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An Economic Model for RADTRAN

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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 could occur. Affected areas will need decontamination and evacuation may be required following such a releases. This report develops a model of the economic impact of cleanup and evacuation which will be implemented into the RADTRAN accident risk assessment and accident and incident-free dose calculation code. An earlier version, RADTRAN 4, calculates a cost of post-accident cleanup, but the model is outdated and not scenario-specific. The report is intended to develop and document a more realistic cost model, which will allow the user to define certain parameters to better account for variations such as radioactive material cleanup level, type of cleanup, and land use.

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1.0 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. These input parameter values are either defined by the analyst or default values in RADTRAN using user-defined inputs. Lower limit, upper limit 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

The economic model implemented in RADTRAN uses average default parameter values, shown in Table 1.

Table 1: Economic Model Input Default Values

Parameter Name	Description	Average Value	Units
AF_C	Footprint of commercial buildings	337	m^2
AF_I	Footprint of industrial buildings	6620	m^2
AF_R	Footprint of residential buildings	118	m^2
ALOT_C	Area of commercial lots	930	m^2
ALOT_I	Area of industrial lots	9700	m^2
ALOT_R	Area of residential lots	223	m^2
DRUM_DR_LM	External dose rate per drum of resin	5.0	mrem/hour
CO_DRUM_DR	External dose rate for 1 Ci of Co-60 resin drum	269.7	mrem/hour
CROP_PROFT	Annual crop profit	0.01303	$\$/m^2$
C_WASH	Cost of washing contaminated area	32.29	$\$/m^2$
EVAC_CST_R	Rural evacuation cost	7.88	$\$/person-km^2$
EVAC_CST_S	Suburban evacuation cost	13.61	$\$/person-km^2$
EVAC_CST_U	Urban evacuation cost	13.61	$\$/person-km^2$
F_CR	Rural commercial land use fraction	0.01	
F_CS	Suburban commercial land use fraction	0.14	
F_CU	Urban commercial land use fraction	0.37	
F_IR	Rural industrial land use fraction	0.01	
F_IS	Suburban industrial land use fraction	0.09	
F_IU	Urban industrial land use fraction	0.11	

Table 1: Economic Model Input Default Values continued

Parameter Name	Description	Average Value	Units
F_RR	Rural residential land use fraction	0.03	
F_RS	Suburban residential land use fraction	0.28	
F_RU	Urban residential land use fraction	0.24	
F_SR	Rural soil land use fraction	0.95	
F_SS	Suburban soil land use fraction	0.41	
F_SU	Urban soil land use fraction	0.09	
FBC	Fraction of building surfaces contaminated	0.449	
FR_C	Rural soil land use fraction for crops	0.20	
FR_L	Rural soil land use fraction for livestock	0.28	
OH_C	Average commercial building outside height	16.40	m
OH_I	Average industrial building outside height	6.05	m
OH_R	Average residential building outside height	5.32	m
RHO_RD_R	Rural road density	5.97E-04	m of road/m^2 of land
RHO_RD_S	Suburban road density	8.11E-04	m of road/m^2 of land
RHO_RD_U	urban road density	8.06E-02	m of road/m^2 of land
RHO_RESIN	Resin density	1.28	g/cm^3
ROAD_W	Road width	8.84	m
SOIL COST	Cost of soil removal	10.00	\$/m^3
SOIL_DPTH	Contaminated soil depth	0.03	m
STCK_PROFIT	Bi-annual profit from livestock	0.02499	\$/m^2
VOL_DRUM	Volume of waste container	0.2167	m^3

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 Federal Emergency Management Agency (FEMA) loans and grants (FEMA, 2003). Political and social 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. Only contaminated surfaces are washed down. 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.

2.0 RADTRAN

A discussion of RADTRAN may be found in the RADCAT User Guide (Weiner, et al, 2006) and in the RADTRAN 5 Technical Manual (Neuhauser, et al, 2000). RADTRAN is a Sandia developed risk- and dose-assessment code for the transportation of radioactive materials (RAM), first used in NUREG-0170 (NRC, 1977). RADTRAN models both accident and incident-free scenarios in the transportation of RAM, although only the accident scenario is applicable to the economic model. The RADTRAN output for an accident scenario includes groundshine, cloudshine, inhalation, resuspension, and ingestion doses (the resuspension dose is an inhalation dose).

When a vehicle transporting a shipment containing RAM is involved in an accident, a cask breach may occur. If RAM is released, it may become aerosolized and 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. Figure 1 provides an example of the dispersion plume footprint modeled by RADTRAN. The curves shown in Figure 1 are curves of constant concentration or isopleths.

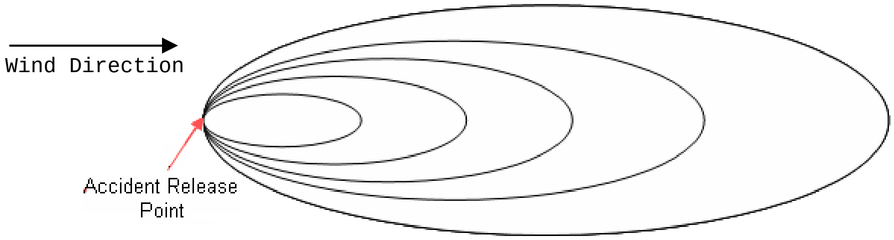

Figure 1: RADTRAN Isopleth Model

RADTRAN reports ground deposition in curies or becquerels per square meter. The economic model in RADTRAN uses this output to calculate the decontamination costs from the difference between the radioactivity deposited on the ground and the radioactivity remaining after a user defined acceptable cleanup level. RADTRAN provides a default value of 0.2 $\mu Ci/m^2$ for a cleanup level.

RADTRAN analyses a universe of accidents and calculates risks and consequences of all the accident types comprising that universe. Each accident type is characterized in RADTRAN by a conditional probability (called a “severity fraction”) and the fraction of each physical type of radioactive material released in that accident (called a “release fraction”). An example is shown in Table 2. Although RADTRAN calculates risks and consequences for accidents corresponding to all severity fractions, the cleanup costs are calculated only for the accident corresponding to the first severity fraction in this example. Therefore, the analysts should choose the accident for which cleanup costs are to be calculated, and should make that the first severity fraction and category. If costs for more than one accident scenario are to be calculated, a separate RADTRAN analysis will be needed for each accident scenario.

Table 2: Severity and release fractions for transport of PWR fuel in a truck cask

Accident category	**Severity fraction**	**Release fractions for each physical group**				
		Kr	**Cs**	**Ru**	**Particulates**	**Crud**
1	0.99993	0.00000	0.00000	0.00000	0.00000	0.00000
2	6.06E-05	1.36E-01	4.09E-09	1.02E-07	1.02E-07	1.36E-03
3	5.86E-06	8.39E-01	1.68E-05	6.71E-08	6.71E-08	2.52E-03
4	4.95E-07	4.49E-01	1.35E-08	3.37E-07	3.37E-07	1.83E-03
5	7.49E-08	8.35E-01	3.60E-05	3.77E-06	3.77E-06	3.16E-03
6	3.00E-10	8.40E-01	2.40E-05	2.14E-05	5.01E-06	3.17E-03

RADTRAN will output the total cost; the sum of cleanup, sequestration, and emergency evacuation costs. This value is intended to approximate the scenario-specific costs of a radiation transportation accident.

3.0 SURFACE CONTAMINATION

Any exposed surface can be contaminated by deposited radioactive material. Potentially contaminated surfaces include open land and anything that grows on open land, roads and parking lots, and both vertical and horizontal surfaces of building.

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. This section will develop a range of fractions to serve as a guide for inputs into RADTRAN.

Population density definitions usually used in RADTRAN are the same as those used by TRAGIS (Johnson and Michelhaugh, 2003), a transportation routing analysis program. The TRAGIS population zone definitions are shown in Table 3.

Table 3: TRAGIS Population Zones

Population Zone	Population density (person/km^2)	U.S. land area (%)
Rural	0 - 53	90.96%
Suburban	54 - 1284	8.94%
Urban	> 1284	0.09%

3.1 POTENTIAL CONTAMINATION OF RURAL LAND

Exposed soil fractions in rural areas were developed on a state-by-state basis from the 1997 Five-Year National Resources Inventory (U.S. Department of Agriculture, 2000). The lower and upper limits shown in Table 4 represent the minimum soil fraction, 0.1389 in Nevada, and the maximum soil fraction, 0.9583 in Maine. The exposed soil fractions include only forest land, rangeland, pastureland, and cropland. In many western states, federal land, some of which may not be counted as soil fraction, makes up between 30 percent and 85 percent of all land area (U.S. Department of Agriculture, 1997). For this reason, land use fractions are provided only as a guide for RADTRAN inputs. The actual value depends on geography.

Table 4: Rural Land Use Fractions

Zone	Variable	Lower Limit	Upper Limit	Default
Residential	$F_{res,R}$			0.03
Commercial	$F_{com,R}$			0.01
Industrial	$F_{ind,R}$			0.01
Soil	$F_{S,R}$	0.14	0.96	0.95

Vesterby and Krupa (1997) estimate the total United States acreage of rural residential areas (rural areas used for housing) 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 an approximation from which the RADTRAN user can define a suitable fraction. The rural commercial and industrial land use fractions are assumed to be evenly divided among the rest of the rural area. Default land use fractions for all rural building categories are given in Table 3.

