+01	2.52E-01	1.31E-05
Kr-85	Gas	9.77E+01	2.49E-01	1.29E-05
Nb-94	Particulate	3.60E-02	1.91E-01	9.97E-06
Ni-63	Particulate	1.11E+01	1.88E-01	9.77E-06
Pm-147	Particulate	7.55E+01	8.14E-02	4.24E-06
Cm-245	Particulate	1.29E-02	7.49E-02	3.90E-06
Co-60 (Structure)	Crud	4.88E+01	4.32E-02	2.25E-06
Am-242m	Particulate	3.20E-01	3.29E-02	1.71E-06
Cs-134	Volatile	3.20E+01	2.48E-02	1.29E-06
Eu-155	Particulate	9.77E+00	2.10E-02	1.09E-06
Cm-246	Particulate	4.04E-03	1.32E-02	6.86E-07
Cm-243	Particulate	5.77E-01	1.12E-02	5.83E-07
Cl-36	Volatile	2.80E-04	8.48E-03	4.42E-07
Sb-125	Particulate	5.33E+00	5.17E-03	2.69E-07
C-14	Particulate	1.33E-02	2.99E-03	1.56E-07
Y-90	Particulate	1.60E+03	2.93E-03	1.53E-07
Cd-113m	Particulate	5.33E-01	2.29E-03	1.19E-07
H-3	Gas	8.88E+00	9.25E-04	4.82E-08
Fe-55	Particulate	1.78E+00	7.37E-04	3.84E-08
Co-60 (Crud)	Crud	3.91E-01	3.46E-04	1.80E-08
Th-230	Particulate	4.40E-06	2.18E-04	1.13E-08
U-233	Particulate	1.42E-06	1.47E-04	7.65E-09
Ru-106	Volatile	4.88E-01	1.46E-04	7.59E-09
Cm-242	Particulate	2.62E-01	7.92E-05	4.12E-09
U-232	Particulate	1.07E-03	4.98E-05	2.59E-09
Pa-231	Particulate	1.47E-06	3.10E-05	1.62E-09
Ac-227	Particulate	5.77E-07	7.98E-09	4.16E-13

For this analysis, it is assumed that all the Co-60 released will behave as one chemical/physical group, Crud, although most of the Co-60 mass is structural material. It is further assumed that the radionuclides in the chemical/physical groups Volatile, Gas, and Iodine will either have no deposition velocity (Gas) or such a small deposition velocity that they will not be included in the cleanup costs since they will be below the minimum cleanup levels. Thus the only radionuclides analyzed are those in the chemical/physical groups for Crud and Particulate.

The default value for cleanup level[2] (0.2 $\mu Ci/m^2$) was kept constant for all radionuclides analyzed. To better understand this cleanup level, a beta/gamma or alpha contamination field instrument would determine this contamination level to be 4,400 $dpm/100cm^2$.

Deposition velocities were determined using the following equation:

$$V_d = \frac{gd^2\rho}{18\mu} \qquad (1)$$

Where:
V_d = deposition velocity (cm/s)
g = gravity (cm/s^2)
d = aerodynamic particle diameter (cm)
ρ = density (g/cm^3)
μ = dynamic viscosity for 25 ^{o}C dry air (g/cm-s)

It was assumed that the mean aerodynamic particle diameter[a] is 13.5 μm. It was also assumed that all radionuclides in the chemical/physical group "Particulate" had the same density as uranium dioxide (10.96 g/cm^3). This results in a deposition velocity of 4.91 cm/s for the Chemical/Physical group Crud and a deposition velocity of 6.10 cm/s for the Chemical/Physical group Particulate.

[a] The mean aerodynamic particle diameter is the diameter that the particle would have if it were a sphere of density 1 gm/cm^3.

The analysis determined the economic cleanup costs for three population zones: Rural, Suburban, and Urban. The population densities within each of these zones were assumed to be the national averages as cited in the RadCat 2.3 User guide[7]:

- Rural – 6 persons/km^2
- Suburban – 720 persons/km^2
- Urban – 3800 persons/km^2

It is assumed that the entire swept volume is released, aerosolized, and respirable. The RADTRAN calculations were conducted for a ground level release using RADTRAN's National Weather Average. This release provided a contamination area of 10.3 km^2 in which the contamination level is greater than the cleanup level.

