AN ECONOMIC MODEL OF A RADIOACTIVE MATERIALS TRANSPORTATION ACCIDENT FOR THE RADTRAN RISK-ASSESSMENT CODE

R. F. Weiner
Sandia National Laboratories
P.O. Box 5800, Albuquerque, NM 87185-6141, USA

S. Hamp
U. S. Department of Energy

J. J. Penisten
Summer Student from the University of Michigan

ABSTRACT

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 can 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 radiation transportation accident. This study develops a cost model, which will be implemented into the RADTRAN accident risk assessment and accident and accident-free dose calculation code. An earlier version, RADTRAN 4.0, calculates a cost of post-accident cleanup, but the model in place is inaccurate and hardly scenario-specific. The study presented in this report is intended to develop and document a more realistic cost model, which will allow the user to define their own parameters to better account for variations such as radioactive material cleanup level, type of cleanup, and land use.

INTRODUCTION

Following an accidental release of radionuclides, the population must be evacuated and the affected area decontaminated. This study develops a generalized economic model of such events by estimating a total cost. Results of this study will be incorporated into the most current release of RADTRAN (© Sandia National Laboratories), to provide the RADTRAN user with an estimate of the economic ramifications of a radioactive material (RAM) release accident.

The costs developed in this document depend on the size of the release, the number of people and land area affected by the release, the radioactivity released, and the "goal" cleanup level. These variables are all either defined by the analyst or calculated by RADTRAN using user-defined inputs. The costs are intended to best reflect the specifics of the analyst's scenario, rather than be general and non-specific. Thus, the analyst will have control over the majority of the values being used to determine the total post-accident costs. For this reason, lower limit and upper limit values for many user-defined variables are provided, to give the user a conventional range of values based on actual data.

The costs are divided into the following categories, which will be considered independently of each other:

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

Each cost category will be treated in a section of this report. The paper will begin with an introduction to RADTRAN, and will end with conclusions and further work.

RADTRAN

RADTRAN [16] is a Sandia risk- and dose-assessment code for the transportation of radioactive materials (RAM). It was first used in NUREG-0170 [13] in 1977. RADTRAN models both accident and incident-free scenarios in the transportation of RAM. In an accident-free scenario, the RADTRAN output includes doses to persons residing within a mile of the route, persons driving by the shipment, and employees handling the shipment (e.g., truck drivers). In an accident scenario, the RADTRAN output includes groundshine, cloudshine, inhalation, and ingestion doses.

When a vehicle transporting a cask containing RAM is involved in an accident, a cask breach may occur. If RAM is released, it becomes aerosolized and is carried downwind. RADTRAN models the downwind aerosolized RAM concentration as elliptical isopleths, with constant concentrations across an isopleth. RAM eventually deposits on the ground, buildings, and roads with a user-specified deposition velocity.

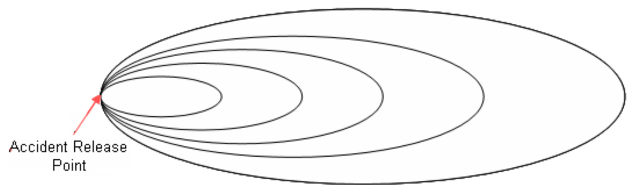

Fig. 1. RADTRAN isopleth model, with wind direction left to right.

LAND USE FRACTIONS

Land use fractions will be defined for residential buildings, commercial buildings, industrial buildings, and exposed soil, for each population zone. Land use fractions define the fraction of land area used for residential, commercial, or industrial buildings, or covered by exposed soil. These fractions will be used to determine the building surface area and soil area which are contaminated by deposited radionuclides. We will develop a range of fractions, to serve as a guide for the user as they define their own fractions in RADTRAN.

