DEVELOPING SITE-SPECIFIC DERIVED CONCENTRATION GUIDELINE LEVELS FOR MULTIPLE MEDIA AT THE CONNECTICUT YANKEE HADDAM NECK PLANT

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ABSTRACT

As part of the license termination process, site-specific Derived Concentration Guideline Levels for the Haddam Neck Plant site are developed for soil, groundwater, concrete left standing, and concrete demolished that satisfy the radiological criteria for unrestricted use as defined in 10 CFR 20.1402. Background information on the license termination process and characteristics of the Haddam Neck Plant site are presented. The dose models and associated resident farmer and building occupancy scenarios, applicable pathways, and critical groups developed to establish the Derived Concentration Guideline Levels are described. A parameter assignment process is introduced wherein general population values are used to establish behavioral and metabolic parameters representative of an average member of the critical group, while the uncertainty associated with important physical parameters is considered. A key element of the parameter assignment process is the use of sensitivity analysis to identify the dose-sensitive physical parameters and to ensure that such parameters are assigned conservative values. Structuring the parameter assignment process, completing the formal sensitivity analyses, and assigning conservative values to the sensitive physical parameters in a consistent way establishes a calculation framework that lead to Derived Concentration Guideline Levels with a uniform level of conservatism across all media and all radionuclides.

INTRODUCTION

On December 5, 1996, Connecticut Yankee Atomic Power Company notified the U. S. Nuclear Regulatory Commission (NRC) of the permanent cessation of operations of its Haddam Neck Plant (HNP) and the permanent removal of all fuel assemblies from the reactor vessel and their emplacement in the spent fuel pool. As part of the follow-on decommissioning activities, a License Termination Plan (LTP) was prepared and submitted to the NRC. The LTP (1) describes the decommissioning processes to be followed that will reduce residual radioactivity levels that permit release of the site for unrestricted use.

Radiological criteria for unrestricted use are defined in 10 CFR 20.1402. A site will be considered acceptable for unrestricted use if the residual radioactivity that is distinguishable from background radiation results in a total effective dose equivalent (TEDE) to an average member of the critical group that does not exceed 25 mrem/year, including that from groundwater sources, and that residual radioactivity has been reduced to levels that are as low as reasonably achievable (ALARA). The associated residual radioactivity levels that correspond to the 25-mrem/year TEDE limit are termed derived concentration guideline levels (DCGLs). The NRC has published in the Federal Register interim DCGL screening values of common radionuclides for soil surface contamination levels that would be deemed in compliance with the unrestricted use dose limit in 10 CFR 20.1402. However, these values are not applicable to sites with subsurface and/or with groundwater contamination, such as is the case at the HNP. The NRC has also published analogous values for building surfaces; however, the decommissioning plans for the HNP allow for the possibility of demolishing buildings and placing the resulting debris in the subsurface. This scenario differs from the building occupancy scenario used by the NRC to develop interim DCGL screening values for building surfaces. It was therefore necessary to develop site-specific DCGLs for the HNP site.

The process used to develop site-specific DCGLs for various media at the HNP site is the subject of this paper. Site characteristics of the HNP are described. The dose modeling approach used to develop site-specific DCGLs is discussed, and the scenarios, critical groups, applicable pathways, and computer codes used to represent the dose models are described. The process developed to assign parameter values to the different dose models is presented.

Dose modeling results and the associated DCGLs are discussed for the each media. Finally, the application of the DCGLs to the final status survey process is described.

