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ECONOMIC CONSEQUENCES OF ACCIDENTAL RELEASES FROM FUEL FABRICATION AND RADIOISOTOPE PROCESSING PLANTS

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ABSTRACT

At the request of the Nuclear Regulatory Commission, a determination was made of the quantities of various radioactive materials whose release from fuel fabrication or radioisotope processing plants and dispersal in the environment could conceivably result in off-site decontamination and exposure costs approximating $140 million (i.e., the limit of nuclear liability insurance presently available from the private sector). The Gaussian plume dispersion model was used to express the spread of radioactivity downwind from its point of release and define areas of decreasing contamination and exposure levels. Unit costs for decontamination and exposure within the defined areas were used in estimating the economic losses.

The licensed possession limits for many radioisotopes exceeded the amounts which, if released in respirable form, could cause an off-site economic loss of $140 million. The estimated quantities of fresh U-233 and U-235 fuel causing the same loss under inversion conditions were 20 and 12,000 kg respectively. The estimated quantity of fresh plutonium fuel resulting in such an off-site economic loss under inversion conditions was <100 g.

Estimates were made of the radioactivity released from a postulated maximum accident in a spent fuel storage pool and an accident involving spent fuel in transit. A criticality incident involving fresh uranium fuel was also assessed in terms of the potential off-site economic loss. The releases from the accidents involving spent fuel and the criticality incident with fresh uranium fuel were found not to be significant when the potential off-site economic losses were compared with available private insurance coverage.

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1. INTRODUCTION

In May 1977 the Nuclear Regulatory Commission (NRC) requested that ORNL assist in a study of the economic consequences resulting from the accidental releases of radioactivity from plutonium processing and fuel fabrication plants, highly enriched uranium processing and fuel fabrication

plants, large [illegible]roduct materials source plants, and spent fuel storage plants. The study was to provide the basis for a feasibility report to the NRC commissioners on extending Price-Anderson indemnification to these facilities.

The study was initiated with a search of the technical literature and a review of current nuclear insurance practice. Licenses and/or environmental statements (where available) of pertinent facilities were reviewed in order to obtain a list of relevant isotopes, possession limits, surrounding population densities, etc. A determination was then made of the quantities of various radioactive materials whose dispersal in the environment under a given meteorological condition could conceivably result in decontamination and exposure costs approximating $140 million -- the limit of nuclear liability insurance presently available from the private sector. Finally, estimates were made of the radioactivity released from a postulated accident in a spent-fuel storage pool and an accident involving spent fuel in transit. A criticality incident involving fresh uranium fuel was also assessed. The releases from the accidents involving spent fuel and the criticality incident with fresh uranium fuel were found not to be significant in terms of the purpose of this study.

A comprehensive and detailed study was made in 1964 by Guthrie and Nichols of the possible economic consequences of accidental releases from U-233 and Pu-239 fuel fabrication and radioisotope processing plants.[1] They concluded that "accidents having more than a theoretical possibility of occurring would not result in a monetary loss due to damage to the surroundings exceeding the limits of private insurance coverage currently available (60,000,000)." However, they conceded that it was possible to postulate "incredible" accidents which could theoretically result in off-site damage which would greatly exceed the $60 million limit. A detailed identification of actual facilities was not made in the Guthrie and Nichols report, and the population densities used in assessing monetary losses were, in the light of the present study, quite low. However, the methodology of Guthrie and Nichols for estimating the economic consequences of radioactive releases is employed in the present report, using updated unit costs and more relevant population densities. Accident scenarios of

various severities are discussed in the Guthrie and Nichols report, but we have not addressed them here and have limited the economic loss assessment to a determination of the amounts of radioactive releases which could result in monetary losses approximating $140 million.

The appendix contains information about firms licensed by the NRC and the Agreement States to possess significant quantities of radioactive by-product material. It also contains information about some major fuel fabrication facilities.

2. METHODOLOGY FOR ESTIMATING THE ECONOMIC CONSEQUENCES OF A RADIOACTIVE RELEASE

To estimate the economic consequences of a given accidental radioactive release, three zones of surface contamination and three zones of exposure (i.e., air concentration) of varying severity were defined by the use of the Gaussian dispersion model[2] to express the spread of radioactivity downwind from the point of its release. The dispersion model was used to define areas for which the contamination levels (Ci m^{-2}) were within or exceeded certain contamination limits, called deposition isopleths (Ci m^{-2} Ci^{-1}). Similarly, areas for which the air concentrations (Ci m^{-3}) were within or exceeded certain air concentration limits, called exposure isopleths (Ci sec m^{-3} Ci^{-1}), were established. The numbers of people within the various contamination and exposure zones were calculated by multiplying the areas within the zones by a uniform population density developed from population data for actual facilities. Per capita costs were assigned for the economic losses associated with decontamination in the contaminated zones and exposures in the exposure zones. Finally, the total economic loss associated with a given release was obtained by multiplying the per capita costs by the number of people within the various zones and adding the results. Hence the total economic loss consists of the sum of three collective losses due to contamination (i.e., three contamination zones) and three due to exposure (i.e., three exposure zones).

3. DISPERSION OF RADIOACTIVE MATERIAL

The formulation of the Gaussian plume dispersion model for ground level exposure with no depletion of material from the plume is:

$$\chi(x,y,o) = \frac{Q}{\pi u \sigma_y \sigma_z} \exp\left[-\frac{y^2}{2\sigma_y^2} - \frac{h^2}{2\sigma_z^2}\right], \quad (1)$$

where:

Q = total quantity of curies released;

u = wind speed, m sec^{-1};

σ_y = horizontal dispersion coefficient, m;

σ_z = vertical dispersion coefficient, m;

x = distance downwind from the source, m;

y = distance crosswind from the source, m;

h = elevation of source above ground level, m;

$\chi(x,y,o)$ = ground level air concentration, Ci m^{-3},

and σ_y and σ_z are functions of x.[2]

Since the radioactive materials that are considered in this study have half-lives of at least several days, it was not necessary to allow for radioactive decay during atmospheric transport. It is necessary, however, to provide for depletion of the plume in order to account for the particles that are deposited on downwind surfaces. The correction for plume depletion is made as follows:

$$\chi(x,y,z) = \chi(x,y,o)\, e^{-D(x)}, \quad (2)$$

where

$$D(x) = \frac{V_g}{u}\int_o^x \left(\frac{\chi(r,y,o)}{\int_o^\infty \chi(r,y,z)dz}\right) dr = \frac{2^{V_g}\sqrt{2}}{u\sqrt{\pi}} \int_o^x \frac{dr}{\sigma_z}, \quad (3)$$

and

V_g is the deposition velocity, m sec^{-1}.