Population density definitions most commonly utilized by RADTRAN users are from TRAGIS [12], a transportation routing analysis program. The TRAGIS definitions are: Rural, 0 to 53 persons/km^2; Suburban, 54 to 1284 persons/km^2; and Urban, > 1284 persons/km^2. Based on these population densities, the counties were separated into their respective population zones. Percents of total U.S. land area categorized under a certain population zone are:

- Rural – 90.96%
- Suburban – 8.94%
- Urban – 0.09%

Exposed soil fractions in rural areas were developed on a state-by-state basis from the 1997 Five-Year National Resources Inventory [23]. The lower and upper limits shown in Table I represent the minimum soil fraction, 0.1389 in Nevada, and the maximum soil fraction, 0.9583 in Maine. It should be noted, however, that the exposed soil fractions include only forest land, rangeland, pastureland, and cropland. In many western states, federal land is the predominant land use designation and makes up between 30 percent and 85 percent of all land area [23]. In Nevada, federal lands include the Nevada Test Site, which is an exposed soil area, but is excluded from the soil fraction calculation. For this reason, all land use fractions are provided as a guide from which the RADTRAN user will select an appropriate values dependent on geography.

Vesterby and Krupa [25] define the total United States acreage of rural residential areas—rural areas utilized for housing purposes—to be 73 million acres. This results in a rural residential fraction of 0.0349. Although a range is not available for the rural residential fraction, 0.0349 is meant to be a "ballpark figure," from which the RADTRAN user can define a suitable fraction.

Rural commercial and industrial fractions were unavailable. It is left to the analyst to use the suburban and urban land use fractions as a guide to estimate suitable fractions.

Austin, Texas (957 persons/km^2) [2], Tucson, Arizona (1133 persons/km^2) [5], and Shelby, Montana (1049 persons/km^2) [4], were utilized as land use models for the suburban population zone. New York City (9832 persons/km^2) [17] and Seattle (2478 persons/km^2) [3] were used as land use models for the urban population zone. In the suburban and urban population zones, the maximum and minimum fractions for each land use type across all cities in the given population zone are cited in Table I.

Note that the land use fractions for a given city need not sum to unity. There are other land uses such as roadways and federal lands, which are not accounted for in the fractions tabulated here.

Table I. Land use Fractions, all Population Zones.

	Variable	**Lower Limit**	**Upper Limit**
RURAL			
Residential	$F_{res,R}$	0.03	
Commercial	$F_{com,R}$		
Industrial	$F_{ind,R}$		
Soil	$F_{S,R}$	0.14	0.96
SUBURBAN			
Residential	$F_{res,S}$	0.25	0.31
Commercial	$F_{com,S}$	0.06	0.22
Industrial	$F_{ind,S}$	0.09	0.09
Soil	$F_{S,S}$	0.38	0.43
URBAN			
Residential	$F_{res,U}$	0.01	0.47
Commercial	$F_{com,U}$	0.04	0.70
Industrial	$F_{ind,U}$	0.03	0.34
Soil	$F_{S,U}$	0.00	0.17

BUILDING AND ROAD CLEANUP

Building and Road Cleanup Procedures

Building and road surfaces which are covered with deposited RAM are washed with a water jet. The contaminated water is collected in resins then evaporated off. The resins are finally disposed of at a low level waste site. The total cost of these procedures is:

$$C_{BR} = \left(C_{wash} \cdot A_{clean}\right) + C_{disp} \quad \text{(Eq. 1)}$$

Where C_{BR} is the total building and road cleanup cost; C_{wash} is the water-jetting and water collection cost; A_{clean} is the total surface area covered with deposited RAM; and C_{disp} is the resin disposal cost. The cost of transporting the resins to the disposal facility is not included in C_{BR} since the distance between the RAM release and the low level waste site varies so greatly depending on where in the country the release occurs. If so desired, the user can calculate the resin transportation cost can be independently of RADTRAN, then add it to RADTRAN's total cost output. The variable C_{wash} ranges from \$3.00 to \$5.00 per square foot [18].

The procedures described above assume the Theorem of Microscopic Reversibility, which allows an irreversible process to be represented by a series of reversible microscopic processes. That is, RAM removal can be represented as the dissolution and suspension of the oxides and salts deposited on building and road surfaces.