SITE CHARACTERISTICS

The HNP is located on the east bank of the Connecticut River in the town of Haddam, Middlesex County, Connecticut, approximately 21 miles south-southeast of Hartford. The plant began commercial operation in January 1968 and was permanently shutdown in December 1996 after 28 years of operation. The plant incorporated a four-loop, closed-cycle, pressurized water-type nuclear steam supply system; a turbine generator and electrical systems; engineered safety features; radioactive waste systems; fuel handling systems, instrumentation and control systems; the necessary auxiliaries; and structures to house plant systems and other onsite facilities. The HNP was designed to produce 1,825 MW of thermal power and 590 MW of gross electrical power. Figure 1 illustrates the layout of the site.
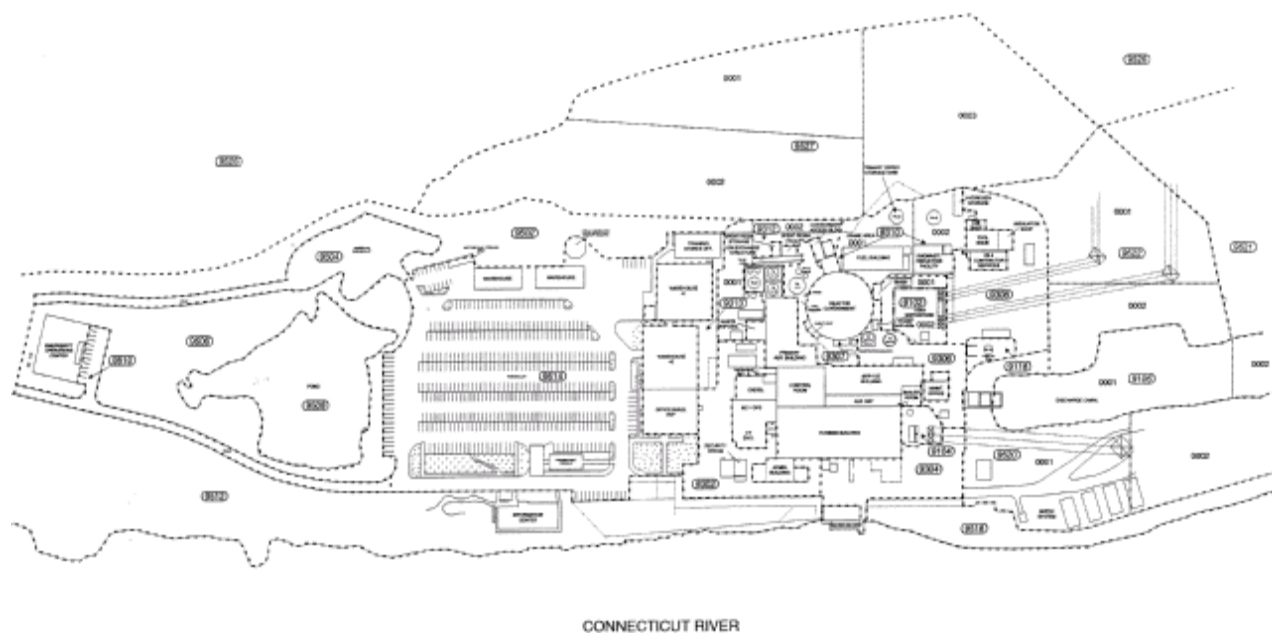
Fig. 1. Layout of the Haddam Neck Plant site.

The industrial area of the HNP is sited on a level, 600 ft wide terrace at an elevation of approximately 21 ft mean sea level. East of the industrial area, the topography rises steeply to elevations of over 300 ft mean sea level. The geologic materials present in the industrial area include unconsolidated sediments overlying metamorphic bedrock. The unconsolidated sediments average less than 20 ft thick in the industrial area and include imported fill, a variety of coarse-grained alluvial materials, and glacial till. During construction, much of the original overburden was removed and the bedrock excavated to allow construction of the containment building, primary auxiliary building, turbine building, discharge tunnel, and spent fuel pool. Groundwater occurs in both the unconsolidated sediments and bedrock, with depths to the water table averaging about 10 ft in the industrial area. Groundwater generally flows southwest across the industrial area towards the Connecticut River. Locally, groundwater flow patterns are distorted due to the subsurface portions of the containment building and other impermeable structures founded on bedrock. Downward vertical gradients are present near the base of the hill slope, while upward vertical gradients are present near the discharge canal and the Connecticut River. This information, developed from piezometric head data acquired from monitoring wells, indicates that the groundwater underlying the industrial area ultimately discharges to the Connecticut River and discharge canal.