Hence, assuming that the radioactive materials are released at ground level (h = 0), the air concentration at ground level at a point (x,y,o) downwind of the source is

$$\chi(x,y,o) = \frac{Q}{\pi u \sigma_y \sigma_z} \exp\left[- \frac{y^2}{2\sigma_y^2} - \frac{2V_g x\sqrt{2}}{\sigma_z u \sqrt{\pi}} \right] . \quad (4)$$

The surface concentration (Ci m^{-2}) of material deposited at point (x,y,o) is

$$W(x,y) = \chi(x,y,o) V_g \quad (5)$$

The crosswind distance corresponding to a given value of exposure or air concentration (χ/Q) is

$$y = \sigma_y \sqrt{2} \left[\frac{2V_g x\sqrt{2}}{\sigma_z u \sqrt{\pi}} - \ln \sigma_y \sigma_z \pi u \frac{\chi}{Q} \right]^{1/2} . \quad (6)$$

Equation (6) can be solved by numerical integration, and the area enclosed within a given isopleth of exposure is

$$A = 2 \int_0^{\bar{x}} y \, dx , \quad (7)$$

where $\bar{x}$, the maximum downwind extent of the isopleth, is the real, nonzero value of x that may be determined by setting y = 0 in Eq. (6).

For the purpose of estimating the consequences of an accidental release of radioactive materials, areas within various exposure isopleths were calculated by assuming a 0.001-m sec^{-1} settling velocity and dispersion parameters which correspond to a fairly average meterological condition (slightly stable: $\sigma_y = 0.05\ x$, $\sigma_z = 0.07\ x^{1/2}$, and a 2-m sec^{-1} wind speed) and an inversion condition (moderately stable: $\sigma_y = 0.02\ x$, $\sigma_z = 1.05\ x^{2/5}$, and a 1-m sec^{-1} wind speed). Figure 1 plots the areas within the exposure isopleths versus the exposure isopleths for the two radiological conditions. Note that the area enclosed within a deposition isopleth, W/Q, is the same

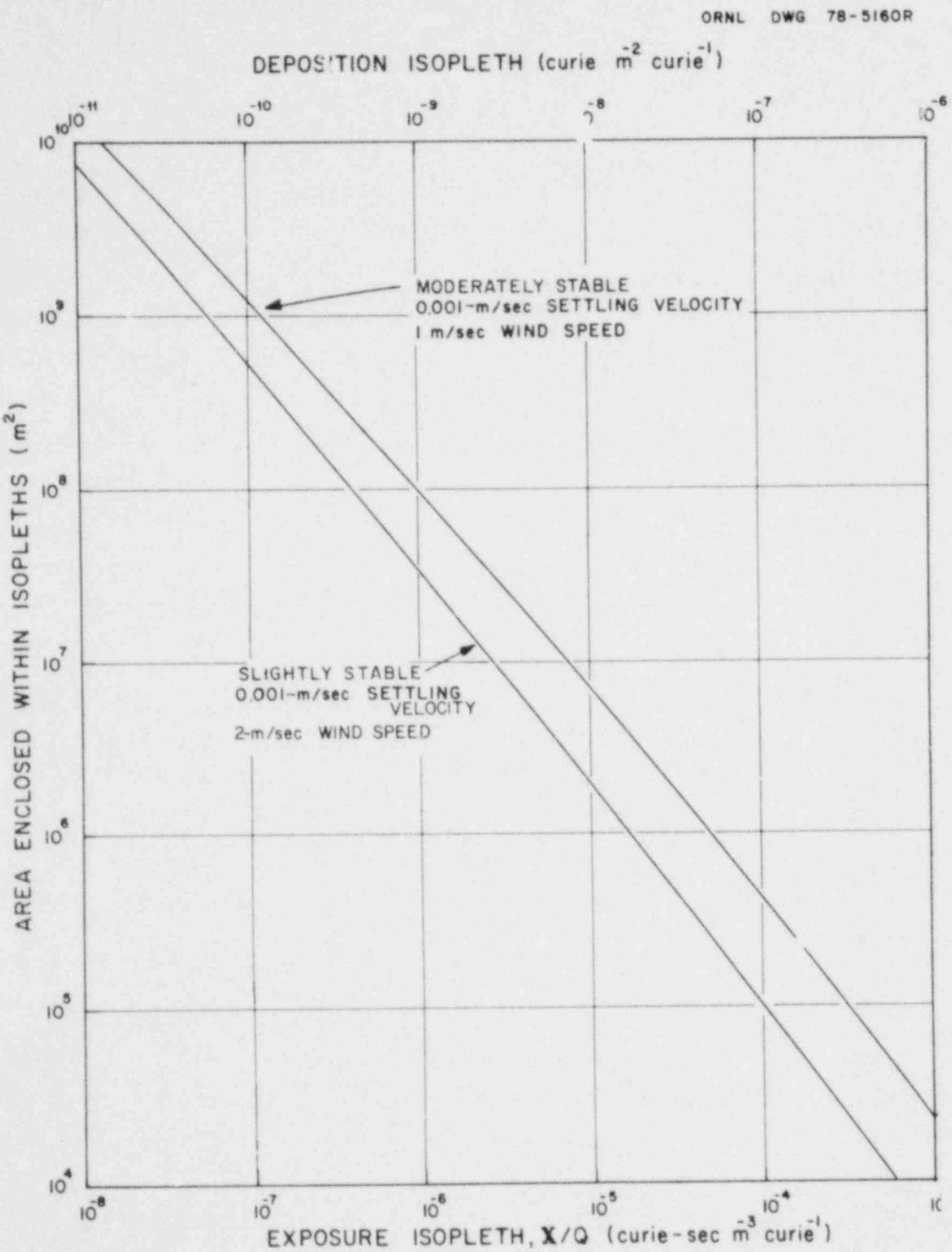

Fig. 1. Area enclosed within isopleths of exposure and contamination.