II.A. Economic Input Defaults

The RADTRAN economic input defaults[4] are provided in Table 2. The defaults were determined through experimentation, modeling, data analysis, and conservative estimates. These inputs can be varied by the RADTRAN user.

TABLE 2: Economic Model Input Default Values

Description	Average Value	Units
Footprint of commercial buildings	337	m^2
Footprint of industrial buildings	6620	m^2
Footprint of residential buildings	118	m^2
Area of commercial lots	930	m^2
Area of industrial lots	9700	m^2
Area of residential lots	223	m^2
External dose rate per drum of resin	5.0	mrem/hour
External dose rate for 1 Ci of Co-60 in a drum	269.7	mrem/hour
Annual crop profit	0.01303	\$/m^2
Cost of washing contaminated area	32.29	\$/m^2
Rural evacuation cost	7.88	\$/person-km^2
Suburban evacuation cost	13.61	\$/person-km^2
Urban evacuation cost	13.61	\$/person-km^2
Rural commercial land use fraction	0.01	
Suburban commercial land use fraction	0.14	
Urban commercial land use fraction	0.37	
Rural industrial land use fraction	0.01	
Suburban industrial land use fraction	0.09	
Urban industrial land use fraction	0.11	
Rural residential land use fraction	0.03	
Suburban residential land use fraction	0.28	
Urban residential land use fraction	0.24	
Rural soil land use fraction	0.95	
Suburban soil land use fraction	0.41	
Urban soil land use fraction	0.09	
Fraction of building surfaces contaminated	0.449	
Rural soil land use fraction for crops	0.2	
Rural soil land use fraction for livestock	0.28	
Average commercial building outside height	16.40	m
Average industrial building outside height	6.05	m
Average residential building outside height	5.32	m
Rural road density	5.97E-04	m of road/m^2 of land
Suburban road density	8.11E-04	m of road/m^2 of land
urban road density	8.06E-02	m of road/m^2 of land
Resin density	1.28	g/cm^3
Road width	8.84	m
Cost of soil removal	10	\$/m^3
Contaminated soil depth	0.03	m
Bi-annual profit from livestock	0.02499	\$/m^2
Volume of waste container	0.2167	m^3

III. RESULTS

The results for the scenario combined the following economic cleanup costs to calculate the total cost of cleanup:

- The cost of decontaminating all buildings, roads and parking lots using a liquid wash down method and passing the liquid through resin columns to remove all contaminates.
- The cost of resin disposal as Class-A waste.
- The cost of agricultural and residential soil removal as Class-A waste.

- The cost of crop and livestock sequestering for rural areas only.
- The cost of evacuation for the affected population.

The RADTRAN results produced contamination levels greater than cleanup level out to about 11.1 km downwind of the event for a contaminated area a little larger than 10.3 km^2 and thus comparable to the assumed 10 km^2 contaminated area cited in Reference 1. Table 3 provides the total cost of cleanup for the swept mass for all three population areas.

TABLE 3: Economic Cleanup Cost Results
(in millions of dollars)

Costs	Rural	Suburban	Urban
Resin Cost	$22.5	$219.5	$751.9
Decon Wash Down Cost	$15.7	$153.5	$526.7
Soil Removal Cost	$1.6	$1.7	$0.28
Crop/Livestock Cost	$0.094	$0.00	$0.00
Evacuation Cost	$0.002	$0.40	$2.1
Total Cost	$39.9	$375.1	$1,281.0

A second iteration of the RADTRAN Economic Model was conducted to try to determine the amount of swept material that would be needed to produce about $10 billion in clean up for an urban area. With the same assumptions listed in this paper, it would take about 160 kg (about 1/3 of a PWR fuel assembly) of swept material to produce a total cleanup cost of about $9.2 billion. With such a large amount of material released, the cleanup area was determined to be about 55.2 km^2 with a downwind distance of ~21.3 km for a contamination area greater than the cleanup level.