Defining Building and Road Cleanup Area

Buildings are organized into three categories, with buildings in a given category having similar dimensions:

- Residential—Single- and multi-family residences
- Commercial—Retailers, office buildings
- Industrial—Manufacturing, utilities, institutions

One must sum over these three building types to find the building surface area covered with deposited RAM. Adding this sum to the road area results in an expression for the total surface area needing to be cleaned:

$$A_{clean} = \sum_{n=0}^{m}\left[\left(A_n \cdot R_\rho \cdot R_W\right) + \sum_{R,C,I}\left(\frac{A_n \cdot F_{RCI} \cdot A_{BS,RCI} \cdot F_{BC}}{FS}\right)\right] \quad \text{(Eq. 2)}$$

Where A_n is the area under the n^{th} isopleth; R_ρ is the road density (road length per land area); R_W is the road width; F_{RCI} is the fraction of land area covered by the respective building type (defined in Table I); $A_{BS,RCI}$ is the building type surface area; F_{BC} is the building cover fraction; and FS is the average building type floor space. The sum is taken over all *m* isopleths. This equation assumes that all road surfaces are covered by deposited RAM, whereas not all exposed building surfaces are necessarily covered. The variables utilized in equation 2 are discussed in detail in the sections entitled "Road Parameters" and "Building Parameters."

Road Parameters

The total length of pavement in an isopleth is calculated from a "road density," ρ_{road}, the number of miles of road per square mile of area. A unique road density is developed for each population zone, based on the total road length and land area in that population zone in the United States [20, 21]. Road densities are universal constants in RADTRAN:

- Rural 5.97E-04 m of road/m2 of land
- Suburban 8.11E-04 m of road/m2 of land
- Urban 8.06E-04 m of road/m2 of land

RADTRAN performs population dose analyses based on the assumption that the population density and zone in which the accident occurred is consistent throughout all isopleths.

The road width, R_W, is a user-defined parameter used for all population zones and isopleths. On average, road widths range from 5.49 m to 12.19 m [26].

Building Parameters

Building dimensions are needed to determine the surface area exposed to aerosolized RAM. Standard values for average outside heights are calculated by averaging heights of each building type in Los Angeles, Phoenix, and Salt Lake City, weighted by the land area each building type occupies in the respective city [1].

When contamination is deposited on a building surface, however, the entire exposed surface area is not covered. This can be verified by simply spraying an aerosol over rectangular boxes in a downwind manner—approximately half of the exposed surface area is covered when the aerosol deposits on the surface. We performed sixty independent trials of spraying aerosolized water particles over cardboard boxes. These trials yielded building cover fractions between 0.185 and 0.680, with a mean of 0.449 and sample variance 0.013. Variations were due to box size, box height relative to release height, and box orientation.

The experimental outcomes may be used as a guide for the analyst to define a building cover fraction for all buildings across all isopleths. The experimental outcomes should not be taken as absolutes, since the experimental conditions varied and since aerosolized water particles act more ballistically than do aerosolized RAM.

What can be learned from the experiment, however, is that some vertical surfaces are covered as well as the top-facing horizontal surface (i.e., the roof of the building). In previous RADTRAN models, only top-facing surfaces are considered as deposition areas. The experiment suggests that vertical surfaces cannot be ignored in defining the total surface area covered by deposited RAM.

Table II. Building Dimensions [1, 7, 8, 14].

	Lower Limit	Upper Limit
RESIDENTIAL		
Floor space (m^2)	117.8	211.1
Outside Height (m)	3.8	9.6
COMMERCIAL		
Floor space (m^2)	93.0	46454.5
Outside Height (m)	8.5	24.5
INDUSTRIAL		
Floor space (m^2)	1914.3	146913.0
Outside Height (m)	5.1	10.8

Contributing Radionuclides

Before computing the cost of disposing the resins, the radionuclides contributing to dose must be identified.

Spent fuel transportation is commonly modeled in RADTRAN. In the case of a spent fuel cask breach, the primary contributors to dose would be Sr-90, Cs-137, and Pu- 241. These isotopes contribute to 90.9 percent of the total activity of a 10-year cooled PWR spent fuel assembly [24], and are present in spent fuel in the form of SrO, CsI, and PuO_2 [10].