as the area enclosed within an exposure isopleth χ/Q equal to $(W/Q)/V_g$. The effect of assuming that the releases occur at ground level is to overestimate the downwind concentrations at ground level since buoyancy effects from possible heat sources are neglected.

4. ECONOMIC CONSEQUENCES OF THE RELEASE OF RADIOACTIVE MATERIALS

The economic consequence model defines ranges of personnel exposure and surface contamination and assigns unit costs within these ranges to provide an estimate of the monetary losses that would result from radioactive contamination and radiation injuries. The downwind area for which the surface contamination or exposure level exceeds a given reference level was estimated from the plots in Fig. 1. The number of persons within the computed area for the by-product materials source plants was estimated using a uniform population density of 3000 persons/sq mile, approximately the average value of the population densities surrounding the various facilities (see Appendix, Tables A.1 and A.2). For the fuel fabrication plants, a uniform population density of 500 persons/sq mile--the average of the population densities surrounding six major fuel fabrication plants--was used. (See Appendix, Table A.3.)

4.1 Assumed Ranges of Surface Contamination and Personnel Exposure

Tables 1, 2, and 3 define the ranges of surface contamination and personnel exposure together with estimated unit costs that were used in assessing the economic consequences of airborne releases of radioactive materials. A ground contamination level for nonrestricted use was established for isotopes other than Sr-90, I-131, and Cs-137 by using a resuspension factor of 10^{-5} m^{-1} (ref. 3) in combination with the maximum permissible concentration in air for nonrestricted areas given in 10 CFR 20, Appendix B, Table II. The contamination levels for Sr-90, I-131, and Cs-137 were conservatively based on their getting into the food chain, as developed in ref. 4 (see Table 2). Three surface contamination ranges were defined consisting of zones of severe, moderate, and minor contamination.

Table 1. Monetary loss assumptions for area contamination and personnel exposure

Range		Assumed loss ($/person)
I	Severe contamination	
	Long-term evacuation (≥ 1 year) Severe decontamination Possible value loss	20,000
II	Moderate contamination	
	Short-term evacuation (≥ 3 months) Moderate decontamination	3,000
III	Minor contamination	
	No evacuation Minor decontamination	1,000
A	Upper range of exposure	
	>1500-rem 50-year dose commitment	100,000
B	Intermediate range of exposure	
	>150-rem 50-year dose commitment	20,000
C	Lower range of exposure	
	>15-rem 50-year dose commitment	4,000

Table 2. Contamination ranges assumed in estimating decontamination costs

Isotope	10 CFR 20 168-hr MPC_{air} ($\mu Ci\ cm^{-3}$)	Specific Activity ($Ci\ g^{-1}$)	Maximum contamination for nonrestricted use[a] ($Ci\ m^{-2}$)	Range III minor restrictions: no evacuation minor decontamination ($Ci\ m^{-2}$)	Range II moderate restrictions: short-term evacuation moderate decontamination[b] ($Ci\ m^{-2}$)	Range I severe restrictions long-term evacuation severe decontamination[c] ($Ci\ m^{-2}$)
Co-60	3×10^{-10}	1.1×10^{3}	3×10^{-5}	3×10^{-5} to 3.1×10^{-4}	3.1×10^{-4} to 3.4×10^{-3}	3.4×10^{-3}
Sr-90[d]	3×10^{-11}	1.4×10^{2}	1.7×10^{-7}	1.7×10^{-7} to 1.7×10^{-6}	1.7×10^{-6} to 1.7×10^{-5}	1.7×10^{-5}
Sb-124	7×10^{-10}	1.8×10^{4}	7×10^{-5}	7×10^{-5} to 2.0×10^{-3}	2.0×10^{-3} to 4.4×10^{-1}	4.4×10^{-1}
I-131[d]	3×10^{-10}	1.2×10^{5}	1.2×10^{-6}	1.2×10^{-6}	-	-
Cs-137[d]	5×10^{-10}	8.7×10^{1}	2×10^{-6}	2×10^{-6} to 2×10^{-5}	2×10^{-5} to 2×10^{-4}	2×10^{-4}
Ce-144	2×10^{-10}	3.2×10^{3}	2×10^{-5}	2×10^{-5} to 2.5×10^{-4}	2.5×10^{-4} to 4.9×10^{-3}	4.9×10^{-3}
Pm-147	3×10^{-9}	9.3×10^{2}	3×10^{-4}	3×10^{-4} to 3.2×10^{-3}	3.2×10^{-3} to 1.9×10^{-2}	1.9×10^{-2}
Tm-170	1×10^{-9}	6.1×10^{3}	1×10^{-4}	1×10^{-4} to 1.6×10^{-3}	1.6×10^{-3} to 7.1×10^{-2}	7.1×10^{-2}
Ir-192	9×10^{-10}	9.2×10^{3}	9×10^{-5}	9×10^{-5} to 2.1×10^{-3}	2.1×10^{-3} to 2.7×10^{-1}	2.7×10^{-1}
Po-210	7×10^{-12}	4.5×10^{3}	7×10^{-7}	7×10^{-7} to 1.1×10^{-5}	1.1×10^{-5} to 4.4×10^{-4}	4.4×10^{-4}
U-233[e]	2×10^{-12}	2.0×10^{-2}	2×10^{-7}	2×10^{-7} to 2×10^{-6}	2×10^{-6} to 2×10^{-5}	2×10^{-5}
U-235[f]	4×10^{-12}	8.3×10^{-5}	4×10^{-7}	4×10^{-7} to 4×10^{-6}	4×10^{-6} to 4×10^{-5}	4×10^{-5}
Pu-238	7×10^{-14}	1.7×10^{1}	7×10^{-9}	7×10^{-9} to 7×10^{-8}	7×10^{-8} to 7×10^{-7}	7×10^{-7}
Pu Fuel[g]	6×10^{-14}	1.66[h]	1.1×10^{-7}	1.1×10^{-7} to 1.1×10^{-6}	1.1×10^{-6} to 1.2×10^{-5}	1.2×10^{-5}
Am-241	2×10^{-13}	3.43	2×10^{-8}	2×10^{-8} to 2×10^{-7}	2×10^{-7} to 2×10^{-6}	2×10^{-6}
Cm-242	4×10^{-12}	3.3×10^{3}	4×10^{-7}	4×10^{-7} to 5.9×10^{-6}	5.9×10^{-6} to 1.9×10^{-4}	$>1.9 \times 10^{-4}$
Cm-244	3×10^{-13}	8.1×10^{2}	3×10^{-8}	3×10^{-8} to 3×10^{-7}	$\times 10^{-7}$ to 3.1×10^{-6}	$>3.1 \times 10^{-6}$