3.2 POTENTIAL CONTAMINATION OF SUBURBAN LAND

Austin, Texas (957 persons/km^2), Tucson, Arizona (1133 persons/km^2), and Shelby, Montana (1049 persons/km^2) are land use models for the suburban population zone. Austin (City of Austin, 2002) and Tucson (City of Tucson, 1999) data were in the form of percent of land area dedicated to a given use. Shelby (City of Shelby, 2004) data were given in total acres, from which percents were calculated. In the suburban population zones, the maximum and minimum fractions for each land use type across all cities in the given population zone are shown in Table 5. It should be noted that the land use fractions for a given city need not sum to unity. Other land uses like roads are not accounted for in the tabulated fractions.

Table 5: Suburban Land Use Fractions

Zone	Variable	Lower Limit	Upper Limit	Default
Residential	$F_{res,S}$	0.25	0.31	0.28
Commercial	$F_{com,S}$	0.06	0.22	0.14
Industrial	$F_{ind,S}$	0.09	0.09	0.09
Soil	$F_{S,S}$	0.38	0.43	0.41

3.3 POTENTIAL CONTAMINATION OF URBAN LAND

New York City (9832 persons/km^2) and Seattle (2478 persons/km^2) were used as land use models for the urban population zone. In the urban population zone, the maximum and minimum fractions for each land use type across all cities in the given population zone are shown in Table 6. Note that the land use fractions for a given city need not sum to unity. Other land uses, like roads are not accounted for in the fractions tabulated.

Table 6: Urban Land Use Fractions

Zone	Variable	Lower Limit	Upper Limit	Default
Residential	$F_{res,U}$	0.01	0.47	0.24
Commercial	$F_{com,U}$	0.04	0.70	0.37
Industrial	$F_{ind,U}$	0.03	0.34	0.11
Soil	$F_{S,U}$	0.00	0.17	0.09

The New York City Department of City Planning (NYC, 2002) tabulated fractions of land area dedicated to various uses, grouped by borough. Table 7 provides the New York City urban land use.

Table 7: New York City Urban Land Use Fractions

Borough	Residential	Commercial	Industrial	Soil
Bronx	0.3460	0.055	0.139	0.052
Brooklyn	0.3975	0.0435	0.110	0.040
Manhattan	0.2965	0.1575	0.147	0.035
Queens	0.4675	0.0385	0.089	0.060
Staten Island	0.3650	0.035	0.133	0.174
New York City	0.4010	0.049	0.114	0.075

Seattle data (City of Seattle, 2003) consisted of tabulated percentages of land area dedicated to various land uses. The data for the sections of Seattle that encompass downtown and abut the Port of Seattle were separated into four regions: Commercial Core, Denny Triangle, Belltown, and Rest of Downtown. Each of these regions was further divided into one of three zoning areas: Downtown Office Core 1 or 2 (DOC 1 or DOC 2) or Downtown Mixed Commercial (DMC). The DOC 1 zone has the densest land use pattern and consists primarily of full- and half-block office buildings and hotels. There are few residential and retail structures in the DOC 1 zone. The DOC 2 zone is a transition area between the DOC 1 zone and the less-dense historic districts. It is comprised of more low-rise, historic, commercial, residential, and parking structures than in the DOC 1 zone. The DMC is a relatively low-density land use pattern, mixed with occasional denser uses. Few large office buildings are scattered amongst surface parking lots, older warehouse buildings, smaller-scale commercial structures, academic institutions, and relatively new residential developments. Table 8 provides the Seattle downtown urban land use.

Table 8: Seattle Urban Land Use Fractions

Subarea	Residential	Commercial	Industrial	Soil
Commercial Core				
DOC 1	0.01	0.70	0.25	0.00
DOC 2	0.02	0.34	0.31	0.11
DMC	0.19	0.37	0.26	0.00
Denny Triangle				
DOC 2	0.05	0.42	0.34	0.00
DMC	0.05	0.50	0.13	0.00
Belltown				
DOC 2	0.03	0.40	0.03	0.00
DMC	0.12	0.65	0.04	0.01
Rest of Downtown	0.10	0.55	0.20	0.04

4.0 BUILDING CLEANUP

Buildings can be contaminated by radionuclides deposited on the building surface. An experiment to determine the fraction of building surfaces that could be contaminated was performed, using to-scale cardboard boxes as buildings and a directed water mist as the aerosolized radiation plume. Experimental results show a range in fractions of building surfaces contaminated.

4.1 FACTORS AFFECTING BUILDING CLEANUP

Building cleanup procedures include using a water-jet to wash the surfaces which are covered with contamination, collecting the waste water on resins, evaporating, and then disposing of resin as Class-A low level waste. The cost of water-jetting surfaces and collecting the waste water ranges from $3.00 to $5.00 per square foot of surface area being cleaned (Rice, 2004). The default value in RADTRAN, C_WASH, is $3.00 per ft^2 ($32.29 per m^2). Since the cost depends on square footage, this section will develop a range of values for the surface area requiring cleanup.

The method of decontamination described above is only one of several possible methods. For example, a new technology being developed by Argonne National Laboratories is a super-absorbent containment gel, which draws radioactive particles out of porous structure materials. The gel is then vacuumed and recycled, leaving only a small amount of radioactive waste (Goff, 2004).

Buildings are organized into three major categories for the purpose of determining the average size of each class of building:

1. *Residential* – Single-family and multi-family residences
2. *Commercial* – Retail and office buildings
3. *Industrial* – Manufacturing, utilities, and institutions

4.2 DEVELOPMENT OF BUILDING PARAMETERS

Building cleanup costs were developed such that the final cost will be dependent upon the surface area and number of buildings in a given isopleth area. Average dimensions for each building type were obtained to determine the surface area of each type of building. It is assumed that there is no variance in building size across population zones.

Building dimensions are tabulated in Table 9; the standard (i.e., default) values as well as a range of values are specified. The average building footprint was determined by assuming an integral number of floors for each type and adjusting the footprint area as to generate the standard floor space from the resulting floors and footprint area. The building footprint and lot size were also compared to U.S. county public land records to ensure realism for all population zones. Hence:

- Residential buildings were assumed to have 2 floors of about 1200 ft^2 (111.5 m^2)
- Commercial buildings were assumed to have 3 floors of about 5000 ft^2 (465 m^2)
- Industrial buildings were assumed to have 1 floor of 71500 ft^2 (6643 m^2)

Table 9: Dimensions of Various Building Types

	Standard	Lower Limit	Upper Limit
RESIDENTIAL			
Average Floor space (m^2)	211.08	117.8	211.08
Average Outside Height (m)	5.32	3.8	9.6
Average Footprint (m^2)	118		
Average Lot Size (m^2)	223		
COMMERCIAL			
Average Floor space (m^2)	1347.09	93.0	46454.5
Average Outside Height (m)	16.40	8.5	24.5
Average Footprint (m^2)	337	46.5	5806
Average Lot Size (m^2)	930		
INDUSTRIAL			
Average Floor space (m^2)	6620.0	1914.33	146913.0
Average Outside Height (m)	6.05	5.1	10.8
Average Footprint (m^2)	6620		
Average Lot Size (m^2)	9700		

The standard values for the average outside heights were calculated by taking an average of heights of each building type in Los Angeles, Phoenix, and Salt Lake City, weighted by the land area percent each building type occupies in the respective city. The exposed surface area of a building is calculated from the parameters given in Table 9 and is assigned the variable A_{BS} using the square root of the footprint, as the average width on each side. The roof area is assumed to be the same as the building footprint. The average lot size is larger than the footprint only in rural and suburban zones. The buildings in urban zones are assumed to cover essentially the entire lot.

4.3 BUILDING COVER FRACTION EXPERIMENTAL PROCEDURE

When contamination is deposited on a building surface, the entire exposed surface area is not covered. A simple experiment was conducted in order to estimate values for the fraction of a building's surface area which is covered by deposited contamination. Residential, commercial, and industrial buildings were modeled as cardboard boxes of varying heights and sizes. A scale was developed for each box, depending on its height and the "standard" height in Table 8 for each building type modeled. Each "building" was tested with release heights of 24 inches and 84 inches, which, when scaled, translated into varying release heights for the different buildings. The scaled downwind distances also varied by building height, although for this experiment it was held to 84 inches. A skyscraper model was also utilized in order to depict an urban release. Since there is no "standard" skyscraper, a RADTRAN release height and downwind distance cannot be calculated.

The experimental setup is shown in Figure 2. The release height, orientation angle, and box height are adjusted for each of the twelve different scenarios shown in Table 10. The spray angle (0 degrees to the ground) and downwind distance remain constant for each scenario.

