DOCKET NO: A-93-02
V-B-25

TECHNICAL SUPPORT DOCUMENT FOR

SECTIONS 194.51, 194.52, AND 194.55: DOSE VERIFICATION EVALUATION

U. S. ENVIRONMENTAL PROTECTION AGENCY
Office of Radiation and Indoor Air
Center for the Waste Isolation Pilot Plant
401 M. Street, S. W.
Washington, DC 20460

MAY, 1998

Technical Support for this document was provided by TechLaw, Inc. and its subcontractors under EPA Contract 68D50174.

TABLE OF CONTENTS

LIST OF TABLES

Table No.		Page No.

1. INTRODUCTION

Conservative estimates of groundwater pathway doses were projected by the U.S. Department of Energy (DOE) for a person residing next to the Waste Isolation Pilot Plant (WIPP) as part of the WIPP Compliance Certification Application (CCA) (DOE, 1996; DOE, 1997). Additional dose projections were prepared for the Performance Assessment Verification Test (PAVT) mandated by the U.S. Environmental Protection Agency (EPA) (DOE, 1997b). This report discusses the independent calculations made to confirm the DOE dose modeling conducted for the CCA and PAVT. The doses reported for the groundwater pathway are verified, and doses for more extensive use of the contaminated groundwater are projected. Section 2 of this report discusses the methodology used in the verification procedure. Section 3 presents the results of the dose calculations.

2. DOSE VERIFICATION METHODOLOGY

The dose projections prepared for the CCA and the PAVT were based on the assumption that contaminated brine in the anhydrite beds would be forced up an abandoned borehole to the Culebra Formation or the Dewey Lake Redbeds. For the CCA, the receptor, or critical population group, was assumed to use water drawn from either of these formations for drinking water, crop irrigation, and watering animals. The dose projections conducted for the PAVT assumed water was used only as a supply of drinking water. In both cases, receptor doses were based on the assumption that present-day human activity and consumption patterns applied, despite the fact that any exposures would be delayed for thousands of years. Given the high total dissolved solids (TDS) in the water, about 324,000 parts per million (ppm), the brine was assumed to be diluted by a factor of 32.4 prior to its use so that the groundwater's TDS content would not exceed 10,000 ppm. The groundwater pathway doses projected for the CCA and PAVT were calculated using the GENII computer code.

The dose verification process assessed doses for the drinking water pathway and examined the potential impacts of more extensive use of groundwater. The approach used to project drinking water doses is discussed in Section 2.1. Section 2.2 describes the modeling approach used for the all-pathways analysis.

2.1 <u>DRINKING WATER PATHWAY ANALYSIS</u>

Exposures for the drinking water pathway analysis were modeled using a spreadsheet. As mentioned earlier, radionuclide concentrations in the water consumed by the individual were calculated assuming they would be reduced from their concentrations in the brine by a factor, D_f, of 32.4. This dilution is expressed as:

$$C_{w,i} = C_{b,i} / D_F$$

where

$C_{w,i}$ = concentration of radionuclide i in well water (Ci/m^3)

$C_{b,i}$ = brine concentration of radionuclide I (Ci/m^3)

D_f = brine dilution factor = 32.4

The radionuclide concentrations in the brine were taken directly from the groundwater modeling results reported in the CCA and PAVT; these concentrations are summarized in Table 2-1

Table 2-1. Radionuclide concentrations in the Salado Interbeds at the disposal system boundary.[a]

	Maximum Concentration (Ci/L)			
Groundwater Realization No.	**Am-241**	**Pu-239**	**U-234**	**Th-230**
CCA Realizations				
1	1.4E-17	4.3E-12	5.8E-13	2.1E-14
2	---[b]	5.1E-14	6.8E-15	1.9E-17
3	---[b]	1.4E-15	1.7E-16	7.0E-18
4	1.3E-17	7.2E-14	9.8E-15	9.4E-16
5	---[b]	6.2E-18	---[b]	---[b]
6	---[b]	5.2E-16	7.4E-17	---[b]
7	3.5E-18	3.1E-13	4.3E-14	1.1E-16
8	6.0E-17	7.4E-14	9.1E-15	2.3E-15
9	5.4E-17	5.9E-12	7.6E-13	4.7E-15
PAVT Realizations				
1	---[b]	5.96E-17	---[b]	---[b]
2	1.04E-15	3.75E-13	3.21E-14	4.09E-15
3	---[b]	3.21E-16	2.41E-18	---[b]
4	---[b]	1.61E-18	---[b]	---[b]
5	---[b]	5.23E-18	1.73E-18	---[b]
6	---[b]	9.29E-18	---[b]	---[b]
7	---[b]	9.90E-16	---[b]	---[b]
8	7.65E-17	1.61E-13	1.36E-14	7.81E-16

Groundwater Realization No.	Maximum Concentration (Ci/L) Am-241	Pu-239	U-234	Th-230
9	---[b]	3.40E-16	4.14E-17	3.35E-18
10	---[b]	7.66E-18	---[b]	---[b]
11	---[b]	9.64E-16	1.16E-17	---[b]
12	---[b]	9.21E-16	---[b]	---[b]
13	2.51E-18	2.61E-15	2.61E-18	5.82E-18
14	---[b]	4.07E-18	---[b]	---[b]
15	9.37E-18	4.72E-14	7.07E-16	6.78E-17

a.Source: DOE, 1996.
b.Maximum concentration was less than $1x10^{-18}$ Ci/L.

Given the radionuclide concentrations in the water drawn from the well, the potential doses to the receptor were calculated. This dose is proportional to the amount of radioactivity ingested, which was calculated by multiplying the radionuclide concentrations in the water, $C_{w,i}$, by the water consumption rate, U. The annual intake of a given radionuclide multiplied by the ingestion dose conversion factor, DCF_{ing}, yields the dose for that radionuclide. The total dose was calculated by summing over all radionuclides present in the water. This calculation is expressed mathematically as:

$$D_{dw} = \sum_{i=1}^{n} C_{w,i} \, U \, DCF_{ing,i}$$

where

D_{dw}	=	projected dose for the drinking water pathway analysis (mrem/year)
i	=	radionuclide index
n	=	total number of radionuclides in the groundwater
U	=	consumption rate of drinking water (m^3/yr)
$DCF_{ing,i}$	=	ingestion dose conversion factor for radionuclide I (mrem/yr per Ci/yr)

For this calculation, the consumption rate was set equal to 0.73 m^3/yr, which is equivalent to the 2-L/day consumption requirement in 40 CFR 194.52 (EPA, 1996).