[a] Assumed resuspension factor: 1×10^{-5}.

[b] Contamination limit reflects 3-months decay.

[c] Contamination limit reflects 1-year decay.

[d] Contamination levels for these isotopes based on dairy farming. Limits for all other isotopes based on resuspension and inhalation.

[e] U-233 containing 500 ppm of U-232.

[f] U-235 containing 1.3 wt % U-234.

[g] Isotopic composition of fresh fuel, wt %: 0.053, Pu-238; 86.5, Pu-239; 11.8, Pu-240; 1.4, Pu-241; 0.2, Pu-242. Source: RDT Standard E13-1T, FFTF Ceramic Grade Plutonium Dioxide (June 1971).

[h] Alpha plus beta activity; alpha activity = 0.089 $Ci\ g^{-1}$.

Table 3. Short-term exposure to various isotopes that would cause a 15-rem 50-year dose commitment to the critical organ

Isotope	Critical organ	50-year dose commitment for unit inhalation[a] intake (rems μCi^{-1})	Inhalation intake for 15-rem 50-year dose commitment (μCi)	Exposure[b] ($Ci\text{-}sec\ m^{-3}$)
Co-60	Lungs	0.74	20.3	9.2×10^{-2}
Sr-90	Bone	11.08	1.35	6.1×10^{-3}
Sb-124	Lungs	0.34	44.1	2.0×10^{-1}
I-131	Thyroid	1.44	10.4	4.7×10^{-2}
Cs-137	Liver	0.79	19.0	8.6×10^{-2}
Ce-144	Bone	1.20	12.5	5.7×10^{-2}
Pm-147	Bone	0.19	79.0	3.6×10^{-1}
Tm-170	Bone	0.32	46.9	2.1×10^{-1}
Ir-192	Lungs	0.25	60.0	2.7×10^{-1}
Po-210	Lungs	32.4	0.46	2.1×10^{-3}
U-233[c]	Lungs	147	0.10	4.6×10^{-4}
U-235[d]	Lungs	53.8	0.28	1.3×10^{-3}
Pu-238	Bone	5710	0.0026	1.2×10^{-5}
Pu Fuel[e]	Bone	463	0.0324	1.5×10^{-4}
Am-241	Bone	2070	0.0072	3.3×10^{-5}
Cm-242	Bone	50.9	0.29	1.3×10^{-3}
Cm-244	Bone	1260	0.012	5.5×10^{-5}

[a] Source: A Methodology for Calculating Radiation Doses from Radioactivity Released to the Environment, compiled by G. G. Killough and L. R. McKay, ORNL-4992 (March 1976), Table 4-2.

[b] These exposures are assumed to constitute the lower limits for range C. The lower limits of exposure for ranges B and A are higher by factors of 10 and 100, respectively.

[c] Uranium-233 containing 500 ppm of U-232.

[d] Uranium-235 containing 1.3 wt % U-234.

[e] Isotopic composition of fresh fuel, wt %: 0.053, Pu-238; 86.5, Pu-239; 11.8, Pu-240; 1.4, Pu-241; 0.2, Pu-242. Specific activity: alpha plus beta = 1.66 Ci/g, alpha = 0.089 Ci/g. Source: RDT Standard E13-1T, FFTF b Ceramic Grade Plutonium Dioxide (June 1971).

In Range I, the contamination level is greater than 100 times the estimated limiting contamination level for nonrestricted use. Contamination Ranges II and III consist of contamination levels 10 to 100 and 1 to 10 times the nonrestricted contamination level, respectively. The limits of contamination for Ranges I and II reflect decay times of 1 year and 3 months, respectively. These times allow for periods of evacuation from the areas during decontamination.

Table 3 shows the intake in microcuries and curie-seconds per cubic meter (Ci-sec m^{-3}), giving a 50-year dose commitment of 15 rem to the critical organ. The units of curie-seconds per cubic meter were used for the sake of convenience in calculating the exposure isopleths resulting from a release. A respiration rate of 220 cm^3 sec^{-1} has been assumed for converting from microcuries to curie-seconds per cubic meter. Exposure Ranges A, B, and C were defined for exposures greater than 100, 10 to 100, and 1 to 10 times a 50-year dose commitment of 15 rem to the critical organ, respectively. A 50-year dose commitment of 15 rem means that an individual will receive a 15-rem dose over 50 years as the result of a given exposure or intake. The annual permissible occupational dose for most organs recommended by the NCRP (as well as the ICRP and FRC) is 15 rem.[5]

In the highest contamination range (Range I), it is assumed that long-term evacuation (1 or more years), relocation, and extensive decontamination operations would be required in urban areas and that the cost of these operations would equal or exceed the total property value. In the Rasmussen report (WASH-1400)[6] this cost is estimated at about $20,000 per capita. In Range II, where short-term evacuation (≥ 3 months) is anticipated, the decontamination cost of $3000 per capita represents the upper limit of the range of decontamination costs for developed property estimated for a decontamination factor of 20 in the Rasmussen report.