RADTRAN is also used to analyze the transportation of medical radionuclides, often found in the following forms: $^{60}CoCl$, $^{89}SrCl$, and $^{137}CsCl$.

The resins used to collect the contamination can collect activity up to the activity concentration limit (Ci/m^3) of certain isotopes in order for the waste to be handled as Class A waste, a limit which is specified in the Code of Federal Regulations Title 10 Part 61.55 [6]. Activity concentration limits are shown in Table III.

Table III. Activity Concentration Limits for Class A Handling of Contributing Radionuclides [6].

Radionuclide	Activity Concentration Limit (Ci/m^3)
Co-60	700.00
Sr-90	0.04
Tc-99	3.00
Cs-137	1.00
Pu-241	0.35

Defining the Disposal Cost

In its simplest form, the resin disposal cost, C_{disp}, is:

$$C_{disp} = BDC \times m_R \times Mult \times N_R \qquad \text{(Eq. 3)}$$

Where BDC is the base disposal charge in dollars per gram; m_R is the weight of each resin prior to water absorption; Mult is the dose rate multiplier; and N_R is the number of resins utilized in cleanup. Each of these variables will be discussed in detail here.

The number of resins is given by:

$$\boldsymbol{N_R = RC / A_R} \quad \text{(Eq. 4)}$$

$$RC = \left(\sum_n DEP_n^0\right) - \left(CULVL \cdot A_{clean}\right) \quad \text{(Eq. 5)}$$

Where RC is the contamination that must be removed to achieve the cleanup level; A_R is the activity per resin (defined below); DEP_n^0 is the radioactivity deposited in n^{th} isopleth area [15]; and CULVL is the user-defined or defaulted cleanup level. In the current release of RADTRAN, the user is able to specify a cleanup level, CULVL, expressed in $\mu Ci/m^2$, which is the level to which contaminated surfaces will be cleaned. The default value is 0.2 $\mu Ci/m^2$, the 1977 EPA guideline [16]. The cleanup level applies to the sum total of all deposited activities for all radionuclides.

The initial mass of each resin is:

$$\boldsymbol{m_R = V_R \times \rho_R} \quad \text{(Eq. 6)}$$

The RADRAN analyst defines a resin density, ρ_R, which ranges from 1.14 g/cm^3 and 1.42 g/cm^3 for polymer resins. For ease of calculation, it is assumed that the resin volume, V_R, is a cubic meter.

The base disposal charge, BDC, is obtained from Barnwell, South Carolina [19], and is dependent upon the density of the waste. For simplification, assume that the collection of radionuclides in the resin does not change the density and mass of the resin. Base disposal charges are shown in Table IV. A dose rate multiplier is factored in to the base charges for varying dose rates as shown in Table V.

Table IV. Base Disposal Charges as Dependent on Resin Density [19].

Density (g/cm^3)	BDC ($/g)	Density (g/cm^3)	BDC ($/g)
2.2426	0.010534	0.6407	0.020834
1.9222	0.010765	0.5606	0.021991
1.6018	0.011111	0.4806	0.023149
1.4417	0.011460	0.4005	0.027778
1.2815	0.011806	0.3204	0.031251
1.2014	0.012037	0.2883	0.035303
1.1213	0.013426	0.2563	0.041667
1.0412	0.014121	0.2243	0.050927
0.9611	0.015047	0.1922	0.060186
0.8810	0.016898	0.1602	0.074075
0.8009	0.018519	0.1281	0.092594
0.7208	0.019676	0.0961	0.127317

Table V. Dose Rate Multipliers [19].