A historical site assessment along with preliminary site characterization data indicate that soil, groundwater, and building surfaces have been radiologically impacted through plant operations as well as unplanned releases. Soil within portions of the industrial area has been contaminated by releases that occurred during the operation of the facility. Based on documented release mechanisms and the results of site characterization surveys, the contamination is generally confined to the surface soil layer, although some subsurface contamination exists. Groundwater underlying portions of the industrial area has been contaminated by unplanned liquid releases. Operation-related radionuclides known to be present in the groundwater include H-3, Sr-90, Tc-99, and Cs-137. The concrete comprising some of the HNP buildings has been contaminated from liquid releases or by activation. Buildings with surfaces known to be impacted include the fuel building, the primary auxiliary building, the reactor containment building, the waste disposal building, and the radioactive waste reduction facility. Radionuclides potentially present in the impacted soil, groundwater, and building surfaces were identified using waste characterization data from the HNP site. Twenty radionuclides were identified, which included fission products, activation products, and fuel components.

DOSE MODELING APPROACH

Overview

Dose models are necessary to derive levels of residual radioactivity in various site media at the time of site release that would result in a 25-mrem/year TEDE to the public per 10 CFR 20.1402. These levels are termed derived concentration guideline levels, or DCGLs. Any media with radioactivity levels in excess of the DCGLs would require remediation to or below the DCGL prior to release of the site for unrestricted use. Potentially impacted media to remain onsite following decommissioning and site release include soil, groundwater, and building concrete. The LTP allows for buildings to be either (a) left standing, or (b) demolished and the resulting debris used to backfill subsurface foundations. Because the scenarios and exposure pathways for buildings left standing versus buildings demolished differ significantly, it was necessary to determine separate DCGLs for these two cases. Site-specific DCGLs were therefore developed for soil, groundwater, and concrete for buildings left standing and buildings demolished.

The scenario, the critical group, and the exposure pathways define a dose model. Two scenarios were determined to be applicable to the HNP site: the resident farmer scenario and the building occupancy scenario. Descriptions of both scenarios and the associated major exposure pathways of direct exposure to penetrating radiation, and the inhalation and ingestion of radioactive materials are given by (2). The selection of a scenario also identifies the critical group, which is the group of individuals reasonably expected to receive the greatest exposure to residual radioactivity with the assumptions of a particular scenario. The TEDE requirements included in 10 CFR Part 20, Subpart E apply to the average member of the critical group. The scenarios, critical groups, and exposure pathways used to develop site-specific DCGLs for the HNP are described below along with the computer codes selected to represent the dose models.

Resident Farmer Scenario

The resident farmer scenario was selected to estimate human radiation exposures resulting from residual radioactive contamination in soil, groundwater, and concrete from demolished buildings and to determine corresponding DCGLs. This scenario is also referred to as the residential scenario (2). The critical group was determined to be the resident farmer who lives on the plant site following decommissioning, grows all or a portion of their diet on the site, and uses the water from a groundwater source on the site for drinking water and irrigation. The pathways considered in this scenario are as follows (2):

- Direct exposure to external radiation from the contaminated media;
- Internal dose from inhalation of airborne radionuclides; and
- Internal dose from ingestion of
    - Plant foods grown in the contaminated media and irrigated with contaminated water,
    - Meat and milk from livestock fed with contaminated fodder and water,
    - Drinking water from a contaminated well,
    - Fish from a contaminated pond, and
    - Contaminated media.

The RESidual RADadioactivity (RESRAD) code was selected for modeling the resident farmer scenario. Both deterministic and probabilistic versions of RESRAD were used. Deterministic Version 5.91 (3) was used for the calculation of TEDEs and DCGLs for the residential farmer scenarios, while probabilistic Version 6.1 (4, 5) was used to complete a sensitivity analysis.