All of the radionuclides listed in Table 2-1 undergo radioactive decay, which ultimately produces several radioactive decay products, or daughters. The activities of these daughters will increase over extended periods and may result in doses greater than those from consuming the parent radionuclides alone. Consequently, drinking water doses were projected for two cases. In the first case, no daughter ingrowth was assumed to occur. Hence, the projected doses were due entirely to consumption of the radionuclides included in Table 2-1. In the second case, radioactive decay and ingrowth were assumed to occur over a 10,000-year period, before consumption of the radionuclides. This period of ingrowth is consistent with the fact that the radionuclide concentrations listed in Table 2-1 were projected to occur at the end of the 10,000-year compliance period. The projected concentrations of daughter radionuclides in the brine were based on the assumption that all decay products would be transported at the same rate as their parent radionuclides. This assumption separated the time dependence of the problem from the problem's space dependence so that the activities of the decay products could be calculated using the simple, time-dependent Bateman equations. To conduct this calculation, parent activities corresponding to the beginning of the 10,000-year ingrowth period were needed. These activities were estimated by using the radioactive decay equation to determine the radionuclide concentrations at year zero that would give the concentrations listed in Table 2-1 at year 10,000.

The final parameter in Equation (2-2) is the ingestion dose conversion factor. The dose conversion factors used in the dose calculations were 50-year whole body committed effective dose equivalent factors taken from EPA Federal Guidance Report No. 11 (EPA, 1988a). These dose conversion factors are listed in Table 2-2 for all radionuclides included in the dose verification, including decay products.

Table 2-2. Radionuclide dose conversion factors.[a]

Radionuclide	Ingestion (mrem/µCi)	Inhalation (mrem/µCi)	Air Immersion (mrem/yr/µCi/m^3)	Soil Gamma (mrem/yr/µCi/m^3)
Th-230	5.5E+02	3.3E+05	2.0E+00	7.5E-04
Ra-226	1.3E+03	8.6E+03	3.7E+01	1.9E-02
Rn-222	---[b]	---[b]	2.2E+00	1.3E-03
Po-218	---[b]	---[b]	5.2E-02	3.1E-05
Pb-214	6.3E-01	7.8E+00	1.4E+03	7.8E-01
Bi-214	2.8E-01	6.6E+00	8.9E+03	5.1E+00
Po-214	---[b]	---[b]	4.8E-01	2.8E-04
Pb-210	5.4E+03	1.4E+04	6.6E+00	1.5E-03
Bi-210	6.4E+00	2.0E+02	3.8E+00	2.2E-03
Po-210	1.9E+03	9.4E+03	4.9E-02	2.9E-05
U-234	2.8E+02	1.3E+05	8.9E-01	2.5E-04
Th-230	5.5E+02	3.3E+05	2.0E+00	7.5E-04
Ra-226	1.3E+03	8.6E+03	3.7E+01	1.9E-02
Rn-222	---[b]	---[b]	2.2E+00	1.3E-03
Po-218	---[b]	---[b]	5.2E-02	3.1E-05
Pb-214	6.3E-01	7.8E+00	1.4E+03	7.8E-01
Bi-214	2.8E-01	6.6E+00	8.9E+03	5.1E+00
Po-214	---[b]	---[b]	4.8E-01	2.8E-04
Pb-210	5.4E+03	1.4E+04	6.6E+00	1.5E-03
Bi-210	6.4E+00	2.0E+02	3.8E+00	2.2E-03
Po-210	1.9E+03	9.4E+03	4.9E-02	2.9E-05
Pu-239	3.5E+03	4.3E+05	4.9E-01	1.8E-04
U-235	2.7E+02	1.2E+05	8.4E+02	4.4E-01
Th-231	1.4E+00	8.8E-01	6.1E+01	2.3E-02
Pa-231	1.1E+04	1.3E+06	2.0E+02	1.1E-01
Ac-227	1.4E+04	6.7E+06	6.8E-01	3.1E-04
Th-227	3.8E+01	1.6E+04	5.7E+02	3.1E-01

Table 2-2. Continued.

Radionuclide	Ingestion (mrem/µCi)	Inhalation (mrem/µCi)	Air Immersion (mrem/yr/µCi/m^3)	Soil Gamma (mrem/yr/µCi/m^3)
Fr-223	8.6E+00	6.2E+00	2.7E+02	1.2E-01
Ra-223	6.6E+02	7.8E+03	7.1E+02	3.6E-01
Rn-219	---[b]	---[b]	3.1E+02	1.8E-01
Po-215	---[b]	---[b]	9.8E-01	5.8E-04
Pb-211	5.3E-01	8.7E+00	2.9E+02	1.7E-01
Bi-211	---[b]	---[b]	2.6E+02	1.5E-01
Po-211	---[b]	---[b]	4.4E+01	2.6E-02
Tl-207	---[b]	---[b]	1.9E+01	1.1E-02
Am-241	3.6E+03	4.4E+05	9.5E+01	2.7E-02
Np-237	4.4E+03	5.4E+05	1.2E+02	4.9E-02
Pa-233	3.6E+00	9.6E+00	1.1E+03	6.0E-01
U-233	2.9E+02	1.4E+05	1.9E+00	8.4E-04
Th-229	3.5E+03	2.2E+06	4.5E+02	2.0E-01
Ra-225	3.8E+02	7.8E+03	3.3E+01	6.9E-03
Ac-225	1.1E+02	1.1E+04	8.4E+01	3.9E-02
Fr-221	---[b]	---[b]	1.7E+02	9.2E-02
At-217	---[b]	---[b]	1.7E+00	1.0E-03
Bi-213	7.2E-01	1.7E+01	7.5E+02	4.4E-01
Po-213	---[b]	---[b]	0.0E+00	0.0E+00
Tl-209	---[b]	---[b]	1.2E+04	6.7E+00
Pb-209	2.1E-01	9.5E-02	9.5E-01	4.8E-04

a.Sources: EPA, 1988a, pages 121-153, 155-179; EPA, 1993b, pages 58-73, 148-163.
b.No dose conversion factor was provided.