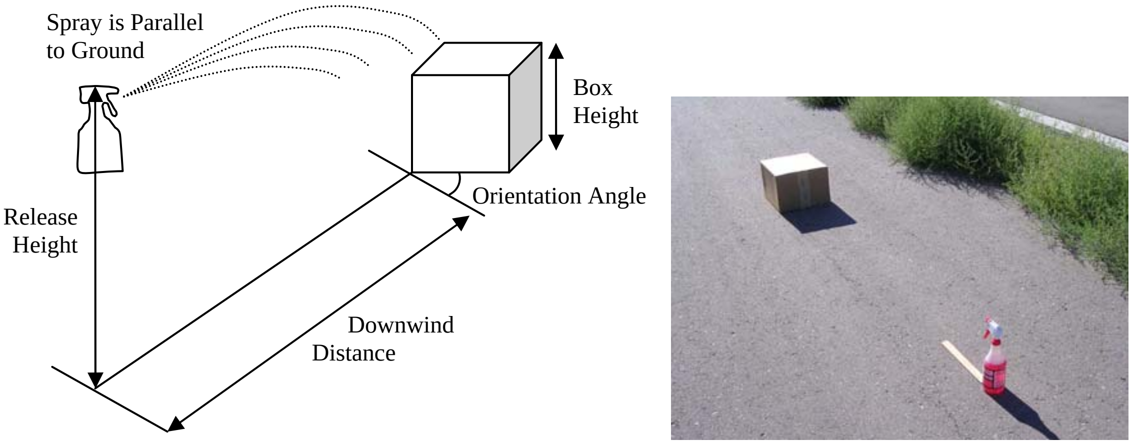

Figure 2: Experimental Setup

Table 10: Experimental Scenarios
R = residential, C = commercial, I = industrial, S = skyscraper

Scenario Number	Building Type	Building Standard Height (m)	Box Height (in)	Scale (1 inch = x meters)	Experimental Release Height (in)	RADTRAN Release Height (m)	Experimental Box-Release Distance (in)	RADTRAN Downwind Distance (m)	Box Orientation
1	R	5.32	6.75	0.79	84	66.2	84	66.2	0
2	R	5.32	6.75	0.79	84	66.2	84	66.2	45
3	R	5.32	6.75	0.79	24	18.92	84	66.2	45
4	C	16.40	14	1.17	84	98.4	84	98.4	0
5	C	16.40	14	1.17	84	98.4	84	98.4	45
6	C	16.40	14	1.17	24	28.11	84	98.4	0
7	I	6.05	10.5	0.58	84	48.4	84	48.4	45
8	I	6.05	6.25	0.97	24	23.23	84	81.31	0
9	I	6.05	6.25	0.97	24	23.23	84	81.31	45
10	S		32		84		84		0
11	S		32		24		84		45
12	S		32		24		84		0

The cover fractions are estimated as blocks of area, rather than by summing individual water droplets. The basis for such a measurement is that workers will wash the entire area contaminated by RAM rather than washing each individual small contaminated area. The photo in Figure 3 shows the Scenario 9 trial. The entire top was covered, and the side shown is estimated as complete coverage with the exception of the trapezoidal area outlined in red.

Figure 3: Example of Contamination Area

4.3.1 EXPERIMENTAL LIMITATIONS

The experiment is not applicable to ground-level releases. Two tests were performed with a ground-level release, but the water spray did not reach the box for either scenario. This is due to the ballistics of water at ground level, where air turbulence is inadequate to carry water droplets the required distance. In reality the wind turbulence does carry the aerosolized RAM in upward and downward motions. At higher release heights such as those tested experimentally, this air perturbation is ample to preserve the aerosol properties of water. Thus water is a reasonable model for aerosolized RAM for an elevated release, but not for a ground-level release..

Specific cases of wind turbulence, such as eddies, were not modeled. However, the box was always placed downwind of the release. The force of the spray action is the experimental equivalent of the impact which produces the release but only in a preset direction.

The experimental results are only accurate for rectangular buildings. Any building with concave or convex surfaces and roof overhangs will not experience building cover as observed in the experiment.

4.3.2 EXPERIMENTAL RESULTS

Each of the scenarios listed in Table 10 was repeated five times. Table 11 provides the building cover fraction for each experiment and the maximum and minimum for each scenario.

Table 11: Experimental Results by Scenario

Scenario	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Minimum	Maximum
1	0.330	0.449	0.506	0.396	0.522	0.330	0.522
2	0.332	0.531	0.467	0.588	0.374	0.332	0.588
3	0.621	0.621	0.598	0.621	0.544	0.544	0.621
4	0.251	0.185	0.334	0.437	0.431	0.185	0.437
5	0.450	0.446	0.462	0.465	0.432	0.432	0.465
6	0.369	0.408	0.479	0.408	0.494	0.369	0.494
7	0.501	0.484	0.465	0.498	0.471	0.465	0.501
8	0.527	0.494	0.503	0.494	0.494	0.494	0.527
9	0.649	0.680	0.639	0.649	0.649	0.639	0.680
10	0.282	0.328	0.310	0.282	0.314	0.282	0.328
11	0.457	0.343	0.432	0.328	0.453	0.328	0.457
12	0.320	0.369	0.336	0.334	0.326	0.320	0.369

Two trends are evident in this experiment:

1. The release height affects the coverage:
   a. Too close to the ground and the release goes to the ground
   b. Too high and most of the release goes over the building
   c. A lower release covered more of the building

2. The orientation of the spray effects the distance traveled:
   a. A 0-degree orientation implies that half of the release already has a downward velocity vector hence causing more of the release to hit the ground.
   b. A 45-degree spray release travels further and covers a larger area.

Figure 4 shows the results of each trail for each scenario according to release height and orientation.

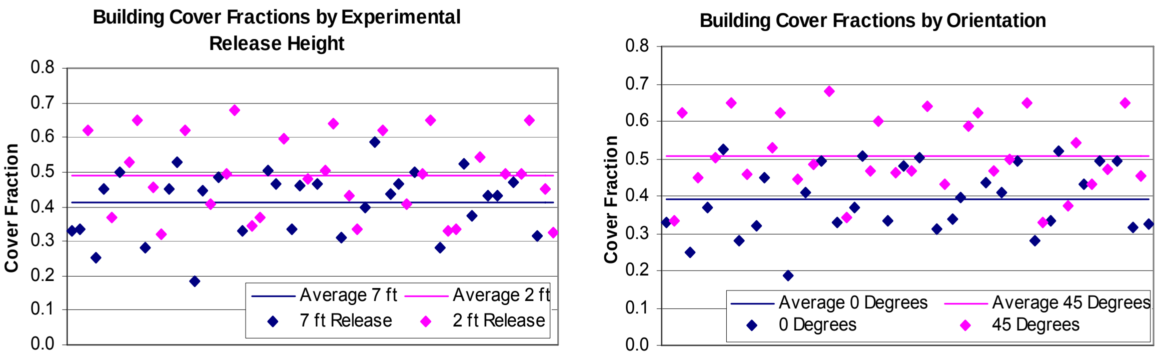

Figure 4: Fractions of Building Area Covered

The average cover fractions plotted in Figure 4 are:

- Release height 2 ft: 0.488
- Release height 7 ft: 0.411
- Orientation 0 degrees: 0.390
- Orientation 45 degrees: 0.508

Building cover fraction trends are examined for each RADTRAN release height. There is an inverse relationship between the building cover fractions and the release height, which correlates with the results presented in Figure 4. This can be seen in Figure 5. The skyscraper buildings are not plotted in Figure 5 because there is no applicable scale for such a building type. Table 12 provides the average, minimum, and maximum building cover fractions for the calculated RADTRAN release heights.

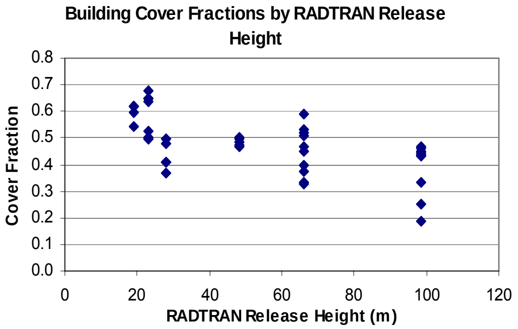

Figure 5: Building Cover Fractions by Release Height for Residential, Commercial, and Industrial Buildings

Table 12: Building Cover Fractions by Release Height

Release Height (m)	Average Fraction Covered	Lower Limit Fraction Covered	Upper Limit Fraction Covered
18.92	0.601	0.544	0.621
23.23	0.578	0.494	0.680
28.11	0.431	0.369	0.494
48.40	0.484	0.465	0.501
66.20	0.449	0.330	0.588
98.40	0.389	0.185	0.465

Figure 6 shows a cross-comparison of building cover fractions by building type. Industrial buildings tend to have larger cover fractions, while commercial buildings and skyscrapers have lower cover fractions. Skyscrapers, in an urban area, consist primarily of commercial office space. It is thus expected and reasonable that commercial buildings and skyscrapers have similar building cover fractions. Table 13 provides the average, minimum, and maximum building cover fractions for each building type.