Building Occupancy Scenario

The building occupancy scenario considers potential exposure pathways associated with residual radioactivity in the concrete from buildings left standing. The critical group was determined to be a group of adults engaging in light industrial work within the buildings following decommissioning of the site. Exposure pathways for this scenario include the following (2):

- Direct exposure to external radiation from
    - Source,
    - Material deposited on the floor,
    - Submersion in airborne dust;
- Internal dose from inhalation of airborne radionuclides; and
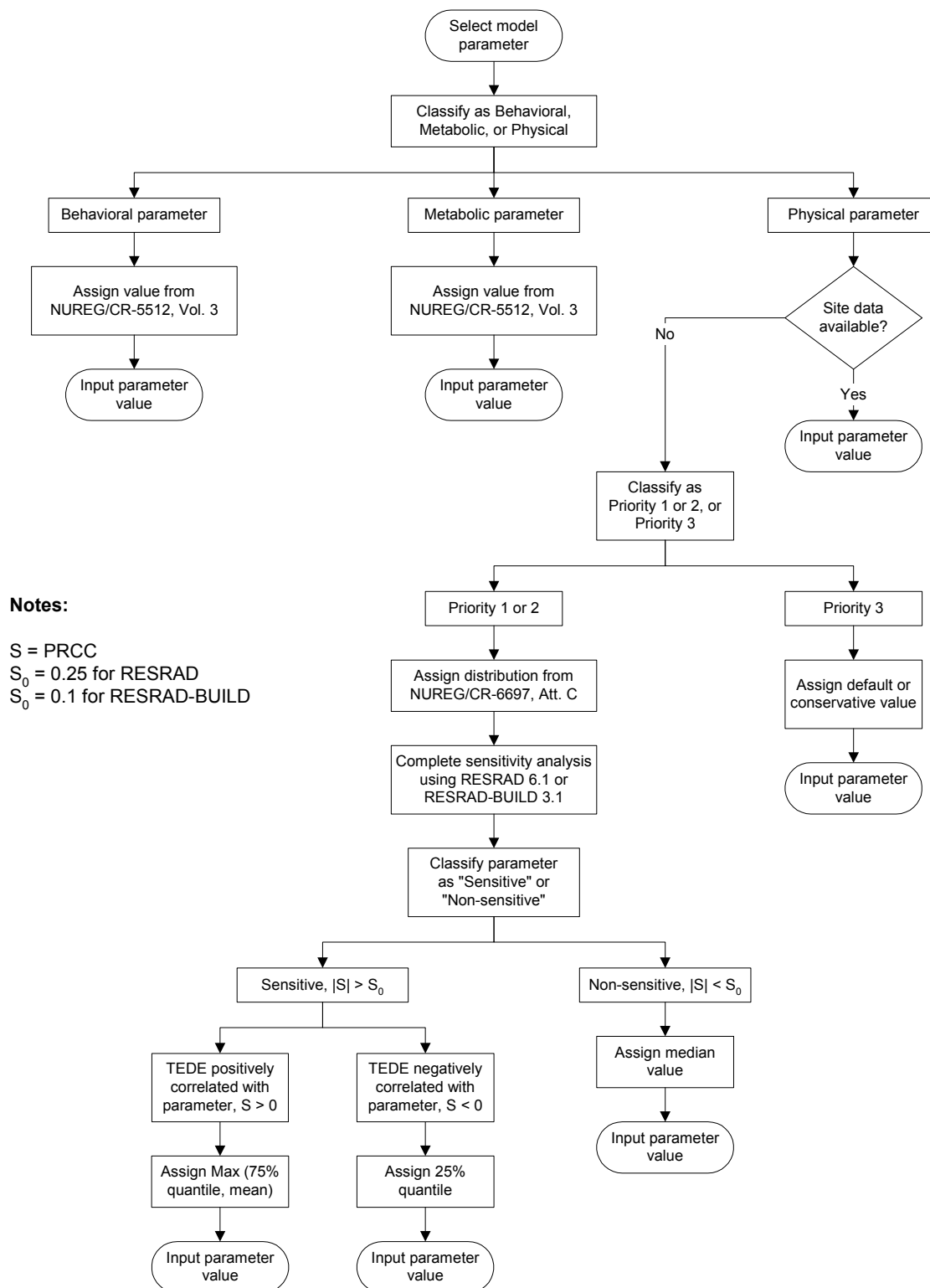- Internal dose from inadvertent ingestion of radionuclides.