2.2 <u>ALL-PATHWAYS ANALYSIS</u>

The initial dose analysis that DOE conducted for the CCA assumed the receptor would use water drawn from the Culebra Formation or the Dewey Lake Redbeds only for direct consumption (DOE, 1996, page 8-4). Subsequent analyses examined additional potential doses from ingesting crops irrigated with contaminated groundwater, inhaling resuspended soils contaminated during irrigation, and ingesting meat taken from animals raised on contaminated feed and water (DOE, 1997a, page 4). The dose assessment conducted for the PAVT was similar to the original CCA modeling insofar as it assumed that water was only used for direct consumption (DOE, 1997b).

The potential consequences of more extensive use of the water were investigated as part of the independent dose verification process. Specifically, the water drawn from the well was assumed to be used to spray-irrigate forage and food crops (i.e., leafy vegetables and produce) grown by the resident. The forage crops were assumed to be fed to cattle and cows raised by the resident to supply meat and milk. The exposure routes considered in this analysis included:

- Ingestion of contaminated vegetables and produce raised by the individual.
- Ingestion of meat and milk taken from animals raised by the individual.
- Ingestion of water drawn from the well.
- Inhalation of resuspended soils contaminated during irrigation.
- Direct radiation from airborne radioactivity.
- Direct radiation from contaminated surface soils.

Doses for the all-pathways analysis were projected using a spreadsheet. The models used in these calculations are described below. The models used to project radionuclide concentrations in the environmental media used or contacted by the individual are discussed in Section 2.2.1. The equations used to project contaminant intakes and doses are discussed in Section 2.2.2.

2.2.1 Environmental Transport Modeling

The all-pathways dose projections require calculations of the radionuclide concentrations in groundwater, surface soils, crops and animal products consumed by the individual, and air above the resident's lot. All of these concentrations depend upon the contaminant concentrations in the groundwater, which were based on the groundwater modeling results reported in the CCA and PAVT. The models used to project radionuclide concentrations in the other environmental media are discussed below.

Radioactivity in the water used to spray-irrigate the resident's crops will be deposited not only on the crops, but also on the cultivated surface soil. The receptor can receive doses from this contaminated soil through both direct, inadvertent consumption of the soil and consumption of vegetation that has assimilated radionuclides in the soil through its roots. Hence, estimates of food chain doses for the individual must account for radionuclide concentrations in surface soils.

The amount of radioactivity that is deposited on the surface soils annually as a result of irrigation was obtained by multiplying the irrigation rate, I_r, by the radionuclide concentration in the water, $C_{w,i}$, and then multiplying that product by the number of hours in a year that the crops are irrigated, 8,760 f_r. Although the contaminated irrigation water will fall on both the crops and soil, this approach conservatively assumes that all radionuclides in the irrigation water will be deposited on the surface soil. This calculation is given mathematically as:

$$Q_{s,i} = C_{w,i}\, I_r\, 8{,}760\, f_r$$

where

$Q_{s,i}$	=	rate of application of radionuclide i to soil (Ci/m^2-yr)
I_r	=	irrigation rate (m^3/m^2-hr)
8,760	=	hours-per-year conversion factor
f_r	=	fraction of the year crops are irrigated

The input values used for the irrigation rate and the fraction of the year crops are irrigated are summarized in Table 2-3. These values were based on data developed by the EPA for a generic disposal setting in the southwestern U.S. (EPA, 1988b).

Table 2-3. Pathway parameters used in the all-pathways dose analysis.

Parameter	Units	Variable Name Used in Text	Value	Source
Bulk density of soil	kg/m^3	ρ_s	1.6E+03	EPA, 1988b
Soil contamination buildup period	yr	t_b	3.0E+01	EPA, 1989, page 5-34
Soil mixing depth	m	d	1.5E-01	NRC, 1977, page 1.109-68
Average dust loading at site	kg/m^3	m_{at}	1.0E-07	Assumed - see text
Human consumption rate:				
Leafy vegetables	kg/yr	U	1.7E+01	EPA, 1988b
Produce	kg/yr	U	9.4E+01	EPA, 1988b
Meat	kg/yr	U	6.2E+01	EPA, 1988b
Milk	L/yr	U	1.2E+02	EPA, 1988b
Water	L/yr	U	7.3E+02	EPA, 1996
Soil	kg/yr	U	3.7E-02	EPA, 1989
Fraction of food eaten which is grown on site	---	F_j	5.0E-01	EPA, 1988b
Vegetation weathering removal constant	hr^{-1}	λ_w	2.1E-03	EPA, 1988b
Plant retention factor	---	R_w	2.5E-01	EPA, 1988b
Vegetation translocation factor:				
Pasture grass	---	T_v	1.0E+00	NCRP, 1984, page 61
Leafy vegetables	---	T_v	1.0E+00	NCRP, 1984, page 61
Grain/produce	---	T_v	1.0E-01	Ng et al., 1978, pages 18-28
Delay time between harvest/slaughter and consumption:				
Pasture grass	hr	t_h	0.0E+00	EPA, 1988b
Stored feed	hr	t_h	2.2E+03	EPA, 1988b
Leafy vegetables	hr	t_h	2.4E+01	EPA, 1988b

Parameter	Units	Variable Name Used in Text	Value	Source
Grain/produce	hr		1.4E+03	EPA, 1988b
Meat	hr	t_s	4.8E+02	EPA, 1988b
Agricultural productivity:				
Pasture grass	kg/m^2	Y_v	4.0E-02	EPA, 1988b
Leafy vegetables	kg/m^2	Y_v	7.6E-01	EPA, 1988b
Grain/produce	kg/m^2	Y_v	7.6E-01	EPA, 1988b
Dry:wet weight fraction:				
Pasture grass	---	D_v	2.4E-01	Nelson, 1985, pages 1-2
Stored feed	---	D_v	6.8E-01	Nelson, 1985, pages 1-2
Leafy vegetables	---	D_v	6.6E-02	Nelson, 1985, pages 1-2
Grain/produce	---	D_v	1.9E-01	Nelson, 1985, pages 1-2
Irrigation rate	m^3/m^2-hr	I_r	1.1E-04	EPA, 1988b
Fraction of year crops are irrigated	---	f_r	6.5E-01	EPA, 1988b
Growing season:				
Pasture grass	hr	t_g	7.2E+02	EPA, 1988b
Leafy vegetables	hr	t_g	1.4E+03	EPA, 1988b
Grain/produce	hr	t_g	1.4E+03	EPA, 1988b
Animal consumption rate:				
Cattle - water	L/d	Q_{wc}	5.0E+01	EPA, 1988b
Cattle/milk cow - feed	kg/d	Q_f	5.0E+01	EPA, 1988b
Milk cow - water	L/d	Q_{wm}	6.0E+01	EPA, 1988b
Fraction of stored feed that is:				
Pasture grass or hay	---	S_p	6.2E-01	Nelson, 1985, page 2