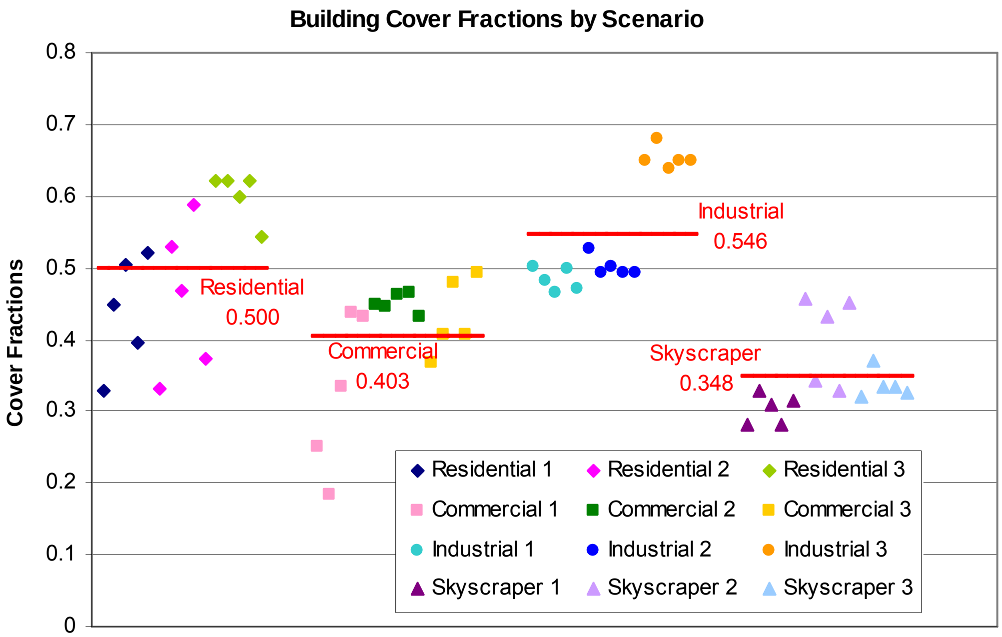

Figure 6: Building Cover Fraction by Building Type

Table 13: Building Cover Fractions by Building Type

Building Type	**Average Fraction Covered**	**Lower Limit Fraction Covered**	**Upper Limit Fraction Covered**
Residential	0.500	0.330	0.621
Commercial	0.403	0.185	0.494
Industrial	0.546	0.465	0.680
Skyscraper	0.348	0.282	0.457

Industrial buildings have the largest building cover fractions. Since the majority of area that contributes to the cover fraction is the top of the building, industrial buildings which include factories and warehouses, have a lot of floor space (refer to Table 9). Skyscrapers have limited floor space per level, and the majority of its surface area is from the four vertical sides; it thus follows that the building cover fraction should be lower.

Building cover fractions can be classified by downwind distance. Figure 7 depicts an inverted parabolic relationship between fraction covered and downwind distance. Table 14 provides the average, minimum, and maximum building cover fractions for downwind distance.

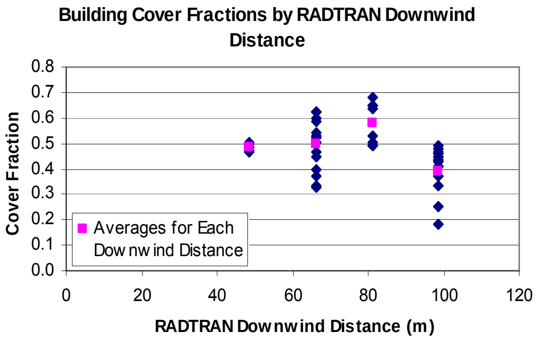

Figure 7: Building Cover Fraction by Downwind Distance for Residential, Commercial, and Industrial Buildings

Table 14: Building Cover Fractions by Downwind Distance

Downwind Distance (m)	Average Fraction Covered	Lower Limit Fraction Covered	Upper Limit Fraction Covered
48.4	0.484	0.465	0.501
66.20	0.500	0.330	0.621
81.31	0.578	0.494	0.680
98.40	0.389	0.185	0.465

For an assumed point source with no reflection from the ground, the downwind concentration is expressed as:

$$C(x,y,z)=\frac{Q}{2\mu\pi\sigma_y\sigma_z}\exp\left\{-\frac{1}{2}\left[\frac{y^2}{\sigma_y{}^2}+\frac{(z-H)^2}{\sigma_z{}^2}\right]\right\} \qquad \text{Equation 1}$$

Where:

C = Gaseous concentration (usually μg/m^3)
Q = Emission source strength (usually μg/s)
μ = Deposition velocity (m/s)
σ_y = Isopleth standard deviation in y-direction (m)
σ_z = Isopleth standard deviation in z-direction (m)
H = Release height, taken to be 0 for ground-level releases (m)

A plot of the pollutant concentration versus downwind distance is a Gaussian distribution, which resembles the shape of the plot shown in Figure 8.

4.3.3 STATISTICAL ANALYSIS OF EXPERIMENTAL RESULTS

A statistical analysis to determine the accuracy of the experimental measurements is performed for each of the twelve scenarios. It is assumed that the data obey a normal, or Gaussian distribution, which has a probability density function, P(x), given by the following:

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[\frac{-(x-\mu)^2}{2\sigma^2}\right] \qquad \text{Equation 2}$$

Where σ^2 is the standard deviation and μ is the true mean. Normal distributions are usually used if the measured values are large (i.e., greater than approximately 20 or 30). However, it can be used in this analysis if the building cover fractions are taken as percentages.

The standard normal distribution is generated by setting $\mu = 0$ and $\sigma^2 = 1$ in a general normal distribution. An arbitrary normal distribution can be converted to the standard normal distribution by changing variables from x to z, with $Z = (X - \mu)/\sigma$, and $dz = dx/\sigma$:

$$P(x)dx = \frac{1}{\sqrt{2\pi}} e^{-z^2/2} dz \qquad \text{Equation 3}$$

A pictorial representation of the standard normal distribution is shown in Figure 8.

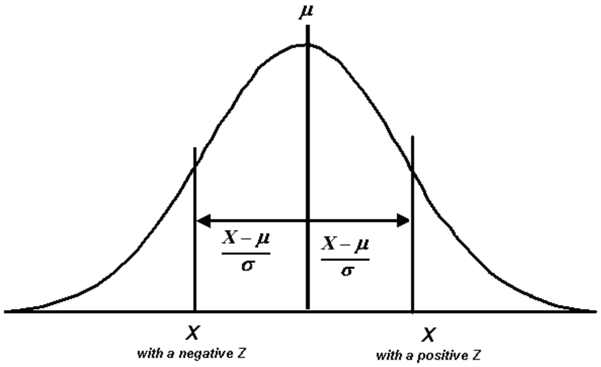

Figure 8: Normal Distribution

A normal distribution is used to determine the confidence level, C, of a measurement. The maximum and minimum X-values for the area under the curve of Figure 8 are $X_{\max}$ and $X_{\min}$, respectively, and represent the boundaries of the confidence interval. A 95% confidence level represents a corresponding 95% chance of a measurement between $X_{\min}$ and $X_{\max}$. The probability of observing a value outside of the confidence interval is 5%. From the standard normal distribution, the corresponding Z-value of a 95% confidence level is 1.96; in other words, the $X_{\min}$ and $X_{\max}$ values are within $\pm 1.96\sigma$ from the mean (μ). The statistical analysis will determine the confidence interval and its relative size, based on a 95% confidence level for each scenario.

The deviation is the absolute difference between a measurement and the true mean. However, for the purposes of this analysis, the deviation is taken to be the absolute difference between a measurement and the experimental mean:

$$\varepsilon_i = \left|x_i - \mu\right| \approx \left|x_i - \overline{x}\right| \qquad \text{Equation 4}$$

Where:

ε_i = Deviation of experimental measurement 'i' from true mean
x_i = Experimental measurement 'i'
i = Trial number, ranges from 0 to 5
$\overline{x}$ = Experimental mean

The standard deviation is given by:

$$\sigma^2 = \frac{\sum_{i=1}^{N}\left(\varepsilon_i{}^2\right)}{N-1} \qquad \text{Equation 5}$$

Where:

N is the number of trials performed for the given scenario.

The upper and lower bounds of the confidence interval are determined with the mean, μ, and σ determined for each scenario from the experimental data and Z set to 1.96 for a 95% confidence level:

$$X = \mu \pm Z\sigma \qquad \text{Equation 6}$$

The percent differences shown in Table 14 are the fraction of the mean which is the deviation of $X_{\min}$ or $X_{\max}$ from μ:

$$\%Diff = \frac{\left|X_{\max} - \mu\right|}{\mu} \cdot 100\% = \frac{\left|\mu - X_{\min}\right|}{\mu} \cdot 100\% \qquad \text{Equation 7}$$

Applying Equations 4 through 7, Table 15 is obtained.