The RESRAD-BUILD code was chosen for modeling the building occupancy scenario. Both deterministic and probabilistic versions of the code were applied. Deterministic Version 2.37 (6) was used for the calculation of TEDEs and DCGLs for the building occupancy scenario. Probabilistic Version 3.1 (5) was used to complete a sensitivity analysis.

PARAMETER SELECTION PROCESS

Quantifying the TEDEs and associated DCGLs for the resident farmer and building occupancy models for the four media using the RESRAD and RESRAD-BUILD codes requires the assignment of a relatively large number of parameters. For example, the RESRAD model used to represent the resident farmer scenario for determining soil DCGLs requires the assignment of about 370 model parameters for the 20 radionuclides potentially present at the HNP site. Some of these parameters significantly affect the TEDE and the DCGL. Furthermore, parameter values must be conservatively assigned such that the dose models generally overestimate rather than underestimate the potential dose. In the development of site-specific DCGLs, however, the model parameters to which the TEDE and DCGL are most sensitive are not known *a priori*. Therefore, a structured parameter selection process was developed and applied consistently to the dose models used to determine the DCGLs for the four media and twenty radionuclides of interest. This process was developed such that: (a) behavioral and metabolic parameters are assigned values representative of the average member of the critical group; (b) site-specific measurements, where available, are used to assign values to the physical parameters; and (c) physical parameters for which no site-specific measurements are available are identified and assigned conservative values. The resulting process is illustrated in Figure 2 and discussed below.

Parameters were classified initially as behavioral, metabolic, and physical based on criteria given in Attachment A of (7). Any parameter whose value depends on the receptor's behavior and the scenario definition is classified as a behavioral parameter. For the same group of receptors, a parameter value could change if the scenario changed. If a parameter represents the metabolic characteristics of the potential receptor and is independent of the scenario, it is classified as a metabolic parameter. Any parameter whose value would not change if a different group of receptors were considered is classified as a physical parameter. Physical parameters are determined by the source, its location, and geologic and hydrogeologic characteristics of the site.

Behavioral and metabolic parameters were assigned values that represent averages for the general population. The use of averages is appropriate because the TEDE requirements included in 10 CFR Part 20, Subpart E apply to the average member of the critical group. Most values assigned to the behavioral and metabolic parameters were taken from (8). It was necessary to adopt some RESRAD and RESRAD-BUILD default values for a few parameters not documented in (8).

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                                    │ Classify as      │
                                    │ Behavioral,      │
                                    │ Metabolic, or    │
                                    │ Physical         │
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Notes:

S = PRCC
$S_0 = 0.25$ for RESRAD
$S_0 = 0.1$ for RESRAD-BUILD

- Behavioral parameter → Assign value from NUREG/CR-5512, Vol. 3 → Input parameter value
- Metabolic parameter → Assign value from NUREG/CR-5512, Vol. 3 → Input parameter value
- Physical parameter → Site data available? → No / Yes
  - Yes → Input parameter value
  - No → Classify as Priority 1 or 2, or Priority 3
    - Priority 1 or 2 → Assign distribution from NUREG/CR-6697, Att. C → Complete sensitivity analysis using RESRAD 6.1 or RESRAD-BUILD 3.1 → Classify parameter as "Sensitive" or "Non-sensitive"
      - Sensitive, $|S| > S_0$
        - TEDE positively correlated with parameter, $S > 0$ → Assign Max (75% quantile, mean) → Input parameter value
        - TEDE negatively correlated with parameter, $S < 0$ → Assign 25% quantile → Input parameter value
      - Non-sensitive, $|S| < S_0$ → Assign median value → Input parameter value
    - Priority 3 → Assign default or conservative value → Input parameter value

Fig. 2. Process used to select behavioral, metabolic and physical parameters for the residential farmer and building occupancy dose models.