The per capita cost in Range II[illegible] selected as $1000. On this basis, decontamination costs would be $780/acre for a relatively low population density, such as the 500 persons/sq mile assumed for the fuel fabrication plants. This may be compared with the $230/acre cost for decontaminating farmland estimated in the Rasmussen report and the minimum cost of $500/acre

proposed by the EPA.[7] For a suburban area with an assumed density of 3000 people/sq mile for evaluating the by-product facilities, a $1000 per capita cost would result in a decontamination cost of 11¢/ft^2, which compares with the 10¢/ft^2 estimated for restoring the Barnwell site after the buildings are razed[8] and a similar unit cost estimated for the external decontamination of an urban site.[9]

The per capita costs for personnel exposure were selected as $100,000 for Range A, $20,000 for Range B, and $4000 for Range C. These may be compared with $250,000 for an accidental death and $40,000 for a spontaneous cancer fatality estimated by Gotchy,[10] and with $57,000 to $72,000 for a delayed cancer death in ref. 11. Gotchy also puts the cost of a serious accidental injury at $63,000 and an injury with no permanent disability at $2500.

4.2 Method of Estimating Costs

Figure 2 is a schematic of deposition isopleths for a radioactive ground-level release under inversion conditions. The isopleths are for contamination limits separated by multiples of 10. The lateral scale has been exaggerated by a factor of 5 for the sake of clarity. The outer isopleth represents the estimated maximum contamination level for nonrestricted use of the land (the outer boundary of Range III). The two inner isopleths represent contamination levels 10 and 100 times greater than the acceptable limit for nonrestricted use (outer boundaries of Ranges II and I). Similar schematics could be made for the exposure Ranges A, B, and C where the isopleths would represent air concentration levels.

To estimate decontamination costs, the contamination limits shown in Table 2 are divided by the number of curies released to give deposition or contamination isopleths (Ci m^{-2} Ci^{-1}) for the given release. One then obtains the areas enclosed within the isopleths from Fig. 1, determines the population within the various zones using a uniform population of 3000 persons/sq mile, and calculates the cost using the per capita costs of Table 1.

Fig. 2. Deposition isopleths for a ground level release under inversion conditions. Crosswind distance is exaggerated by a factor of 5 for the sake of clarity. Zone contamination limits differ by factors of 10.

The limiting exposure for Range C for a given isotope in Table 3 is obtained by dividing the microcurie intake for a 15-rem exposure by a respiration rate of 220 Ci sec^{-1}. This constitutes the lower limit for Range C. By dividing this exposure by the number of curies released, one obtains an exposure isopleth (Ci-sec m^{-3} Ci^{-1}), which is the outer boundary of Range C, and then determines the enclosed area from Fig. 1. Isopleths representing the outer boundaries of Ranges B and A and the enclosed areas are similarly obtained. Populations in the various zones are calculated using a uniform population of 3000 persons/sq mile, and the economic loss for exposure is calculated using the per capita costs of Table 1.

A sample calculation in which the economic consequences of the release of 7 Ci of Am-241 are estimated under inversion conditions is given below. The population density surrounding the facility is assumed to be 3000 persons/sq mile.

Range	Deposition or exposure isopleth	Area enclosed (from Fig. 4) m^2	Area enclosed (from Fig. 4) sq mile	Economic Loss ($ x 10^6)
I	2.9×10^{-7} m^{-2}	1.15×10^5	0.044	2.6
II	2.9×10^{-8} m^{-2}	2.0×10^6	0.73	6.6
III	2.9×10^{-9} m^{-2}	2.9×10^7	10.4	31.2
A	4.7×10^{-4} sec m^{-3}	6.0×10^4	0.023	6.9
B	4.7×10^{-5} sec m^{-3}	1.1×10^6	0.040	24.0
C	4.7×10^{-6} sec m^{-3}	1.7×10^7	6.14	73.7
				Total 145

Tables 4 and 5 show the amounts of radioactive materials whose release results in an estimated economic loss of $140 million. The last columns show the fractions of this cost associated with decontamination and exposure. It should be noted that the costs in Range III dominate the decontamination costs and those in Range C dominate the exposure costs. Hence the validity of the costs shown in these tables depends very much on the validity of the unit costs that are assumed for these ranges (i.e., $1000 per capita in Range III and $4000 per capita in Range C).

Table 4. Quantities of radioactive by-product materials causing a monetary loss of approximately $140 million if dispersed in the atmosphere under indicated meteorological conditions

(Conditions: 3000 persons/sq mile, ground-level release)

Isotope	Quantities causing a loss of $140 million				Source of costs	
	Under average conditions[a]		Under inversion conditions[b]		Decontamination	Exposure
	(g)	(Ci)	(g)	(Ci)	(%)	(%)
Co-60	40	45,000	13	15,000	46	54
Sr-90	3	450	1	160	94	6
Sb-124	6	110,000	2	35,000	39	61
I-131	0.03	3,500	0.01	1,400	94	6
Cs-137	60	5,200	22	1,900	95	5
Ce-144	9	28,000	3	9,900	43	57
Pm-147	251	233,000	87	81,000	22	78
Tm-170	20	123,000	7	41,000	33	67
Ir-192	14	130,000	5	42,000	45	55
Po-210	0.2	1,000	0.08	350	43	57
Pu-238	0.4	7	0.15	2.5	30	70
Am-241	6	20	2	7	28	72
Cm-242	0.2	600	0.07	220	45	55
Cm-244	0.4	30	0.14	11	31	69

[a]Slightly stable, 2-m sec^{-1} wind speed, 0.001-m sec^{-1} settling velocity.