Parameter	Units	Variable Name Used in Text	Value	Source
Grain	---	S_g	3.8E-01	Nelson, 1985, page 2
Fraction of year animals graze on pasture grass	---	F_p	4.7E-01	EPA, 1988b
Fraction of feed that is pasture grass	---	F_s	1.0E+00	EPA, 1988b
Transport time from animal feed to milk	hr	t_m	4.8E+01	EPA, 1988b
Adult breathing rate	m^3/yr	U_a	7.3E+03	EPA, 1989, page 3-6
Resident time allotment:				
Outside of house	hr/yr	T_o	1.6E+02	EPA, 1989, page 5-30
Inside house	hr/yr	T_i	6.0E+03	EPA, 1989, page 5-30
Total time spent at home	hr/yr	T_t	6.1E+03	EPA, 1989, page 5-30
House shielding factor for direct radiation	---	S_f	7.0E-01	NRC, 1977, page 1.109-68

To account for root uptake of radioactivity in the soil, radionuclide concentrations in surface soil were estimated by assuming that the plant root zone would be equal to the plow depth, d. Then, if $Q_{s,i}$ Ci/m^2 per year is deposited on the soil, $Q_{s,i}$/d would be the radionuclide concentration in surface soil from one year's deposition by irrigation, not accounting for radioactive decay and depletion due to leaching. Dividing this concentration by the soil density, ρ_s, gives the annual radionuclide concentration in surface soil in terms of Ci/kg. This calculation is represented as:

$$C_{1,i} = Q_{s,i} / d\, \rho_s$$

where

$C_{1,i}$ = soil concentration of radionuclide i from one year's deposition, ignoring leaching and radioactive decay (Ci/kg-yr)

d = plow depth (m)

ρ_s = bulk density of surface soil (kg/m^3)

Radioactivity in surface soils will accumulate, or build up, as irrigation water is applied in succeeding years. As indicated above, this build up will be counteracted as radionuclides undergo radioactive decay and as water percolating through the site leaches radioactivity from the soil and transports it to greater depths. The modeling conducted for the dose verification conservatively ignored the leaching depletion mechanism; further, since the parents of all radionuclide chains have half-lives significantly longer than the buildup period, it is assumed that radioactivity would build up linearly over the period of time the resident spends at the site. Based on these assumptions, radionuclide concentrations in the soil are calculated using:

$$C_{s,i} = C_{l,i}\, B_f$$

where

$C_{s,i}$ = concentration of radionuclide is in soil (Ci/kg)

B_f = buildup period (yr)

As mentioned earlier, vegetation may become contaminated when radioactivity in water used for spray irrigation is deposited on the plants, and as a result of root uptake of radionuclides in the soil. Radionuclide concentrations in forage and food crops due to the direct deposition of radioactivity during irrigation were calculated using:

$$C_{vd,i} = C_{w,i}\, I_r\, R_w\, (1 - e^{-\lambda_w t_g})\, T_v / (Y_v\, \lambda_w)$$

where

$C_{vd,i}$ = concentration of radionuclide i in vegetation due to deposition (Ci/kg)

R_w = vegetation retention factor

λ_w = weathering removal coefficient (hr^{-1})

t_g = growing season (hr^{-1})

T_v = vegetation translocation factor

Y_v = crop agricultural yield (kg/m^2 (wet weight))

This formulation is commonly used to derive plant contaminant concentrations due to deposition (e.g., EPA, 1987b, page 2-37, and NCRP, 1984, page 60). Radionuclide concentrations in the crops are proportional to the amount of contamination that is applied to the surface of the plants during irrigation, $C_{w,i}\, I_r\, t_g$. This surface concentration times the fraction of the radioactivity initially retained by the plant, R_w, and the fraction of the contamination not lost by weathering, $(1 - e^{\lambda_w t_g}) / (\lambda_w t_g)$, equals the final plant surface concentration. Multiplying this concentration by the fraction of the retained activity that is assimilated into plant tissues, T_v, and dividing by the agricultural yield, Y_v, equals the radionuclide concentration in the plant tissue.

Concentrations of radionuclides in forage and food crops resulting from root uptake of radioactivity in the soil were estimated using:

$$C_{vr,i} = C_{s,i} \, B_{v,i} \, D_v$$

where

$C_{vr,i}$	=	concentration of radionuclide i in vegetation due to root uptake (Ci/kg)
$B_{v,i}$	=	plant concentration factor (Ci/kg dry weight vegetation per Ci/kg dry weight soil) for radionuclide i
D_v	=	dry-to-wet weight ratio for vegetation

Here, then, plant concentrations are directly proportional to the ability of the crop to concentrate radioactivity from the soil.

The concentrations calculated using Equations (2-6) and (2-7) were added together and corrected for decay to estimate total radionuclide concentrations in pasture grass, leafy vegetables, produce, and stored grain at the time of consumption using:

$$C_{v,i} = (C_{vd,i} + C_{vr,i}) \, e^{-\lambda_i t_h}$$

where

$C_{v,i}$	=	concentration of radionuclide i in vegetation (Ci/kg)
t_h	=	time interval between harvest of crop and consumption (hr)

These final concentrations account for crop-specific differences in the translocation factors, plant concentration factors, dry-to-wet weight ratios, and holdup times between harvest and consumption.

The pathway parameter values used to estimate radionuclide concentrations in vegetation are listed in Table 2-3. The retention factor, weathering removal coefficient, crop growing seasons and agricultural yields, and holdup times are based on the southwestern U.S. data set used by the EPA for the development of regulatory guidance on the disposal of low-level radioactive waste (EPA, 1988b). The sources of the remaining parameter values are provided in the table. The plant uptake factors used in Equation (2-7) were adopted from Baes et al. (1984, pages 10, 11, 50, 51) and are listed in Table 2-4. Plant uptake factors for short-lived daughters were assumed to be the same as those for their long-lived parents.