Physical parameters for which site data were available to quantify were assigned site-specific values. The remaining physical parameters were prioritized consistent with Attachment B of (7). Prioritization was based on (a) the relevance of the parameter in the dose calculations, (b) the variability of the dose as a result of changes in the parameter value, (c) the parameter type, and (d) the availability of parameter-specific data. Priority 1 parameters are considered to be high priority; priority 2 parameters are considered to be medium priority; and priority 3 parameters are considered to be of low priority. Priority 1 and 2 physical parameters were established based on the results of a sensitivity analysis to be discussed subsequently. Priority 3 parameters were assigned default values from RESRAD or values from (8) and related guidance documents.

Because the values assigned to the priority 1 and 2 physical parameters may significantly affect the calculated TEDEs and associated DCGLs, it is necessary to, first, identify the subset of these priority 1 and 2 parameters to which the TEDEs and DCGLs are sensitive, and, second, assign conservative values to this subset of sensitive parameters. The first step was accomplished by treating each of the priority 1 and 2 physical parameters as stochastic variables in the probabilistic versions of RESRAD and RESRAD-BUILD. Each priority 1 and 2 physical parameter was assigned a distribution type and defining statistical parameters based on Attachment C of (7). The behavioral, metabolic and priority 3 physical parameters were treated deterministically and assigned values as described above. The probabilistic versions of RESRAD and RESRAD-BUILD were then used to sample the probability distributions of each stochastic input parameter using the Latin Hypercube Sampling technique to develop a matrix of input parameters for the dose models. The relationship of the resultant vector of predicted peak doses to the matrix of input parameters was statistically evaluated to quantify the sensitivity of dose to each stochastic input parameter. A physical parameter was deemed sensitive if the magnitude of its partial rank correlation coefficient (PRCC) for the peak of the mean dose exceeded a threshold value. For the resident farmer scenario, a parameter was identified as sensitive if the $|PRCC| \geq 0.25$ and non-sensitive if its $|PRCC| < 0.25$. For the building occupancy scenario, a parameter was identified as sensitive if the $|PRCC| \geq 0.10$ and non-sensitive if its $|PRCC| < 0.10$. These thresholds were established based on guidance provided by (9).

Once the subset of sensitive physical parameters was established, conservative values were assigned. Sensitive physical parameters that correlated positively with dose were conservatively assigned the 75% quantile of their distribution. Conversely, sensitive physical parameters that exhibited a negative correlation with dose were conservatively assigned the 25% quantile of their distribution. The mean value of the distribution was also calculated for those parameters positively correlated with dose. If the mean value was greater than the 75% quantile (positively skewed distribution), the parameter was assigned the mean value to ensure conservatism. Physical parameters to which the dose had limited sensitivity (i.e., magnitude of the PRCC was less than the threshold) were assigned the median or mean value of their distribution.

With all behavioral, metabolic, and physical parameters assigned, the deterministic versions of RESRAD and RESRAD-BUILD were used to calculate radionuclide-specific DCGLs for the four media of interest.

DOSE MODELING RESULTS

Overview

Following the parameter selection process described above, the RESRAD code was used to determine DCGLs for soil, groundwater, and concrete demolished under the resident farmer scenario. Likewise, the RESRAD-BUILD code was used to determine DCGLs for concrete left standing under the building occupancy scenario. Dose modeling results provide DCGLs for each of the four media for each of the twenty radionuclides potentially present at the HNP site. These values have been termed "Base Case" DCGLs (i.e., residual radioactivity at the DCGL for each radionuclide in any of the media would yield a 25 mrem/year TEDE). The scenarios, critical groups, conceptual models, applicable pathways, and sensitivity analysis, and dose modeling results for each media are discussed briefly below. Complete results can be found in the LTP, which can be accessed from the NRC's ADAMS on-line document retrieval system (http://www.nrc.gov/reading-rm/adams.html).

DCGLs for Soil

The DCGLs for soil were calculated using the resident farmer scenario. The average member of the critical group is the resident farmer that lives on the plant site, grows all or a portion of their diet onsite, drinks water from a groundwater source onsite. The potential pathways used to estimate human radiation exposure resulting from residual radioactivity in the soil include the following:

- Direct exposure to external radiation from soil containing residual radioactivity;
- Internal dose from inhalation of airborne radionuclides; and
- Internal dose from ingestion of
    - Plant foods grown in the soil material containing residual radioactivity;
    - Meat and milk from livestock fed with fodder grown in soil containing residual radioactivity and water containing residual radioactivity;
    - Drinking water containing residual radioactivity from a well,
    - Fish from a pond containing residual radioactivity, and
    - Soil containing residual radioactivity.