[b]Moderately stable, 1-m sec^{-1} wind speed, 0.001-m sec^{-1} settling velocity.

Table 5. Quantities of special nuclear materials causing a monetary loss of approximately $140 million if dispersed in the atmosphere under indicated meteorological conditions

(Conditions: 500 persons/sq mile, ground-level release)

Special nuclear material	Quantities causing a loss of $140 million				Source of costs	
	Under average conditions[a]		Under inversion conditions[b]		Decontamination	Exposure
	(kg)	(Ci)	(kg)	(Ci)	(%)	(%)
U-233 (500 ppm of U-232)	51	1050	20	400	38	62
U-235 (1.3 wt % U-234)	30,000	2500	12,000	1000	47	53
Pu fuel[c]	0.24	400	0.09	150	24	76

[a] Slightly stable, 2-m sec^{-1} wind speed, 0.001-m sec^{-1} settling velocity.

[b] Moderately stable, 1-m sec^{-1} wind speed, 0.001-m sec^{-1} settling velocity.

[c] Isotopic composition of fresh fuel, wt %: Pu-238, 0.053; Pu-239, 86.5; Pu-240, 11.8; Pu-241, 1.4; Pu-242, 0.2. Source: RDT Standard E13-1T, FFTF Ceramic Grade Plutonium Dioxide (June 1971).

4.3 Accidental Release of Radioactivity from Spent Fuel in Pool Storage

An accident is postulated in which a tornado-generated missile penetrates the storage building and lands in the spent-fuel storage pool. Assuming that the missile entered the pool at an optimum angle, a total of 40 BWR assemblies and 27 PWR assemblies containing 20 metric ton (MT) of fuel could be impacted, releasing all the plenum gas in the assemblies to the pool.[12] The spent fuel is assumed to have been irradiated to 33,000 MWd/MT and cooled for 1 year. According to Regulatory Guide 1.25, the plenum gas is assumed to contain 30% of the noble gases and 10% of the iodine in the fuel element. The source term is developed as follows, assuming all the noble gases and 1% of the iodine in the plenum gas are released to the atmosphere:

Isotope	Ci/MT	Activity Released, Ci
Kr-85	8.96×10^{3}	5.4×10^{4}
I-129	3.39×10^{-2}	6.8×10^{-4}

The whole body and organ doses received at a distance of 300 m under inversion conditions from the above release would be <0.1 rem.[13] Areas of significant contamination (>5×10^{-7} Ci/m^2) would be contained within the assumed plant perimeter of 300 m. Economic loss to the public would be negligible.

4.3.1 Criticality accident

The following is taken from the draft GEIS on Handling and Storage of Spent Light Water Power Reactor Fuel.[14]

> Assuming the fuel storage design was adequate, a criticality accident in a spent fuel pool could conceivably approach the power levels (less than 1,000 Kw) of a "swimming pool" type of research reactor. As proven by the operation of such reactors for many years, conditions did not generate enough energy to disperse any radioactive materials to the atmosphere from under more than 12 feet of water.

Hence the release resulting from a criticality accident in a spent-fuel storage pool would not be sufficiently large to be of significance to this study.

4.4 Accidental Release of Radioactivity from Spent Fuel in Transit

An accident is postulated in which a railroad cask containing ten PWR fuel elements is ruptured, releasing coolant and radioactivity to the atmosphere. The fuel is assumed to have been irradiated to 33,000 MWd/MT and cooled for 160 days. It is conservatively assumed that all of the noble gases and iodine and 0.01% of the solids are released.[15,16] The significant activities released, as determined by ORIGEN,[17] are summarized in Table 6.

Basing decontamination costs on Pu-238 and calculating exposure costs for significant isotopes by the methodology of Section 4.2 (3000 persons/sq mile), the potential economic loss for the postulated accident could be about $60 million. However, considering that the accidental release would most likely occur in a rural area with a population density approximating the average population density of the eastern United States (~100 persons/sq mile), the potential economic loss resulting from contamination and personnel exposure would probably be much less. Exposures from 4.4×10^4 Ci of Kr-85 dispersed in the atmosphere would be negiglible except to people in the immediate vicinity at the time of the accident.

4.5 Criticality Accident with Fresh Uranium Fuel

A summary of the hazards from a nuclear accident involving fresh uranium fuel taken from the Convair report, Safety Analysis of Enriched Uranium Processing, is given below.[18]

> For nuclear accidents having magnitudes in the range considered, i.e., up to 10^{20} fissions* the direct radiation from the critical assembly could produce lethal doses on the plant site but not off the site, because plants usually have an exclusion radius of at least 100 meters. One AED** from direct radiation could be

*Comment: For the United States, the highest number of fissions from an actual criticality incident in a solution is estimated at 4×10^{19}; for solids in air, 5×10^{17}.[19]

**Comment: One AED (Acceptable Emergency Dose) as defined in ref. 18 is equal to 25 rem.

Table 6. Estimated quantities of radioactivity released from spent fuel in transportation accident

Isotope	Ci/MT	Activity released, Ci
Kr-85	9.29×10^{3}	4.4×10^{4}
Sr-90	7.67×10^{4}	3.6×10^{1}
I-129	3.39×10^{-2}	1.6×10^{-1}
I-131	1.12	5.3
Xe-131m	2.14	1.0×10^{1}
Cs-137	1.09×10^{5}	5.1×10^{1}
Pu-238	2.29×10^{3}	1.1
Pu-239	3.31×10^{2}	0.16
Am-241	2.11×10^{2}	0.10
Cm-244	1.96×10^{3}	0.9

received out to 300 meters. The radioactive cloud, on the other hand, could give a lethal gamma dose in a narrow band (approximately 50 meters at maximum width) out as far as 300 meters; thus, the general populace could be affected. One AED cloud exposure could extend out as far as 1800 meters.