Table 15: Building Cover Fraction Experimental Means and Error Intervals[1]

Building Type	Scenario Number	Experimental Mean of Building Cover Percentages	σ	X_{min}	X_{max}	Difference
Residential	1	44.04	7.94	28.47	59.61	35%
	2	45.83	10.62	25.01	66.66	45%
	3	60.10	3.32	53.59	66.61	11%
Commercial	4	32.75	11.08	11.03	54.47	66%
	5	45.10	1.33	42.50	47.71	5.8%
	6	43.14	5.27	32.81	53.48	24%
Industrial	7	48.38	1.58	45.28	51.47	6.4%
	8	50.22	1.41	47.44	52.99	5.5%
	9	65.32	1.57	62.25	68.40	4.7%
Skyscraper	10	30.31	2.08	26.24	34.38	13%
	11	40.25	6.21	28.08	52.43	30%
	12	33.68	1.93	29.89	37.47	11%

Statistical results are shown graphically shown in Figure 9. Each point represents the average building cover fraction in percent for a scenario, and the bars above and below the point represents the range of building cover fractions for which there is a 95% confidence level.

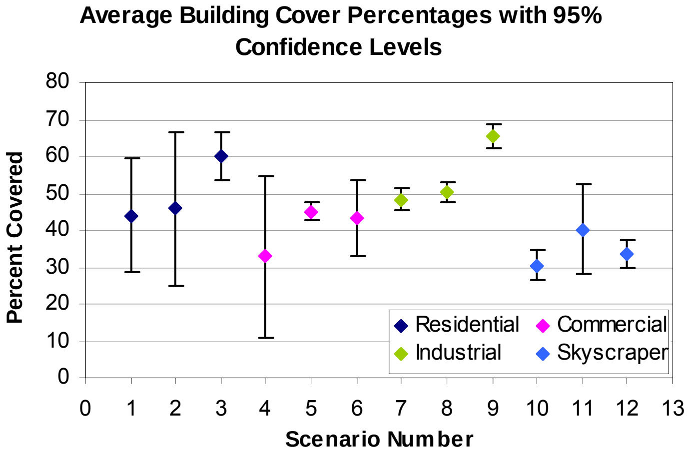

Figure 9: Average Building Cover Fractions

From Figure 9, scenarios 1, 2, and 4, have the widest confidence intervals. This indicates that the experimental measurements are less statistically accurate than scenarios with smaller confidence intervals. Conclusive results cannot be drawn from scenarios 1, 2, and 4, with such large differences. However, scenarios 3, 5, 7 through 10, and 12 have relatively small differences. From this set of scenarios, there is at least one scenario per building type from which statistically accurate results can be drawn.

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[1] Clearly four significant numbers implies a nonexistent degree of precision. The precision is maintained for calculation purposes.

4.4 BUILDING CONTAMINATION CONCLUSIONS

When contamination is deposited on a building surface the entire exposed surface area is not covered. This has been verified by 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 0.45 and sample variance of 0.013. Variations were due to box size, box height relative to release height, and box orientation. The default value for building cover fraction used in the model is the mean, 0.45

The experimental outcomes may be used as a guide 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 the aerosolized water particles are more ballistic than aerosolized RAM.

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

5.0 DEVELOPING CLEANUP COSTS

The costs are divided into the following categories:

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

This study considers the following post-accident costs: building and road cleanup, soil disposal, agricultural sequestration, emergency evacuation, as well as federal loans and grants as financed by the federal government through the Federal Emergency Management Agency (FEMA).

5.1 BUILDING AND ROAD CLEANUP

RADTRAN performs population dose analyses based on rural, suburban, or urban population zones. RADTRAN calculates deposition of radioactive material for each radionuclide deposited and population dose assuming a constant population density over the entire dispersion plume footprint. From the results of the RADTRAN analysis, the radionuclide deposition concentration and areas for cleanup are known.

An isopleth area, A_n, is the area between consecutive isopleths (curves of constant deposition). Figure 10 is a graphical representation of deposition isopleths and isopleth areas. The distance between these lines is a function of the RADTRAN input. In the National Average Weather and Pasquill Stability Class Weather options in RADTRAN, centerline distances, isopleth areas, and dilution factors, which have been calculated in another program, are imported. The User-defined Weather option provides a more site specific method for calculating centerline distances, isopleth areas, and dilution factors dependent on the current site meteorological conditions.

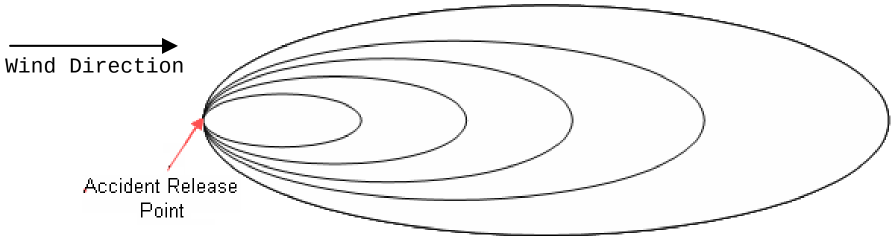

Figure 10: Deposition Isopleths

Building and road surfaces which are covered with deposited RAM are washed with high pressure hosing or fire hosing. The contaminated water is collected in resins and is then allowed to evaporate. The resins are disposed of at a low level radioactive waste disposal facility. The cost of these procedures is:

$$C_{BR} = C_{wash} + C_{\mathrm{Resin}} \qquad \text{Equation 8}$$

Where:

C_{BR} = Total building and road cleanup cost
C_{wash} = Total wash down and water collection cost
C_{Resin} = 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 depending on where in the country the release occurs. If desired, the resin transportation cost can be calculated independently and added to the total cost with the RADTRAN output. The variable C_{wash} can take values between \$3.00 to \$5.00 per square foot (Rice, 2004). This cost range is for water-jetting and water collection of contaminated surfaces. The cost of water jetting is higher than the expected technique (high pressure hosing or fire hosing) for building and road wash down. Since the values for C_{wash} are based off costs for water jetting and not high pressure hosing or fire hosing, the RADTRAN default value for C_{wash} is the minimum value, \$32.29/m^2.

The procedure described above assumes that an irreversible process, like dissolution of the radioactive contaminant in a water jet, can be represented by a series of microscopically reversible processes (Moore, 1972). That is, RAM removal can be represented as the dissolution and suspension of the radioactive compounds deposited on building and road surfaces.

5.1.1 DEFINING TOTAL SURFACE AREA TO BE CLEANED

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

- *Residential* – Single-family and multi-family residences
- *Commercial* – Retail and office buildings
- *Industrial* – Manufacturing, utilities, and institutions

A sum over these three building types is used to find the building surface area covered with deposited RAM. The fraction within each area that is treated as building, road, or soil is determined from the number of buildings within each area. The number of building lots that are in each residential, commercial, or industrial zone (N_R, N_C, or N_I) is determined from the following equation:

$$N_{RCI} = \frac{A_n \left(F_{RCI}\right)_{RSU}}{Alot_{RCI}} \qquad \text{Equation 9}$$

Where:

A_n = Area within the *n*th isopleth for each chemical/physical group (m^2)
F_{RCI} = Fraction of the area classified as residential, commercial, or industrial
$Alot_{RCI}$ = Average lot size for all zones (m^2) (Table 8)

The total surface area to be cleaned is the sum of the road surface in each isopleth area plus the open area around the buildings used for lawns and parking plus the building roof and the four outside walls. This area varies with building type and isopleth:

$$A_{clean} = \sum_{n=0}^{m}\left[\left(A_n \cdot R_\rho \cdot R_W\right) + \sum_{C,I} N_{CI}\left(Alot_{CI} - AF_{CI}\right) + \sum_{R,C,I} N_{RCI}\left(A_{BS,RCI} \cdot F_{BC}\right)\right] \qquad \text{Equation 10}$$

Where:

A_n = Area under the *n*th isopleth for each chemical/physical group (m^2)
R_ρ = Road density by zone (m of road per m^2 of land)
R_W = Road width (m)
N_{RCI} = Number of lots by zone
$A_{BS,RCI}$ = Building type surface area, includes walls & roof (m^2).
F_{BC} = Building cover fraction
$Alot_{CI}$ = Average building type lot size (m^2) (Table 8)
AF_{CI} = Average building type footprint (m^2) (Table 8)

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 covered. The residential zone difference between the building and lot sizes is assumed to be soil and will be included in the soil category discussed in Section 5.2.

The building surface area, A_{BS}, is defined as:

$$A_{BS,RCI} = AF_{RCI} + 4\,OH_{RCI}\sqrt{AF_{RCI}} \qquad \text{Equation 11}$$

Where:

AF_{RCI} = Average building type footprint for all zones (m^2) (Table 8)
OH_{RCI} = Average height for each building type for all zones (m) (Table 8)

5.1.2 ROAD DENSITY

The total length of pavement in an isopleth area is calculated from a "road density," R_ρ, 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 United States population zone (S. Carolina Energy Office, 2004; U.S. Bureau of the Census, 1996).

• Rural	5.97E-04 m of road/m^2 of land
• Suburban	8.11E-04 m of road/m^2 of land
• Urban	8.06E-02 m of road/m^2 of land

The road width, R_W, is a parameter used for all population zones and isopleths. Average road widths range from 5.49 m to 12.19 m (U.S. DOE, 2002). The default value used in the model is the mean of these: 8.84 m.

5.1.3 CONTRIBUTING RADIONUCLIDES

In the event of a spent fuel cask breach, the primary contributors to dose would be Sr-90, Cs-137, and Pu- 241. These radionuclides contribute 90.9 percent of the total activity of a 10-year cooled PWR spent fuel assembly (U.S. DOE, 2002) and are present in spent fuel in the form of SrO, CsI, and PuO_2 (Goff, 2004).