The conceptual model for this case includes a contaminated zone, an unsaturated zone, and a saturated zone. The residual radioactive materials are contained the contaminated zone, which consists of a soil layer that can be used for residential and light farming activities. The contaminated zone is sufficiently thick to include both surface (≤ 0.15 m deep) and subsurface (> 0.15 m deep) contamination. The contaminated zone is exposed at the ground surface with no uncontaminated soil cover. This contaminated zone serves as the source from which the critical group is exposed via the pathways described above. This conceptual model is consistent with that described by Yu et al. (3, 4).

The area of the contaminated zone area was taken to be 15,600 m^2, which represents the largest subsurface soil survey area. Climatological characteristics were derived from site data. Hydrologic characteristics of the soil comprising the contaminated zone, unsaturated zone, and saturated zone were based on the loamy sand that was imported for fill.

Behavioral, metabolic and physical parameters were assigned as described previously. The priority 1 and 2 physical parameters retained for sensitivity analysis included the following:

- Distribution coefficients for the contaminated, unsaturated and saturated zones;
- Thickness of the contaminated zone;
- Contaminated zone density, erosion rate, total porosity, hydraulic conductivity, and soil "b" parameter;
- Unsaturated zone thickness, density, erosion rate, total porosity, effective porosity, hydraulic conductivity, and soil "b" parameter;
- Saturated zone density, total porosity, effective porosity, hydraulic conductivity, soil "b" parameter, well pump intake depth, and well pumping rate;
- Mass loading for inhalation;
- Indoor dust filtration factor;
- External gamma shielding factor;
- Depth of soil mixing layer;
- Depth of roots;
- Wet weight crop yield;
- Weathering removal constant for vegetation;
- Wet foliar interception fraction for leafy vegetables;
- C-14 evasion layer thickness in soil; and
- Plant, meat, milk and fish transfer factors.

Each of the above quantities were treated as stochastic variables and assigned probability density functions as described above. Probabilistic RESRAD Version 6.1 (4) was then used to sample these distributions using the Latin Hypercube Sampling technique to generate vectors of input parameters for Monte Carlo simulation. To ensure that the statistics of the ensuing simulations would be stable, 300 simulations were performed for each of the 20 radionuclides of interest. The statistical post-processing facilities of RESRAD Version 6.1 were then used to

evaluate the statistical correlations between the values of the input parameters and the calculated magnitude of the peak of the mean dose. Using the |PRCC| ≥ 0.25 criterion, the dose was found to be sensitive to a number of priority 1 and 2 physical parameters. Complete sensitivity analysis results can be found in the LTP. The most sensitive parameters identified for each of the radionuclides, as measured by the magnitude of the PRCC, are highlighted below.

- Depth of roots: H-3 and C-14
- External gamma shielding factor: Mn-54, Co-60, Nb-94, Ag-108m, Cs-134, Eu-152, Eu-154, Eu-155
- Meat transfer factor: Fe-55
- Plant transfer factor: Ni-63, Sr-90, Tc-99, Cs-137, Pu-238, Pu-239, Pu-241, Am-241, Cm-243

With the sensitive parameters identified, conservative values were assigned as discussed in the parameter selection process. Deterministic RESRAD Version 5.91 (3) was then run to calculate the soil DCGLs. Table I summarizes the DCGLs, identifies the time to peak dose, and quantifies the dose contributions from the various water independent and water dependent pathways. These results show that the peak dose for all radionuclides but Pu-241 is expected to occur at zero years (i.e., the time of site release). The peak dose for Pu-241 is calculated to occur at 62 years, which is due to the in-growth of the progeny, Am-241. The results also indicate that, with the exception of H-3, the dose contributions are all from water independent pathways. Even in the case of H-3, the dose contributions from the water dependent pathways are minor. The results further show that the predominant dose contributions correlate with a parameter associated with the same pathway. For example, the dose contributions for Mn-54, Co-60, Nb-94, Ag-108m, Cs-234, Eu-152, Eu-154 and Eu-155 come primarily from external radiation. Sensitivity analysis results identified the external gamma shielding factor as the most sensitive parameter for the same radionuclides.