The thyroid dose (maximum of the inhalation doses for this study) would be less serious than the external dose. The greatest distance at which 1-AED might occur would be about 700 meters.* Ground contamination to any significant degree would not extend beyond about 250 meters after the first several hours. After a few months the main contamination would be Sr-90, which would still extend to 250 meters. This would prohibit the use of this land for agricultural purposes unless further steps were taken to lower the activity level on the surface — such as removing the top layer of dirt, plowing under the top layer of dirt to some depth, diluting deposited material with calcium, or some combination of these.[18]

The above summary serves as the basis for the judgment that a criticality incident in a fuel fabrication plant using highly enriched uranium would not have sufficient economic consequences off-site to be of significance to this study. It is obvious from the size of the contaminated off-site areas and areas in which significant off-site exposures take place that the costs resulting from decontamination and exposure would be very much less than $140 million.

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APPENDIX

Table A.1 Industrial firms licensed by the Nuclear Regulatory Commission to possess significant quantities of radioactive by-product materials

Company and headquarters location	Plant location	Area population density (persons/sq mile)	Principal isotope possession limit(s)		
			Isotope	Form	Quantity (Ci)
Amersham/Searle Corp. Arlington Heights, IL	Arlington Heights, IL	4800	Am-241	any form	350
Kay-Ray, Inc. Arlington Heights, IL	Palatine, IL	4300	Am-241	sealed sources	20
Minnesota Mining and Manufacturing Co. St. Paul, MN	New Brighton, MN	3100	Sr-90	any form	3,000
			Cs-137	any form	6,000
			Po-210	any form	3,000
			Am-241	any form	1,000
New England Nuclear Corp. Boston, MA	Billerica, MA	1400	Sr-90	any form	500
			Am-241	any form	500
Nuclear Research Corp. Southampton, PA	Southampton, PA		Cs-137	sealed sources	1,500
			Am-241	sealed sources	14.4
Picker Corp. Cleveland, OH	Cleveland, OH	8900	Co-60	any form	150,000
			Cs-137	sealed sources	40,000
Technical Operations, Inc. Burlington, MA	Burlington, MA	00	any by-product material except H-3, Co-60, Su-90, Cs-137, Tm-170, Ta-182, Ir-192	sealed sources	21,200
			Co-60	solid metallic or sealed sources	10,000
			Cs-137	sealed sources	10,000

Table A.2 Industr al firms licensed by Agreement States to possess significant quantities of radioactive by-product materials

Company and headquarters location	Plant location	Area population density (persons/sq mile)	Principal isotope possession limit(s)		
			Isotope	Form	Quantity (Ci)
General Electric Company Vallecitos Nuclear Center Pleasanton, CA	Pleasanton, CA	2300	any by-product material	any form	1,000,000
			Co-60	any form	1,500,000
			Sb-124	any form	60,000
			Cs-137	any form	35,000
			Ce-141	any form	50,000
			Ce-144	any form	100,000
			Tm-170	any form	190,000
			Ir-192	any form	150,000
			Am-241	any form	200
			Cm-242	sealed sources	5,000
Union Carbide Corp. Sterling Forest Research Center Tuxedo, NY	Tuxedo, NY		any by-product material	irradiated metals, alloys, components	50,000
			Co-60	sealed sources	50,000
			Co-60	unsealed sources	10,000
			Sr-90	sealed sources	25,000
			Cs-137	sealed sources	50,000
			Ce-144	sealed sources	25,000
			Pm-147	sealed sources	25,000
Gamma Industries A Division of Nuclear Systems, Inc. Baton Rouge, LA	Baton Rouge, LA	6200	any by-product materials (except SNM)	any form	500 per unit, no limit
			any by-product material (except SNM)	sealed sources	8,000
			Co-60	sealed sources	15,000 per source, no limit
			Cs-137	sealed sources	5,000 per source, no limit

Table A.2 (continued)

Company and headquarters location	Plant location	Area population density (persons/sq mile)	Principal isotope possession limit(s)		
			Isotope	Form	Quantity (Ci)
Gamma Industries A Division of Nuclear Systems, Inc. Houston, TX	Houston, TX	2600	Am-241	any form	1,000
Gulf Nuclear, Inc. Houston, TX	Houston, TX	2600	Am-241	any form	200
Nuclear Sources and Services, Inc. Houston, TX	Houston, TX	2600	Am-241	any form	3,300
Neutron Products, Inc. Dickerson, MD	Dickerson, MD		Co-60	singly and doubly encapsulated sources	3,000,000
Pacific Northwest Laboratories A Division of Battelle Memorial Institute Richland, WA	Richland, WA	400[a]	any, atomic nos. 1 to 99, except source, SNM	any form	1,000,000
			total of all radionuclides	any form	10,000,000
United Nuclear Industries Richland, WA	Richland, WA	400[a]	any, atomic nos. 3 to 83, except source, SNM	any form	10,000,000
			total of all radionuclides	any form	20,000,000

[a] Most populous sector.

Table A.3 Average population densities around some major fuel fabrication facilities

Company	Possession limit, kg[a]	Average population density (people/sq. mile) Within 10-mile radius	Within 20-mile radius
Highly enriched uranium fuel fabricators			
Babcock and Wilcox Naval Nuclear Fuel Division Lynchburg, Virginia	20,000	230	100
Babcock and Wilcox Nuclear Materials Division Apollo, Pennsylvania	7,800	340	510
United Nuclear Corporation Naval Products Division Uncasville, Connecticut	12,000	300[b]	300[b]
Plutonium fuel fabricators			
Babcock and Wilcox Nuclear Materials Division Leechburg, Pennsylvania	2,000	470	570
Exxon Nuclear Corporation Mixed Oxide Fabrication Plant Richland, Washington	100	110	70
Westinghouse Electric Corporation Plutonium Fuel Development Laboratory Cheswick, Pennsylvania	395	1850	1400

[a] Uranium containing 97.3% U-235 and 1.3% U-234 or plutonium containing 86.5% Pu-239, 11.8% Pu-240, and 1.4% Pu-241.