RADTRAN also analyzes the transportation of medical radionuclides, which are often present as the chlorides of the particular isotopes. The radionuclides used most often in medical applications are Cs-137, Tc-99, Co-60, and I-131.

During an accident, a fraction of the radionuclides being transported may be released and dispersed. RADTRAN is used to determine the amount released, how it disperses, and the amount deposited within each isopleth area. As noted in Section 5.1, the code can be used to determine the isopleth areas where the concentration of deposited material is reasonably uniform. The concentration has units of Ci/m^2 and is a function of the released isotope, the downwind distance from the source, meteorological conditions, and the severity of the accident.

In RADTRAN a cleanup concentration, CULVL, is the concentration in $\mu Ci/m^2$ to which contaminated surfaces will be cleaned, and the sum of activities of all the deposited radionuclides not removed will be no larger. The default value, 0.2 $\mu Ci/m^2$, is from a 1977 EPA guideline (Weiner et. al, 2006). The activity of each radionuclide removed in each isopleth area is: :

$$Act\_Rm_{nuc,area} = \sum_{Nuclide}\left[Act\_dep_{nuc,area} - \left(\frac{CULVL \times (A_U + A_S)}{10^6}\right)\right] \qquad \text{Equation 12}$$

Where:

$Act\_dep_{nuc,area}$ = Radionuclide activity deposited in each isopleth (Ci)
CULVL = Desired cleanup level ($\mu Ci/m^2$)
A_U = Contaminated building area (m^2)
A_S = Contaminated soil area (m^2)
$Act\_Rm_{nuc,area}$ = Radionuclide activity removed in each isopleth (Ci)

The resin used to collect the radionuclides 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 by Federal regulations (10 CFR 61.55). Table 16 provides the Class A waste concentration limits for all radionuclides provided in 10 CFR 61.55. The radionuclides not specifically identified are determined by either their half-life, or half-life and density (ρ_R), or if they do not have a Class A limit, are assumed to be 700 Ci/m^3. The minimum volume of resin needed is determined by:

$$\mathrm{Resin\_}Vol_{Lnk,Na} = \sum_{Nuclides} \frac{Act\_Rm_{nuc,area}}{\mathrm{Resin\_lim}_{nuc}}$$ Equation 13

Where:

Act_Rm = Radionuclide specific concentration to be removed from isopleth (Ci)
Resin_lim = Activity concentration limit (Ci/m^3) (Table 16 or 700 Ci/m^3)
Resin_Vol = Minimum volume of resin to remove all isotopes in an isopleth (m^3)

Table 16: Concentration Limits for Class A Waste

Radionuclide	Activity Concentration (Ci/m^3)
C-14	0.8
C-14 in activated metal	8
Ni-59 in activated metal	22
Nb-94 in activated metal	0.02
Tc-99	0.3
I-129	0.008
Alpha emitting transuranic nuclides with a half-life greater than 5 years	1.00E-08 x ρ_R
Pu-241	3.50E-07 x ρ_R
Cm-242	2.00E-06 x ρ_R
Total of all nuclides with less than 5 year half-life	700
H-3	40
Co-60	700
Ni-63	3.5
Ni-63 in activated metal	35
Sr-90	0.04
Cs-137	1

5.1.4 CONTAINER DOSE RATE ANALYSIS

Contaminated resins will be accumulated and placed in shipping containers for removal as Class A waste. The container volume may be adjusted. This model assumes the volume of a standard 55-gallon drum (0.2167 m^3). When the drum is filled with contaminated resin, an external dose rate can be determined based on the radionuclide inventory of the container. A container filled with cleanup resin and 1 Ci of Co-60 is used as a basis for this analysis. A MicroShield 7 (Grove Software, 2006) analysis was performed for this case and the dose rate at 1 m from a 55-gallon drum was determined to be 269.7 mrem/hr for the isotropic deep dose equivalent rate with buildup at the midplane of the container. Appendix A provides the MicroShield results for radionuclides analyzed. Because the dose rate will vary with radionuclide inventory, the dose rate for a radionuclide other than Co-60 may be approximated by:

$$DR\_rn = 269.7\left(\frac{A\_rn}{A\_Co}\right)\left(\frac{GRND\_rn}{GRND\_Co}\right)$$ Equation 14

Where:

DR_rn	= Dose rate of resin drum at 1 meter (mrem/hr)
A_rn	= Activity in the resin drum (Ci)
A_Co	= 1 Curie of Co-60
GRND_rn/GRND_Co	= Groundshine DCF (Rem-m^2/μCi-day) Ratio

A series of dose rates were calculated with MicroShield using different radionuclides to verify this approximation. The MicroShield results can be seen in Appendix A. The results shown in Table 17 indicate that the use of the groundshine dose conversion factor (Eckerman and Ryman, 1993) ratio will generate conservative results when compared to the isotropic deep dose equivalent rate with buildup ratio and will provide greater dose rates than a full MicroShield calculation.

Table 17: Groundshine Exposure

Nuclide	GRND_DCF Effective (Rem-m^2/μCi-day)	Dose Rate mRem/hr	Dose / Dose_Co	GRND_rn/ GRND_Co
Co-60	0.00075	269.7	1.000	1.000
Cs-137	0.000178	54.4	0.202	0.237
Cs-134	0.000486	152.1	0.564	0.648
Eu-154	0.00038	134.1	0.497	0.507
Sb-125	0.000136	37.0	0.137	0.181

In actual cleanup scenarios, the cleanup crew may not know which radionuclides are in a particular resin, especially when a mixture of radionuclides is released from a package. However, the cost of cleanup depends on the amount of resin used, which is in turn a function of the dose rate, at one meter from the container, in mrem/hr. The default value for determining when a container contains sufficient contaminated resin is 5 mrem/hr at one meter. This value also limits the quantity of contaminated resin in the 55-gallon drum. The Class A waste limits discussed in Section 5.1.3 combined with a limiting container dose rate will ensure waste drums meet low level waste shipping requirements.

5.1.5 RESIN DISPOSAL COSTS

The deposition of radionuclides depends on the deposition velocity, which is a function of the physical size and density of the dispersed radionuclides. The radionuclides are grouped by chemical and physical properties into chemical/physical groups (e.g., gases, small particles, volatile aerosols, etc.). One package can contain several chemical/physical groups.

RADTRAN reports deposition in each isopleth area separately for each chemical/physical group. If chemical/physical group “Group 1” deposits Co-60 at 0.02 m/s and chemical/physical group “Group 2” deposits Cs-137 at 0.005 m/s, then RADTRAN will calculate the same isopleth area as two separate areas, and cleanup will result in two different resin contaminations. Thus, the number of resin containers being disposed will be slightly overestimated.

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

$$C_{\text{Resin}} = BDC \cdot \rho_R \cdot V_B \cdot N_R \qquad \text{Equation 15}$$

Where:
BDC = Base disposal charge ($/g)
ρ_R = Density of the resin in the 55-gallon drum
V_B = Volume of 55-gallon drum
N_R = Number of drums of resin utilized in cleanup

The number of drums of resin in an isopleth area, N_R is determined from equation 16:

$$N_R = MAX\left(0.0, \frac{\mathrm{Resin}\_Vol_{Lnk,Nu}}{V_B}, \frac{DR\_rn}{DR\_\lim}\right) \qquad \text{Equation 16}$$

Where:
Resin_Vol = Minimum volume of resin to remove all isotopes in an isopleth (m^3)
DR_rn = Dose rate of the resin drum at 1 meter
DR_lim = Dose rate limit at 1 meter during cleanup, 5 mrem/hr (Section 5.1.4)

The deposited radioactivity differs for each isopleth area. Therefore each isopleth area will require different amounts of resin to absorb the radionuclides cleaned from that particular isopleth area. As a result, the doses from the resins will differ, and there will be a different resin container activity limit for each isopleth area.

A range of values for the resin density are presented in Table 18 (MatWeb). The values presented in Table 18 are not representative of all polymer resins, and the selected value for ρ_R should be sensible and suitable. The RADTRAN default resin density limit, 1.28 g/cm^3 is the average of the upper and lower resin density limits.

Table 18: Resin Density

	Resin Density (g/cm^3)	**Resin Water Absorption (fraction)**
Lower Limit	1.14	0.0015
Upper Limit	1.42	0.013

The resin density-dependent base disposal charge, BDC_R, is obtained from Barnwell, South Carolina (South Carolina Energy Office, 2004) and depends on the net density of the Class A waste disposed of at a low level waste facility. For simplification, the density and mass of the resin does not change with the collection of radionuclides in the resin. Base disposal charges, BDC, are shown in Table 19. A dose rate-dependent multiplier is factored in to the base charges, as shown in Table 20.

Barnwell lists dose rates as Roentgen (R) per hour. Since the Roentgen is an unusual dose rate, the Roentgen is converted to Rem for use with RADTRAN. .