Table 2-4. Radionuclide-specific parameters used in the all-pathways dose analysis.[a]

	Plant Uptake Factors		Animal Transfer Factors	
Radionuclide	**Pasture Grass and Leafy Vegetables**	**All Other Crops**	**Forage-to-Meat (d/kg)**	**Forage-to-Milk (d/L)**
Ac-227	3.5E-03	3.5E-04	2.5E-05	2.0E-05
Am-241	5.5E-03	2.5E-04	3.5E-06	4.0E-07
Np-237	1.0E-01	1.0E-02	5.5E-05	5.0E-06
Pa-231	2.5E-03	2.5E-04	1.0E-05	5.0E-06
Pb-210	4.5E-02	9.0E-03	3.0E-04	2.5E-04
Pu-239	4.5E-04	4.5E-05	5.0E-07	1.0E-07
Ra-226	1.5E-02	1.5E-03	2.5E-04	4.5E-04
Th-229	8.5E-04	8.5E-05	6.0E-06	5.0E-06
Th-230	8.5E-04	8.5E-05	6.0E-06	5.0E-06
U-233	8.5E-03	4.0E-03	2.0E-04	8.0E-04
U-234	8.5E-03	4.0E-03	2.0E-04	8.0E-04
U-235	8.5E-03	4.0E-03	2.0E-04	8.0E-04

a.Source: Baes et al., 1984, pages 10, 11, 50, 51.

The animals raised by the resident were assumed to eat pasture grass and stored feed. The stored feed was assumed to consist of pasture grass (i.e., hay) and grain. Projections of radionuclide concentrations in the stored feed were calculated with Equations (2-7), (2-8), and (2-9), taking into account the relative contributions of hay and grain using:

$$C_{sf,i} = (C_{w,i}\, I_r\, R_w\, (1 - e^{-\lambda_w t_g})\, T_{sf} / (Y_{sf}\, \lambda_w) + C_{s,i}\, B_{sf,i}\, D_{sf})\, e^{-\lambda_i t_{sf}}$$

where

$C_{sf,i}$	=	concentration of radionuclide i in stored feed (Ci/kg)
T_{sf}	=	equivalent translocation factor for stored feed
Y_{sf}	=	equivalent agricultural yield for stored feed (kg/m^2)
$B_{sf,i}$	=	equivalent concentration factor (Ci/kg dry weight vegetation per Ci/kg dry weight soil) for radionuclide i in stored feed
D_{sf}	=	dry-to-wet weight ratio for storage feed
t_{sf}	=	interval between harvest of forage crops and consumption of storage feed (hr)

The form of this equation is identical to that indicated by Equations (2-6) through (2-8), except that some of the parameters are averaged over both hay and grain parameters. This is due to the fact that the earlier equations pertain to single food or forage crops, while Equation (2-9) is specific to stored feed (i.e., a combination of hay and grain). The equivalent translocation factors, agricultural yields, and concentration factors used in Equation (2-9) were calculated by weighting the respective factors for pasture grass and grain by their contribution to the stored feed. The equivalent translocation factor was calculated as:

$$T_{sf} = S_p\, T_p + S_g\, T_g$$

where

S_p	=	fraction of stored feed that is pasture grass or hay
T_p	=	translocation factor for pasture grass
S_g	=	fraction of stored feed that is grain
T_g	=	translocation factor for grain

Similarly, the equivalent agricultural yield was estimated using:

$$Y_{sf} = S_p\, Y_p + S_g\, Y_g$$

where

Y_p	=	agricultural yield for pasture grass (kg/m^2)
Y_g	=	agricultural yield for grain (kg/m^2)

Finally, the equivalent plant concentration factors were given by

$$B_{sf,i} = S_p\, B_{p,i} + S_g\, B_{g,i}$$

where

$B_{p,i}$	=	pasture grass concentration factor (Ci/kg dry weight vegetation per Ci/kg dry weight soil) for radionuclide i
$B_{g,i}$	=	grain concentration factor (Ci/kg dry weight vegetation per Ci/kg dry weight soil) for radionuclide i

Since animals eat both pasture grass and stored feed during an entire year, the radionuclide concentrations projected separately for pasture grass and stored feed were combined to arrive at annual average concentrations in the total feed of the animals. These concentrations were given by:

$$C_{f,i} = F_p\, F_s\, C_{p,i} + (1 - F_p\, F_s)\, C_{sf,i}$$

where

$C_{f,i}$	=	concentration of radionuclide i in animal feed (Ci/kg)
F_p	=	fraction of year that animals graze on pasture grass
F_s	=	fraction of daily feed that is pasture grass when the animals graze
$C_{p,i}$	=	concentration of radionuclide i in pasture grass (Ci/kg)

The pathway parameters used in Equations (2-9) through (2-13) were adopted from the EPA's data set for a generic southwestern U.S. disposal site (EPA, 1988b), and are listed in Table 2-3.

Radioactivity ingested by animals consuming contaminated water and forage may result in the contamination of animal products such as meat and milk. Contaminant concentrations in meat at the time of consumption were calculated using:

$$C_{mt,i} = F_{mt,i}\, (C_{f,i}\, Q_f + C_{w,i}\, Q_{wc})\, e^{-\lambda_i t_s}$$

where

$C_{mt,i}$	=	concentration of radionuclide i in meat (Ci/kg)
$F_{mt,i}$	=	forage-to-meat transfer factor for radionuclide i (d/kg)
Q_f	=	consumption rate of forage by cattle and cows (kg/d)

Q_{wc} = consumption rate of water by cattle (kg/d)

t_s = length of time from animal consumption of forage and water to human consumption of the meat (yr)

The first term in the parentheses represents the intake of radioactivity from eating contaminated feed, while the second term represents the intake from drinking contaminated water. The combined intake is multiplied by the forage-to-meat transfer factor, which relates the concentrations of radionuclides in the meat to the daily intake of the radionuclides. The portion of the contamination that is not assimilated by the animal is excreted. The exponential term accounts for radioactive decay between the time the animal consumes the radioactivity and the time a person ingests the meat.