Dose Rate	Multiplier on Base Disposal Charge
0 mrem/h – 0.876 rem/h	1.00
> 0.876 rem/h – 1.752 rem/h	1.08
> 1.752 rem/h – 2.628 rem/h	1.17
> 2.628 rem/h – 3.504 rem/h	1.22
> 3.504 rem/h – 4.380 rem/h	1.27
> 4.380 rem/h – 8.761 rem/h	1.32
> 8.761 rem/h – 21.902 rem/h	1.37
> 21.902 rem/h – 43.903 rem/h	1.42
> 43.903 rem/h	1.48

It is assumed that all contributing radionuclides are distributed evenly over the isopleth and within the water suspension, and thus, each resin contains an activity of each radionuclide in proportion with the activity initially released. It is also assumed that each resin is a cubic meter. As a result of these assumptions, the activity for each isotope *i* within the resin, $A_{R,i}$, is:

$$A_{R,i} = \frac{A_{CL,i} \times A_i}{\sum_i A_i} \qquad \text{(Eq. 7)}$$

Where $A_{CL,i}$ is the activity concentration limit of isotope *i* in a cubic meter (i.e., the resin), and A_i is the initially released activity of isotope *i*. The sum in the denominator is taken over all contributing radionuclides.

The dose rate resulting from each resin is then:

$$DR = \sum_i DCF_i \cdot A_{R,i} \qquad \text{(Eq. 8)}$$

Where DR is the dose rate (rem/h) and DCF_i is the dose conversion factor for exposure to contaminated ground surfaces (rem-m^3/Ci-h) [11]. Again, the sum is taken over all contributing radionuclides. Table V can now be used to determine the dose rate multiplier on the base disposal charge.

The activity per resin, A_R, as used in equation 4, is simply the sum of all $A_{R,i}$ over all isotopes *i*.

SOIL CLEANUP

Exposed areas of soil within the isopleths will be removed up to a user-specified depth, then taken to a radioactive waste site for disposal. Exposed areas of soil are defined to be those areas of land not covered by a building or road (e.g., parks, farmland, forests). Soil fractions are obtained from Section 3 of this report.

Soil cleanup costs are calculated as follows. However, $C_{S,sub}$ is considered only when $d > 23$.

$$C_{S,top} = \left(\sum_n A_n\right) \times F_S \times \left(\frac{d}{100}\rho_{top}\right) \times BDC \times Mult \qquad \text{(Eq. 9)}$$

$$C_{S,sub} = \left(\sum_n A_n\right) \times F_S \times \left(\frac{d-23}{100}\rho_{sub}\right) \times BDC \times Mult \qquad \text{(Eq. 10)}$$

$$C_{soil} = C_{S,top} + C_{S,sub} \qquad \text{(Eq. 11)}$$

Where A_n is the area under the n^{th} isopleth; F_S is the fraction of land area which is exposed soil (defined in Table I); d is the removal depth; ρ_{top} is the topsoil density (1250 kg/m^3 up to 23 cm below surface); and ρ_{sub} is the subsoil density (1400 kg/m^3 below 23 cm).

Note that soil removal costs are not included in C_{soil}; this model is therefore an underestimate of the true soil cleanup costs.

AGRICULTURAL DAMAGE

Agricultural damage can be classified into crop (cropland) damage and livestock (rangeland) damage. Taking for example the Chernobyl accident, this study will require crops to be sequestered for a year following the release of RAM, and livestock to be sequestered for two years following the release.

A key assumption of the agricultural cost category is that all cropland and rangeland are located within rural population zones. The agricultural cost will only factor in to accidents occurring in rural areas.

The analyst must define a "cropland fraction" parameter, F_{RC}, and a "pastureland fraction" parameter, F_{RL}, for rural population zones only, which will be used in the calculation of the total agricultural sequestration cost. The cropland fraction gives the percentage of rural land designated as cropland, and the pastureland fraction gives the percentage of rural land designated as pastureland. This is done since cropland and rangeland percentages in Great Plains states, for example, are relatively larger than for Southwestern states. On average, however, cropland makes up 20.93% of rural land area, and rangeland 19.26% [23].