[b] Average population density within a square containing 900 sq. miles surrounding the facility.

ADDENDUM

C. D. Scott* and W. Fulkerson**

ORNL has recently completed two studies[1,2] for the NRC which involved estimates of the cost of decontamination from releases of radioactivity. Each study was made independently of the other. Results are reported in this document and in ORNL/NUREG-46[†].[2] The cost estimates for decontamination differ considerably between the two reports, with costs in NUREG/CR-0222 being less than those appearing in ORNL/NUREG-46.

Although different methodologies and assumptions were used in obtaining these estimates, a major cause for the cost variances was the extreme difference between the cases considered. The costs of cleanup resulting from a hypothetical accidental airborne release of radioactivity from a radioisotope processing plant or fuel fabrication facility under average siting conditions are reported in NUREG/CR-0222. On the other hand, the costs discussed in ORNL/NUREG-46 represent a sort of worst case in which it is postulated that various radioisotopes are released into the air in a large metropolitan area by malevolent actions.

While NUREG/CR-0222 assesses possible accidental releases of radioactivity in terms of whether the economic consequences would exceed the upper limit of nuclear liability insurance available in the private sector (i.e., $140 million), ORNL/NUREG-46 ranks the various isotopes in terms of the potential economic loss associated with their malevolent releases. Even though the absolute cost numbers differ, both reports probably serve their intended purposes; however, neither is a definitive study on decontamination methods or costs. Some reasons for the differences in estimates of economic loss are discussed briefly below.

The assumptions used in the two studies differ in three main areas: (1) the deposition rate of radioactive aerosols and other meteorological

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†Under classification review.

considerations; (2) permissible contamination levels (PCLs) which determine the extent and degree of cleanup required; and (3) the unit area (or per capita) costs for accomplishing the necessary decontamination. In each of these areas, the assumptions used in ORNL/NUREG-46 resulted in higher estimated costs than those in NUREG/CR-0222.

Rate of Deposition and Meteorology - In both studies, atmospheric dispersion of radioisotope release was calculated using the Gaussian plume formulation;[3] however, time-dependent meteorologies were used in ORNL/NUREG-46. A deposition velocity of 1 cm/sec was used for ORNL/NUREG-46, whereas a value of 0.1 cm/sec was used for NUREG/CR-0222. These different approaches resulted in different areas of contamination, which in turn contributed to different decontamination costs.

Permissible Contamination Levels (PCL) - The maximum permissible air concentration levels for a nonrestricted area given in 10 CFR 20 and an assumed resuspension factor of 10^{-5} m^{-1} were used in NUREG/CR-0222 to set the contamination level for each isotope to which cleanup must be accomplished. An NRC guide[4] for allowable surface contamination levels of facilities and equipment was used in ORNL/NUREG-46. The latter is somewhat more restrictive.

Both studies used an allowable contamination level for ^{238}Pu that is as much as 30 to 100 times lower than other published cleanup levels.[5-8] However, with the exception of ^{238}Pu, the PCLs in ORNL/NUREG-46 are 10 to 100 times lower than those used in NUREG/CR-0222. This has resulted in larger decontamination areas and, thus, larger costs for ORNL/NUREG-46.

Unit Decontamination Costs - In NUREG/CR-0222 it was assumed that for areas of low-level contamination (in this study $\sim$ 90% of the costs are involved with these low-level areas), on-site disposal is possible and a variety of relatively inexpensive methods can be used (e.g., hosing down, shallow plowing, deep plowing, simple removal to nearby landfills, etc.). On the other hand, exterior decontamination costs in ORNL/NUREG-46 are based on the removal of the top layers of earth in the contaminated areas, and packaging and transporting the material to an authorized burial ground.

The per capita costs for interior decontamination used in ORNL/NUREG-46 were also significantly higher than those assumed in NUREG/CR-0222. In this regard, the unit decontamination cost used in ORNL/NUREG-46 probably represents a sort of worst case which might be prudent when considering a large metropolitan area. Lower unit costs would undoubtedly apply to a more rural setting, such as that assumed in NUREG/CR-0222.

Summary and Recommendations - The two reports, representing independent studies, have different objectives, take different approaches, and use different assumptions. Neither study is definitive because of uncertainties regarding key factors. Continued research and policy guidance are needed to better evaluate these factors. Some of the key questions are:

1. under various conditions and situations, what are acceptable contamination levels for each isotope;
2. to what extent are shallow plowing, deep plowing (i.e., burial in place), and simple earth removal to nearby landfill suitable for surface decontamination of areas with "low" levels of contamination;
3. what are realistic costs for various decontamination processes for both exterior and interior cleanup; and
4. how effective are various meteorological calculations for estimating the contamination resulting from radioactive releases (e.g., what are suitable deposition velocities for various particle sizes, particle composition, and for various terrains?).

The resolution of these and similar questions will allow the establishment of guidelines that could provide a common basis for estimating decontamination costs for various situations.

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This report examines the quantities of various radioactive materials whose release from fuel fabrication or radioisotope processing plants and dispersal in the environment could result in off-site decontamination and exposure costs approximating $140 million (i.e., the limit of nuclear liability insurance presently available from the private sector). The Gaussian plume dispersion model was used to express the spread of radioactivity downwind from its point of release and define areas of decreasing contamination and exposure levels. Unit costs within the defined areas were used in estimating the economic losses. Estimates were made of the radioactivity released from a postulated maximum accident in a spent fuel storage pool and an accident involving spent fuel in transit, and criticality incident involving fresh uranium fuel was also assessed in terms of the potential off-site economic loss.

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