Radionuclide concentrations in milk at the time of human consumption were calculated in a manner similar to that for meat, except the forage-to-meat transfer factor, $F_{mt,i}$ was replaced with the forage-to-milk transfer factor, $F_{mk,i}$:

$$C_{mk,i} = F_{mk,i} \, (C_{f,i} \, Q_f + C_{w,i} \, Q_{wm}) \, e^{-\lambda_i t_m}$$

where

$C_{mk,i}$ = concentration of radionuclide i in milk (Ci/kg)

$F_{mk,i}$ = forage-to-milk transfer factor for radionuclide i (d/kg)

Q_{wm} = consumption rate of water by cows (kg/d)

t_m = length of time from animal consumption of forage and water to human consumption of the milk (yr)

The forage and water consumption rates of cattle and cows were adopted from the EPA data set for the generic southwestern U.S. disposal setting (EPA, 1988b). These data are included in Table 2-3. The transfer factors for meat and milk were taken from Baes et al. (1984, pages 10, 11, 50, 51), and are listed in Table 2-4. Transfer factors for short-lived daughters were assumed to be the same as those for their long-lived parents.

Resuspension of radioactivity in surface soils may contaminate the air in the vicinity of the resident's home. Concentrations of radionuclides in the air were estimated using an average mass or dust loading factor and assuming that all the dust in the air would be from the contaminated soil:

$$C_{a,i} = C_{s,i}\, m_{at}$$

where

$C_{a,i}$	=	concentration of radionuclide i in air (Ci/m^3)
m_{at}	=	average mass loading factor (kg/m^3)

Calculated air concentrations were based on an average mass loading of $1x10^{-7}$ kg/m^3. This value is a conservative approximation of the average background dust loading of $4x10^{-8}$ kg/m^3 cited by Anspaugh et al. (1975, page 579) for nonurban areas in the U.S. This model implicitly assumes that all resuspended soils are respirable.

2.2.2 Human Exposures and Dose Projections

The receptor for the all-pathways analysis was postulated to come into contact with radioactivity and receive doses through the ingestion, inhalation, and direct radiation exposure routes. The doses for the ingestion and inhalation exposure routes are a function of radionuclide intakes and the radionuclide dose conversion factors.

Ingestion doses are proportional to the amount of radioactivity ingested, which is calculated by multiplying the radionuclide concentrations in the food, soil, or water by the annual consumption rate of each item, U_jF_j. The product of the annual intake of a given radionuclide in food, soil, or water and the ingestion dose conversion factor, DCF_{ing}, yields the dose for that radionuclide and material. Summing over all the radionuclides and ingested materials provides an estimate of the total ingestion dose. This calculation is expressed mathematically as:

$$D_{ing} = \sum_{j=1}^{m} \sum_{i=1}^{n} U_j\, F_j\, C_{j,i}\, DCF_{ing,i}$$

where

D_{ing}	=	whole body effective dose equivalent from ingestion (mrem/yr)
j	=	index for ingested material (i.e., soil, leafy vegetables, produce, milk, meat, or water)
m	=	total number of contaminated substrates ingested
U_j	=	consumption rate of soil, food, or water (kg/yr)

F_j = fraction of consumed material that is contaminated

$C_{j,i}$ = concentration of radionuclide i in contaminated material (Ci/kg)

$DCF_{ing,i}$ = ingestion dose conversion factor for radionuclide I (mrem/yr per Ci/yr)

The product of U_j, F_j, and $C_{j,i}$ yields the radionuclide intakes for each substrate ingested by the resident. These intakes were multiplied by the dose conversion factors to estimate the doses received by the individual.

The soil, food, and water consumption rates used in Equation (2-17) are included in Table 2-3. The dose conversion factors used in the dose assessment are 50-year whole body committed effective dose equivalent factors. These factors, listed in Table 2-2, were taken from Federal Guidance Report No. 11 (EPA, 1988a, pages 155-179).

The intake of radioactivity from breathing contaminated air was estimated by multiplying the air concentrations, $C_{a,i}$, by the amount of contaminated air the resident inhales in a year, $U_a T_t$ / 8,760. The intake calculated for each radionuclide was then multiplied by the inhalation dose conversion factor, $DCF_{inh,i}$, to estimate the dose for that contaminant. Summing over all of the radionuclides present in the air yields the total inhalation dose. This calculation is given as:

$$D_{inh} = \sum_{i=1}^{n} U_a \, T_t \, C_{a,i} \, DCF_{inh,i} \, / \, 8{,}760$$

where

D_{inh} = whole body effective dose equivalent from inhalation (mrem/yr)

U_a = inhalation rate (m^3/yr)

T_t = total time spent by individual at home (hr/yr)

$DCF_{inh,i}$ = inhalation dose conversion factor for radionuclide I (mrem/yr per Ci/yr)

The exposure time, T_t, was set equal to 6,140 hr/yr (i.e., 5,980 hr/yr inside and 160 hr/yr in the yard), based on information provided by the EPA (1989, page 5-30). The inhalation rate was assumed to be constant over the entire period, so that the resident would breathe 5.1E+03 m^3 of contaminated air annually. The dose conversion factors relate the intake of radioactivity to radionuclide-specific doses received by the resident; these doses were summed over all radionuclides to estimate the total inhalation dose. The 50-year committed inhalation dose equivalent factors used in Equation (2-18), included in Table 2-2, also are based on Federal Guidance Report No. 11 (EPA, 1988a, pages 121-153, 155-179).

The resident may receive direct exposures from airborne radioactivity and contaminated soils. Direct exposures from immersion in airborne radioactivity were estimated by multiplying the air immersion dose conversion factor, $DCF_{air,i}$, by the radionuclide concentration in air, $C_{a,i}$, and the fraction of the year spent immersed in the contamination, $(T_i S_f + T_o) / 8{,}760$. The exposure indoors was assumed to reduced by shielding provided by the dwelling, given as a dimensionless fraction, S_f:

$$D_{ea} = \sum_{i=1}^{n} C_{a,i}\, DCF_{air,i}\, (T_i\, S_f + T_o) / 8{,}760$$

where

D_{ea}	=	whole body effective dose equivalent from air immersion (mrem/yr)
$DCF_{air,i}$	=	air immersion dose conversion factor for radionuclide I (mrem/yr per Ci/m^3)
T_i	=	time individual spends inside house (hr/yr)
S_f	=	shielding factor
T_o	=	time individual spends in yard (hr/yr)

Similarly, direct exposures from contaminated soils were estimated using the following equation:

$$D_{es} = \sum_{i=1}^{n} C_{s,i}\, DCF_{s,i}\, (T_i\, S_f + T_o) / 8{,}760$$

where

D_{es}	=	whole body effective dose equivalent from contaminated soils (mrem/yr)
$DCF_{s,i}$	=	soil external dose conversion factor for radionuclide I (mrem/yr per Ci/m^3)

Doses from direct radiation are directly proportional to the radionuclide concentrations in the air and surface soils, and to the time the individual is exposed to the contamination. Doses were summed over all contaminants to determine total external doses from air immersion and radionuclides in the surface soils.