Table 19: Base Disposal Charges

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

The base disposal charge, BDC_R ($/gm of resin), from Table 19 can be correlated with 97% accuracy using resin density, ρ_R, as:

$$BDC_R = 0.0152 \cdot \rho_R^{-0.8034} \qquad \text{Equation 17}$$

The base disposal charge is also a function of the dose rate for the drum. Thus the total base disposal charge, BDC_T, is:

$$BDC_T = BDC_R \cdot BDC_{DR} \qquad \text{Equation 18}$$

Where:

BDC_{DR} = Dose rate multiplier (Table 20)
BDC_R = Base disposal charge

Table 20: Dose Rate Multipliers

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

5.2 SOIL CLEANUP COSTS

Exposed areas of soil within the isopleth areas where contamination has exceeded the cleanup level can be removed up to a user-specified depth and then taken to a radioactive waste disposal site. Exposed areas of soil are those areas of land not covered by a building or road (e.g., parks, farmland, and forests). Soil fractions are discussed in Section 3.

The area needing cleanup is a function of both the population zone being examined (rural, suburban, or urban) and the land use category (residential, commercial, or industrial). The area around buildings is either parking areas or soil. Only in the case of residential land use in either rural or suburban population zones is there an additional soil quantity of reasonable magnitude. Hence, the total soil area can be determined from the RADTRAN calculations and the model input as:

$$A_{Soil} = \left(\sum_n A_n \right) \cdot F_S + A_{S,resid}$$

Equation 19

Where:

A_n = Area under the n^{th} isopleth

F_S = Fraction of land area which is exposed soil (Tables 4, 5, and 6)

$A_{S,resid}$ = The difference between the lot area and the building footprint for the residential land use

The soil removal cost, C_R, was determined to be $10.00/m^3 (Van Noordenen, 2007). The model uses a soil removal cost and the volume of soil to be removed to determine the cost of soil removal, C_S as:

$$C_S = C_R * \left(A_{Soil} \cdot d_{soil} \right)$$

Equation 20

Where:

d_{soil} = Removal depth (m)

C_R = Soil removal cost ($/m^3)

5.3 COSTS OF AGRICULTURAL DAMAGE

Agricultural sequestration results in loss of profits from crops and livestock. Agricultural damage can be classified as crop (cropland) damage and livestock (rangeland/pastureland) damage. Using the Chernobyl accident as an example, the default for the RADTRAN model sequesters crops for a year following the release of RAM, and livestock, for two years following the release. The model assumes all cropland and rangeland/pastureland are located in the rural population zone. Annual crop profits and biennial livestock profits are both calculated on the basis of a dollar per square meter of rural land to determine the agricultural cost. Because all cropland and rangeland/pastureland are assumed to be located within rural population zones, the agricultural cost will be a factor only in accidents occurring in rural areas.

Damage to fisheries is usually considered part of the cost of agricultural damage. However, this cost is neglected in this study because most U.S. highway interstate and railway miles, which radioactive material will be traveling, are inland away from fisheries. Also, contamination deposited on water surfaces could become too dilute to detect.

A "crop fraction" parameter, F_{RC}, and a "livestock fraction" parameter, F_{RL}, are inputs for accidents occurring in the rural population zone. The crop fraction is the percentage of rural land designated as cropland, and the livestock fraction is the percentage of rural land designated as pastureland or rangeland. On average, however, cropland makes up about 20.0% of rural land area, and pastureland/rangeland makes up about 28.0% of the land use (U.S. Department of Agriculture, 2001).

The total cost of agricultural sequestration, C_A, in each isopleth area where the contamination has exceeded the cleanup level is:

$$C_A = A_n \cdot \left(\left(C_{area} \cdot F_{RC} \right) + \left(L_{area} \cdot F_{RL} \right) \right) \qquad \text{Equation 21}$$

Where:

C_{area} = Annual crop profit per m^2 of rural land
L_{area} = Bi-annual livestock profit per m^2 of rural land
A_n = Area under the *n*th isopleth, which is summed over all isopleths

In order to incorporate a per-unit-area cost, it is assumed that annual crop profits and biennial livestock profits are the only contributors to post-accident agricultural damage costs. As a result of an accident, the cost to the farmer would be the lost profits from crop and livestock production and the cost of soil removal. Cost of soil removal is treated separately.

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, the total U.S. rural land area and the 1997 annual U.S. crop and livestock gross profits, adjusted for inflation (U.S. Department of Agriculture, 1997).

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

5.4 EVACUATION AND EMERGENCY COSTS

Emergency and evacuation costs are modeled using FEMA-generated costs for a 1993 Florida tropical storm. These costs include:

- Disaster housing grants
- Individual and family grants
- Mobile home and inspection services
- Disaster unemployment assistance
- Crisis counseling assistance
- Small business association loans to individuals
- Small business association loans to business owners
- Public assistance to local governments
- Hazard mitigation grant program

Six Florida counties had the highest per person per area cost, equal to or exceeding $0.10 per person per m^2. These counties were considered “hardest-hit” by the storm and required funds similar to what would be required in a RAM transportation accident. An average per person per area cost in these six counties was calculated and tabulated with lower limit and upper limit costs. A default evacuation cost is provided for each population zone, but this calculation is intended to serve as a guide for determining a realistic value. The cost per person per area is then multiplied by the population and isopleth area .

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

All of the costs for an emergency evacuation are assumed to be borne by Federal disaster aid. Federal government disaster assistance data were obtained for the “No-Name Storm” which hit Florida’s Gulf Coast on March 13, 1993 (FEMA, 2003). County-by-county expenditures for the following costs, along with the number of persons per county covered by these costs, were provided by the Federal Emergency Management Agency (FEMA, 2003).

- 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

In Figure 11, gray-colored counties are counties which received Federal disaster aid near or exceeding $0.10 per person per km^2; orange-colored counties received the highest per capita amount of Federal aid.

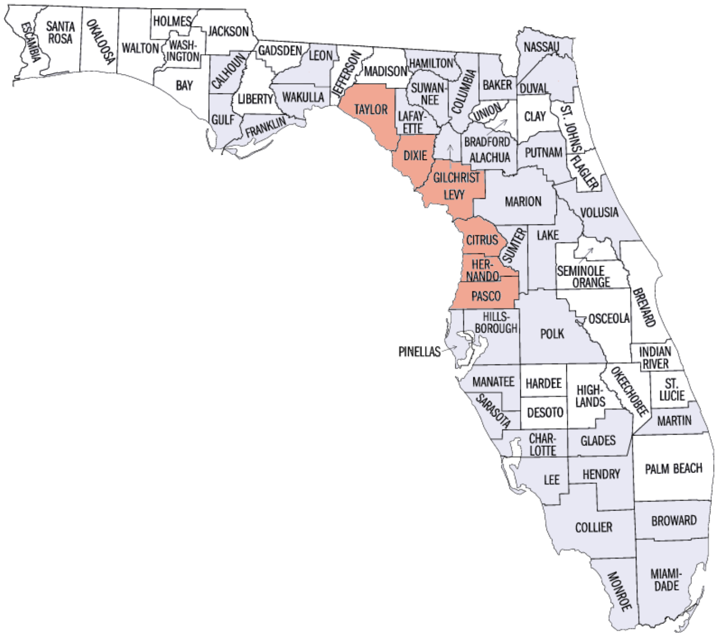

Figure 11: Florida Counties Receiving Federal Disaster Aid

Because the counties shown in orange are in the same region, it is assumed this region was the center of the storm and suffered the most damage. A radiological accident would affect a concentrated region of a few counties, similar to the cluster of orange-colored Florida counties. These six counties were used as a model for evacuation and emergency costs of a radiation accident. It is assumed that all of the costs are in the form of Federal disaster aid. Table 21 shows population and cost data for each of the six counties.

Table 21: Population and Cost Data

County	Population	Area (km^2)	Population Density (persons/km^2)	Total Cost ($)	Cost ($) per Person-km^2
Citrus	93515	1511.5	61.87	369	0.24
Dixie	10585	1823.5	5.80	1289	0.71
Hernando	101115	1238.8	81.62	254	0.21
Levy	25923	2896.8	8.95	270	0.09
Pasco	281131	1929.5	145.70	185	0.10
Taylor	17111	2698.6	6.34	804	0.30
AVERAGE					0.27

Extrapolating the costs to include the entire population of each county and then summing over all the costs, a total extrapolated Evacuation and Emergency cost for each county is calculated. These costs were normalized by the county's population and land area, resulting in a cost per person-km^2, or C_{PA}. The C_{PA} for each county was then adjusted for 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, maximum, and minimum inflation-adjusted C_{PA} values for rural, suburban, and all affected counties are presented in Table 22.

Table 22: Cost per Person-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	7.88	0.10	Calhoun	19.69	Wakulla
Suburban	13.61	1.01	Lee	50.69	Dade
All Affected	10.11	0.10	Calhoun	50.69	Dade

No urban counties were affected by the 1993 storm, so the extrapolation of C_{PA} is based on the suburban C_{PA}. The wide range in C_{PA} is due to the amount of damage occurring in each county. A C_{PA} should be selected nearer to the lower limit for small radionuclide releases, and a C_{PA} selection nearer to the upper limit for large releases.