III.A. Results for Elevated Releases

The preceding RADTRAN simulations used a ground level release with National Weather Average Weather dilution factors. User-defined weather conditions allow analysis of an elevated release as well as a ground level release. The material reaching the ground from an elevated release is more dilute, but the area covered is larger, so elevated releases were also investigated. For comparison, User-Defined weather conditions simulating National Weather Average conditions as nearly as possible were investigated, as well as an elevated release. The User-Defined weather inputs required to produce the ground level release results in Table 4 are the following:

Release Height = 1.5 m
Heat Released = 0.0 cal/s
Source Radius = 1.5 m
Source Length = 3.0 m
Wind Speed = 1.0 m/s
Anemometer Height = 10.0 m
Ambient Temperature = 298.0 K
Atmospheric Mixing Height = 5,000 m
Rain Fall Rate = 0.0 mm/s
Dispersion Model – Pasquill
Stability Class – D
Release Location – Rural

The rural release location was selected because it adds conservatism in the atmospheric modeling.

Table 4 provides the cleanup results and the contamination area greater than the cleanup level for a 19.2 kg swept mass release for the National Weather Average dilution factors and ground level User-Defined dilution factors.

TABLE 4: National Weather Average vs. User-Defined "National Average Weather" Results

National Weather Average

	Rural	Suburban	Urban
Total Cost ($\$10^6$)	$39.9	$375.1	$1,281.0
Cleanup Area	10.3 km^2	10.3 km^2	10.3 km^2

User-Defined

	Rural	Suburban	Urban
Total Cost ($\$10^6$)	$33.9	$317.6	$1,084.2
Cleanup Area	9.5 km^2	9.5 km^2	9.5 km^2

Table 4 shows that the cleanup cost differences for the National Weather Average compared to the User-Defined inputs between population zones range from 8% in suburban areas to 7% in rural areas when adjusted for the difference in cleanup area.

Table 5 provides the RADTRAN economic cleanup costs with the same User-Defined weather but with physical release heights of 10.0 and 50.0 meters. The assumed physical release heights also include the thermal buoyancy that would be expected from an HEDD attack on a truck cask.

TABLE 5: Economic Cleanup Cost Results for an Elevated Release (in millions of dollars)

10 meter release height

	Rural	**Suburban**	**Urban**
Resin Cost	$24.1	$235.2	$806.7
Decon Wash Down Cost	$29.1	$283.7	$973.4
Soil Removal Cost	$2.9	$3.1	$0.51
Crop/Livestock Cost	$0.17	$0.00	$0.00
Evacuation Cost	$0.003	$0.53	$2.8
Total Cost	$56.3	$522.5	$1,783.4

50 meter release height

	Rural	**Suburban**	**Urban**
Resin Cost	$24.5	$238.9	$819.2
Decon Wash Down Cost	$103.1	$1,005.9	$3,451.2
Soil Removal Cost	$10.3	$11.0	$1.8
Crop/Livestock Cost	$0.62	$0.00	$0.00
Evacuation Cost	$0.03	$6.6	$35.1
Total Cost	$138.6	$1,262.4	$4,307.3

A comparison of Table 4 and 5 shows that the elevated releases cause the cleanup costs to increase and in the case of the 50 meter release height, markedly, because higher releases result in larger contaminated areas. A 19.0 km^2 contaminated area with a downwind release of 12.3 km was calculated for the 10 meter release height. A 67.5 km^2 contaminated area with a downwind release of 23.9 km was calculated for the 50 meter release height. The increased cleanup area accounts for the increased costs for all the population zones.

IV. CONCLUSIONS

Contamination from an elevated release is more widespread than that from a ground level release. Since the area to be decontaminated is the most important factor in the cleanup cost calculation, the highest release height in an urban area studied, 50 meters, results in a cost of $4.31 billion. Cleanup costs depend on a number of factors in addition to meteorology including whether the contaminating event is in an urban, suburban, or rural area, the amount of material released, height of the release, the particular radionuclides being dispersed, and the activity of those radionuclides. The RADTRAN default input variables are also an integral part of such a calculation.

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