The fraction of the year the individual is exposed to direct radiation was based on the assumption that the person would spend 5,980 hr/yr inside the house and 160 hr/yr in the yard (EPA, 1989, page 5-30). A shielding factor of 0.7 (NRC, 1977, page 1.109-68) was applied to account for shielding effects during the time spent inside. These factors combine to give an equivalent exposure time fraction, $(T_i\ S_f + T_o)$ / 8,760, equal to 0.50. The dose conversion factors used in Equations (2-19) and (2-20) are listed in Table 2-2 and were taken from Federal Guidance Report No. 12 (EPA, 1993b, pages 58-73, 148-163). The dose conversion factors for soil are based on an infinite source mixed to a depth of 15 cm.

The impacts of daughter ingrowth on the projected doses for the all-pathways analysis were assessed. Separate dose projections were prepared for the case in which no ingrowth was assumed to occur and for the case in which daughter ingrowth was assumed to occur over a 10,000-year period.

3. INDIVIDUAL DOSE VERIFICATION RESULTS

The results of the dose verification are discussed below. Projected doses for the drinking water pathway are presented in Section 3.1 and compared to the doses included in the CCA and PAVT. Doses for the all-pathways analysis are presented and discussed in Section 3.2.

3.1 DRINKING WATER PATHWAY ANALYSIS RESULTS

The drinking water pathway doses projected for the groundwater modeling realizations reported in the CCA are summarized in Table 3-1. Doses are shown for the different assumptions made about daughter ingrowth. The total doses listed in the CCA are included for comparison.

Table 3-1. Projected doses for the CCA drinking water pathway analysis.

	Projected Dose (mrem/yr)		
Groundwater Realization No.	CCA Dose[a]	No Daughter Ingrowth	10,000-Years of Ingrowth
1	3.4E-01	3.5E-01	3.6E-01
2	4.3E-03	4.1E-03	4.2E-03
3	1.1E-04	1.1E-04	1.1E-04
4	5.8E-03	5.8E-03	8.6E-03
5	5.1E-07	5.0E-07	5.0E-07
6	4.3E-05	4.2E-05	4.3E-05
7	2.5E-02	2.5E-02	2.6E-02
8	6.2E-03	6.0E-03	1.8E-02
9	4.7E-01	4.7E-01	4.9E-01

a.Source: DOE, 1996.

The doses projected under the assumption of no ingrowth compare favorably with the total doses listed in the CCA. Doses for four of the realizations match exactly between the two analyses (i.e., within the level of accuracy shown); doses for all nine realizations fall within 5 percent of each other. The slight differences noted are believed to result from slightly different values for the ingestion dose conversion factors used in the two sets of calculations.

The effect of including 10,000 years of daughter ingrowth in the dose calculations is relatively minor. With two exceptions, the projected drinking water doses increase by 5 percent or less when ingrowth is included. The projected dose for Realization 4 increases about 50 percent, while the dose for Realization 8 increases about three-fold. Both of these realizations are characterized by the large contribution of Am-241 to the total dose.

The drinking water pathway doses projected for the groundwater modeling realizations reported in the PAVT are summarized in Table 3-2. With two exceptions, the doses calculated for the PAVT dose verification evaluation under the assumption of no daughter ingrowth compare favorably with the PAVT doses. The PAVT no daughter ingrowth doses estimated for Realization 4 and Realization 15 are approximately three orders of magnitude greater than the corresponding PAVT doses. It appears the PAVT results could be incorrect in these instances, probably as a result of incorrectly converting model output to the units of dose shown in the PAVT report. The effect of including daughter ingrowth in the dose calculations is small for most of the groundwater realizations. The greatest differences occur in those instances where Am-241 is a large contributor to the projected dose.

Table 3-2. Projected doses for the PAVT drinking water pathway analysis.

	Projected Dose (mrem/yr)		
Groundwater Realization No.	**PAVT Dose[a]**	**No Daughter Ingrowth**	**10,000 Years of Ingrowth**
1	4.6E-06	4.7E-06	4.7E-06
2	3.2E-02	3.0E-02	2.3E-01
3	2.6E-05	2.6E-05	2.6E-05
4	1.3E-10	1.3E-07	1.3E-07

	Projected Dose (mrem/yr)		
Groundwater Realization No.	PAVT Dose[a]	No Daughter Ingrowth	10,000 Years of Ingrowth
5	4.4E-07	4.3E-07	4.5E-07
6	7.5E-07	7.4E-07	7.4E-07
7	8.2E-05	7.9E-05	7.9E-05
8	1.3E-02	1.3E-02	2.8E-02
9	2.6E-05	2.7E-05	2.9E-05
10	6.5E-07	6.1E-07	6.1E-07
11	7.9E-05	7.7E-05	7.7E-05
12	7.1E-05	7.3E-05	7.3E-05
13	2.1E-04	2.1E-04	6.9E-04
14	3.4E-07	3.2E-07	3.2E-07
15	3.9E-06	3.8E-03	5.6E-03

a. Source: DOE, 1997b.

3.2 ALL-PATHWAYS ANALYSIS RESULTS

The doses projected for the CCA all-pathways analysis are summarized in Table 3-3. Doses are included for all groundwater realizations for which radionuclide concentrations were provided in the two studies. Separate doses are provided for the different assumptions about daughter ingrowth.

Table 3-3. Projected doses for the CCA all-pathways analysis.

Groundwater Realization No.	Projected Dose (mrem/yr) No Daughter Ingrowth	10,000-Years of Ingrowth
1	4.6E-01	4.8E-01
2	5.4E-03	5.6E-03
3	1.4E-04	1.5E-04
4	7.6E-03	1.1E-02
5	6.5E-07	6.5E-07
6	5.5E-05	5.7E-05
7	3.3E-02	3.4E-02
8	7.9E-03	2.4E-02
9	6.2E-01	6.5E-01

The maximum doses projected by the CCA for the ingestion of crops, inhalation of resuspended soils, and ingestion of meat are 3.1E-04, 4.6E-01, and 3.3E-08 mrem/yr, respectively (DOE, 1997a). These doses are similar to those projected using the methodology described in Section 2.2. For instance, summing over the doses listed above and the maximum drinking water dose of 4.7E-01 mrem/yr (see Table 3-1) yields an annual dose of 9.3E-01 mrem. This dose is 50 percent greater than the maximum all-pathways dose listed in Table 3-2 when daughter ingrowth is not taken into account, and 43 percent greater when the effects of ingrowth are included.