Knowing the average cost per person-km^2, then the total emergency and evacuation costs, C_E, in each isopleth where the contamination has exceeded the cleanup level is:

$$C_E = \sum_n \left(P_n \cdot \frac{A_n}{1000^2} \cdot C_{PA} \right) \qquad \text{Equation 22}$$

Where:

P_n = Population in the *n*th isopleth
A_n = Area under the *n*th isopleth
C_{PA} = Evacuation and emergency cost per person-km^2

6.0 CONCLUSIONS

The preceding section presents the calculations that were used to develop the RADTRAN model for decontamination and evacuation. The RADTRAN model uses five cost categories for a radioactive material release accident, and has been designed to calculate the cost associated with each of the categories. Costs associated with water contamination have yet to be developed.

The release of large amounts of radioactive material in a community entails costs in addition to the cost of decontamination and evacuation. For example, housing must be provided for evacuees, and may need to be permanent if buildings cannot be sufficiently decontaminated. The model presented here is a first step in calculating costs of cleanup.

The RADTRAN model also includes an important flexibility: the cleanup level – the radionuclide concentration to be attained by cleanup – is user defined. That concentration may change as more is learned about the health effects of very small amounts of ionizing radiation.

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APPENDIX A

MicroShield Calculations

Co-60 Analysis

MicroShield 7.01

Project Information

Case Title:	Co-60 55-gallon Drum
Description:	Assume 1 Ci of Co-60 in resin inside a DOT-7A 55-gallon drum
Geometry:	7 – Cylinder Volume – Side Shields

Source Dimensions

Height	84.455 cm
Radius	28.575 cm

Dose Point

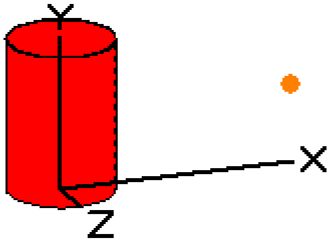
X	Y	Z
128.7 cm	42.228 cm	0.0 cm

Shields

Shield Name	Dimension	Material	Density
Source	2.17E+05 cm^3	Water	1.28
Air Gap		Air	0.00122
Wall Clad	0.121 cm	Iron	7.86
Top Clad	0.152 cm	Iron	7.86

Source Input: Grouping Method – Actual Photon Energies

Nuclide	Curies	μCi/cm^3
Co-60	1.0	4.6159



Buildup: The material reference is the Wall Clad

Integration Parameters

Radial	50
Circumferential	50
Y-direction (axial)	100

Results

Activity (photons/sec)	Fluence Rate (MeV/cm^2/sec) No Buildup	Fluence Rate (MeV/cm^2/sec) With Buildup	Exposure Rate (mR/hr) No Buildup	Exposure Rate (mR/hr) With Buildup
7.401E+10	1.146E+05	2.013E+05	2.016E+02	3.540E+02

Cs-137 Analysis

MicroShield 7.01

Project Information

Case Title:	Cs-137 55-gallon Drum
Description:	Assume 1 Ci of Cs-137 in resin inside a DOT-7A 55-gallon drum
Geometry:	7 – Cylinder Volume – Side Shields

Source Dimensions

Height	84.455 cm
Radius	28.575 cm

Dose Point

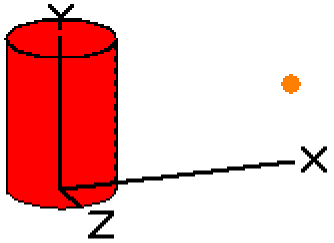
X	Y	Z
128.7 cm	42.228 cm	0.0 cm

Shields

Shield Name	Dimension	Material	Density
Source	2.17E+05 cm^3	Water	1.28
Air Gap		Air	0.00122
Wall Clad	0.121 cm	Iron	7.86
Top Clad	0.152 cm	Iron	7.86

Source Input: Grouping Method - Actual Photon Energies

Nuclide	**Curies**	**$\mu Ci/cm^3$**
Cs-137	1.0	4.6159
Ba-137m	0.946	4.3666



Buildup: The material reference is the Wall Clad

Integration Parameters

Radial	50
Circumferential	50
Y-direction (axial)	100

Results

Activity (photons/sec)	Fluence Rate ($MeV/cm^2/sec$) No Buildup	Fluence Rate ($MeV/cm^2/sec$) With Buildup	Exposure Rate (mR/hr) No Buildup	Exposure Rate (mR/hr) With Buildup
3.441E+10	1.918E+04	3.837E+04	3.718E+01	7.439E+01

Cs-134 Analysis

MicroShield 7.01

Project Information

Case Title:	Cs-134 55-gallon Drum
Description:	Assume 1 Ci of Cs-134 in resin inside a DOT-7A 55-gallon drum
Geometry:	7 – Cylinder Volume – Side Shields

Source Dimensions

Height	84.455 cm
Radius	28.575 cm

Dose Point

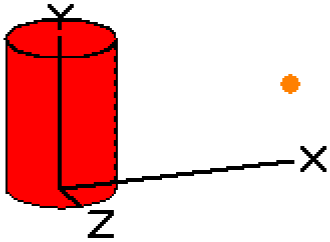
X	Y	Z
128.7 cm	42.228 cm	0.0 cm

Shields

Shield Name	Dimension	Material	Density
Source	2.17E+05 cm^3	Water	1.28
Air Gap		Air	0.00122
Wall Clad	0.121 cm	Iron	7.86
Top Clad	0.152 cm	Iron	7.86

Source Input: Grouping Method – Actual Photon Energies

Nuclide	**Curies**	**μCi/cm^3**
Cs-134	1.0	4.6159



Buildup: The material reference is the Wall Clad

Integration Parameters

Radial	50
Circumferential	50
Y-direction (axial)	100

Results

Activity (photons/sec)	Fluence Rate (MeV/cm^2/sec) No Buildup	Fluence Rate (MeV/cm^2/sec) With Buildup	Exposure Rate (mR/hr) No Buildup	Exposure Rate (mR/hr) With Buildup
8.278E+10	5.490E+04	1.080E+05	1.052E+02	2.071E+02

Eu-154 Analysis

MicroShield 7.01

Project Information

Case Title:	Eu-154 55-gallon Drum
Description:	Assume 1 Ci of Eu-154 in resin inside a DOT-7A 55-gallon drum
Geometry:	7 – Cylinder Volume – Side Shields

Source Dimensions

Height	84.455 cm
Radius	28.575 cm

Dose Point

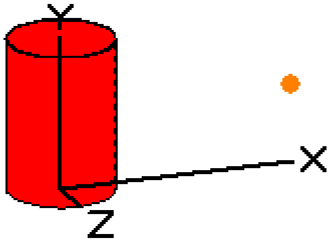
X	Y	Z
128.7 cm	42.228 cm	0.0 cm

Shields

Shield Name	Dimension	Material	Density
Source	2.17E+05 cm^3	Water	1.28
Air Gap		Air	0.00122
Wall Clad	0.121 cm	Iron	7.86
Top Clad	0.152 cm	Iron	7.86

Source Input: Grouping Method – Actual Photon Energies

Nuclide	Curies	$\mu Ci/cm^3$
Eu-154	1.0	4.6159



Buildup: The material reference is the Wall Clad

Integration Parameters

Radial	50
Circumferential	50
Y-direction (axial)	100

Results

Activity (photons/sec)	Fluence Rate ($MeV/cm^2/sec$) No Buildup	Fluence Rate ($MeV/cm^2/sec$) With Buildup	Exposure Rate (mR/hr) No Buildup	Exposure Rate (mR/hr) With Buildup
7.334E+10	5.577E+04	9.960E+04	9.882E+01	1.771E+02

Sb-125 Analysis

MicroShield 7.01

Project Information

Case Title:	Sb-125 55-gallon Drum
Description:	Assume 1 Ci of Sb-125 in resin inside a DOT-7A 55-gallon drum
Geometry:	7 – Cylinder Volume – Side Shields

Source Dimensions

Height	84.455 cm
Radius	28.575 cm

Dose Point

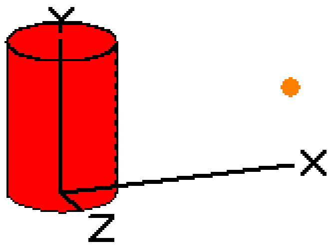
X	Y	Z
128.7 cm	42.228 cm	0.0 cm

Shields

Shield Name	Dimension	Material	Density
Source	2.17E+05 cm^3	Water	1.28
Air Gap		Air	0.00122
Wall Clad	0.121 cm	Iron	7.86
Top Clad	0.152 cm	Iron	7.86

Source Input: Grouping Method - Actual Photon Energies

Nuclide	**Curies**	**$\mu Ci/cm^3$**
Sb-125	1.0	4.6159



Buildup: The material reference is the Wall Clad

Integration Parameters

Radial	50
Circumferential	50
Y-direction (axial)	100

Results

Activity (photons/sec)	Fluence Rate ($MeV/cm^2/sec$) No Buildup	Fluence Rate ($MeV/cm^2/sec$) With Buildup	Exposure Rate (mR/hr) No Buildup	Exposure Rate (mR/hr) With Buildup
5.186E+10	1.274E+04	2.602E+04	2.480E+01	5.102E+01

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