The total cost of agricultural sequestration, C_A, is:

$$C_A = \left(\sum_n A_n \right) \cdot \left(\left(C_{area} \cdot F_{RC} \right) + \left(L_{area} \cdot F_{RL} \right) \right) \qquad \text{(Eq. 12)}$$

Where C_{area} is the annual crop profit per m^2 of rural land; L_{area} is the bi-annual livestock profit per m^2 of rural land; and A_n is the area under the n^{th} isopleth, which is summed over all isopleths.

The annual crop and bi-annual livestock profits per rural land area, C_{area} and L_{area}, are constants calculated from the total U.S. land area dedicated to cropland and rangeland [22], the total U.S. rural land area [22], and the 1997 annual U.S. crop and livestock gross profits [22], adjusted for inflation.

- C_{area} = \$1.303E-02/m^2
- L_{area} = \$2.499E-02/m^2

EVACUATION AND EMERGENCY

A radiation accident requiring cleanup of all buildings and roads, soil disposal, and agricultural sequestration can be likened to a natural disaster resulting in property destruction. Both natural and radiological disasters would require human evacuation, temporary shelter, emergency workers, and government-subsidized personal and business loans.

Assuming that all of the costs in this Evacuation and Emergency category are in the form of Federal disaster aid, Federal government disaster assistance data was obtained for the "No-Name Storm" or the "Storm of the Century," which hit Florida's Gulf Coast on March 13, 1993 [9]. County-by-county expenditures for the following costs, along with the number of persons per county covered by the following costs, are provided by the Federal Emergency Management Agency [9].

- Disaster Housing Grants
- Individual and Family Grants
- Mobile Home and Inspection Services
- Disaster Unemployment Assistance

- Crisis Counseling Assistance
- Small Business Association Loans to Individuals and to Business Owners
- Public Assistance to Local Governments
- Hazard Mitigation Grant Program

Extrapolating the costs to include the entire population of each county, then summing over all of the above costs, one obtains a total extrapolated Evacuation and Emergency cost for each county. These costs were normalized by the county's population and land area, resulting in a cost per person per km^2, or C_{PA}. The C_{PA} for each county was then adjusted for a 1.6% annual inflation rate since 1993.

The counties receiving Federal aid from the 1993 storm were either rural or suburban—no urban counties were affected. Average and range inflation-adjusted C_{PA} values for rural, suburban, and all affected counties are presented in Table VI.

Table VI. C_{PA}, Cost per Person per km^2.

Counties	Average	Lower Limit		Upper Limit	
	C_{PA} ($/person-km^2)	C_{PA} ($/person-km^2)	County	C_{PA} ($/person-km^2)	County
Rural	7.8796	0.1015	Calhoun	19.68759	Wakulla
Suburban	13.6058	1.0135	Lee	50.6875	Dade
All Affected	10.0819	0.1015	Calhoun	50.6875	Dade

Although no urban counties were affected by the 1993 storm, the RADTRAN user can extrapolate a C_{PA} based on the suburban C_{PA}. The wide range in C_{PA} is due to the amount of damage occurring in each county. The RADTRAN user may want to select a C_{PA} nearer to the lower limit for small radionuclide releases, and a C_{PA} nearer to the upper limit for large releases.

Knowing the average cost per person per km^2, one can define the total emergency and evacuation costs, C_E as:

$$C_E = \sum_n \left(P_n \cdot \frac{A_n}{1000^2} \cdot C_{PA} \right) \qquad \text{(Eq. 13)}$$

Where P_n is the population in the n^{th} isopleth; A_n is the area under the n^{th} isopleth; and C_{PA} is the evacuation and emergency cost per person per km^2.

CONCLUSIONS AND FUTURE WORK

In this paper we examined five cost categories of a radioactive material release accident, and developed a formula for calculating the cost associated with each of the categories.

The economic model remains incomplete, as further work must be done to define a cost associated with water contamination. Bodies of water are not included in the cost analysis thus far, since no feasible way has been found to deal with radionuclide contamination of water. However, water contamination poses a major obstacle for cleanup efforts and would contribute largely to the overall costs.

Basic cost research is completed. The work that remains is incorporating the contents of this paper into a usable algorithm for RADTRAN.

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