The all-pathways doses listed in Table 3-2 are about 30 percent greater than the corresponding drinking water doses (Table 3-1). Nevertheless, all projected doses are much less than the 15-mrem/yr performance objective specified in 40 CFR 191.15(a). The greatest projected dose is about 0.7 mrem/yr, based on the results for groundwater realization number 9 and 10,000 years of ingrowth. This dose is less than 5 percent of the dose objective.

The projected doses for the PAVT all-pathways analysis are provided in Table 3-4. These doses are about 30 percent greater than the corresponding drinking water pathway doses shown in Table 3-2. However, all doses projected for the analysis are much less than the 15-mrem/yr performance objective. The effect of daughter ingrowth is greatest in the realizations in which Am-241 makes a significant contribution to the projected doses. The results shown in Table 3-4 cannot be compared to the doses projected by DOE (DOE, 1997b) because the exposures modeled in that analysis were limited to the intake of drinking water.

Table 3-4. Projected doses for the PAVT all-pathways analysis.

	Projected Dose (mrem/yr)	
Groundwater Realization No.	No Daughter Ingrowth	10,000 Years of Ingrowth
1	6.2E-06	6.2E-06
2	4.0E-02	3.1E-01
3	3.4E-05	3.4E-05
4	1.7E-07	1.7E-07
5	5.6E-07	6.0E-07
6	9.7E-07	9.7E-07
7	1.0E-04	1.0E-04
8	1.7E-02	3.7E-02
9	3.6E-05	3.8E-05
10	8.0E-07	8.0E-07
11	1.0E-04	1.0E-04
12	9.6E-05	9.6E-05
13	2.7E-04	9.2E-04
14	4.3E-07	4.3E-07
15	4.9E-03	7.4E-03

REFERENCES

Anspaugh, L.R., et al., 1975, "Resuspension and Redistribution of Plutonium in Soils," Health Physics 29, 571.

Baes, C.F., et al., 1984, "A Review and Analysis of Parameters for Assessing Transport of Environmentally Released Radionuclides through Agriculture," Oak Ridge National Laboratory, ORNL-5786, September 1984.

DOE, 1996, "Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant," U.S. Department of Energy, DOE/CAO-1996-2184, October 1996.

DOE, 1997a, "Analysis Report for Estimating Dose from Cattle, Vegetable Consumption, and Inhalation Pathways Utilizing Contaminated Water from the Top of the Salado, Culebra, and Selected Marker Beds for an Undisturbed Case Supporting Review Compliance Certification Application," Document Version 1.01, Analysis Package in Support of the WIPP CCA. Dose Calculations of Other Pathways. WPO#43298.

DOE, 1997b, "Summary of the EPA-Mandated Performance Assessment Verification Test Results for the Individual and Groundwater Protection Requirements," PAVT Groundwater Protection. WPO#47258.

EPA, 1987a, "PATHRAE-EPA, A Performance Assessment Code for the Land Disposal of Radioactive Wastes", prepared for the U.S. Environmental Protection Agency by Rogers and Associates Engineering Corporation, RAE-8706/1-6, November 1987.

EPA, 1987b, "PRESTO-EPA-POP, A Low-Level Radioactive Waste Environmental Transport and Risk Assessment Code, Volume I, Methodology Manual", prepared for the U.S. Environmental Protection Agency by Rogers and Associates Engineering Corporation, RAE-8706/1-1, November 1987.

EPA, 1988a, "Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion," prepared by K.F. Eckerman et al., Oak Ridge National Laboratory for the U.S. Environmental Protection Agency, Federal Guidance Report No. 11, EPA-520/1-88-020, September, 1988.

EPA, 1988b, "Low-Level and NARM Radioactive Wastes, Draft Environmental Impact Statement for Proposed Rules, Volume 1, Background Information Document," EPA 520/1-87-012-1, June 1988.

EPA, 1989, "Exposure Factors Handbook," U.S. Environmental Protection Agency, EPA/600/8-89/043.

EPA, 1993a, "40 CFR Part 191 Environmental Radiation Protection Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes, Final Rule," Federal Register, Vol. 58, No. 242, pp. 66398-66416, December 20, 1993, Office of Radiation and Indoor Air, Washington, D.C.

EPA, 1993b, "External Exposure to Radionuclides in Air, Water, and Soil," prepared by K.F. Eckerman and J.C. Ryman, Oak Ridge National Laboratory for the U.S. Environmental Protection Agency, Federal Guidance Report No. 12, EPA 402-R-93-081, September 1993.

EPA, 1996, "40 CFR Part 194 Criteria for the Certification and Re-Certification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations, Final Rule," Federal Register, Vol. 61, No. 28, pp. 5224-5245, February 9, 1996, Office of Air and Radiation, Washington, D.C.

NCRP, 1984, “Radiological Assessment: Predicting the Transport, Bioaccumulation, and Uptake by Man of Radionuclides Released to the Environment”, National Council on Radiation Protection and Measurements, NCRP Report No. 76, March 1984.

Nelson, C.B., 1985, "Soil to Plant Transfer Model Recommendations for LLW BID," memorandum from C.B. Nelson, U.S. Environmental Protection Agency, to F.L. Galpin, U.S. Environmental Protection Agency, December 10, 1985.

Ng, Y.C., et al., 1978, “Methodology for Assessing Dose Commitment to Individuals and to the Population from Ingestion of Terrestrial Foods Contaminated by Emissions from a Nuclear Fuel Reprocessing Plant at Savannah River Plant,” Lawrence Livermore Laboratory, UCID-17743, March 1978.

NRC, 1977, “Regulatory Guide 1.109, Calculation of Annual Doses to Man from Routine Release of Effluents for the Purpose of Evaluating Compliance with 10 CFR Part 50, Appendix I,” U.S. Nuclear Regulatory Commission, Revision 1, October 1977.