Table I. Dose Modeling Results and Base Case DCGLs for Soil Based on the Resident Farmer Scenario

Radio-nuclide	DCGL (pCi/g)	Time to Peak Dose (years)	Dose Fraction From Water Independent Pathways (%)						Dose Fraction From Water Dependent Pathways (%)				
			Ground	Inhalation	Plant	Meat	Milk	Soil	Water	Fish	Plant	Meat	Milk
H-3	4.115E+02	0	-	0.91	38.28	5.56	39.9	-	10.08	0.03	1.81	0.57	2.86
C-14	5.655E+00	0	-	0.01	52.9	24.54	22.55	-	-	-	-	-	-
Mn-54	1.742E+01	0	89.50	-	9.76	0.21	0.53	-	-	-	-	-	-
Fe-55	2.738E+04	0	-	0.01	14.34	82.3	2.53	0.83	-	-	-	-	-
Co-60	3.814E+00	0	84.22	-	7.49	6.55	1.74	0.01	-	-	-	-	-
Ni-63	7.230E+02	0	-	-	20.27	1.61	78.1	0.02	-	-	-	-	-
Sr-90	1.547E+00	0	0.04	-	73.46	10.03	16.46	0.01	-	-	-	-	-
Nb-94	7.117E+00	0	99.80	-	0.2	-	-	-	-	-	-	-	-
Tc-99	1.260E+01	0	-	-	89.93	0.12	9.95	-	-	-	-	-	-
Ag-108m	7.141E+00	0	99.69	-	0.08	0.02	0.21	-	-	-	-	-	-
Cs-134	4.666E+00	0	54.35	-	12.15	12.94	20.54	0.02	-	-	-	-	-
Cs-137	7.906E+00	0	38.59	-	16.34	17.41	27.63	0.02	-	-	-	-	-
Eu-152	1.007E+01	0	99.93	-	0.05	0.02	-	-	-	-	-	-	-
Eu-154	9.288E+00	0	99.90	-	0.07	0.02	-	-	-	-	-	-	-
Eu-155	3.922E+02	0	99.35	-	0.44	0.16	0.02	0.03	-	-	-	-	-
Pu-238	2.962E+01	0	0.01	0.92	92.33	1.35	0.05	5.35	-	-	-	-	-
Pu-239	2.667E+01	0	0.01	0.91	92.33	1.35	0.05	5.35	-	-	-	-	-
Pu-241	8.695E+02	62.2	1.28	0.92	91.62	0.7	0.11	5.38	-	-	-	-	-
Am-241	2.578E+01	0	1.30	0.91	91.7	0.67	0.11	5.31	-	-	-	-	-
Cm-243	2.901E+01	0	24.60	0.7	70.34	0.21	0.08	4.07	-	-	-	-	-

DCGLs for Groundwater

Site characterization efforts have shown plant-related radionuclides to be present in the groundwater underlying portions of the industrial area. Because these radionuclides will likely be present when the site is released for unrestricted use, their presence represents a potential dose contribution to a future occupant of the site, particularly if the occupant installs a well and uses the groundwater for drinking water, irrigating crops, and watering livestock. This dose contribution is in addition to that associated with the leaching of radionuclides from soils as was considered in the development of the soil DCGLs. It was therefore necessary to develop DCGLs for groundwater.

The groundwater DCGLs were calculated using the resident farmer scenario. The average member of the critical group is the resident farmer that lives on the plant site, grows all or a portion of their diet onsite and drinks from the groundwater source onsite. The potential water-dependent pathways used to estimate human radiation exposure resulting from residual radioactivity in the groundwater include the following:

- Internal dose from ingestion of
    - Plant foods irrigated with water containing residual radioactivity,
    - Meat and milk from livestock fed with contaminated water containing residual radioactivity, and
    - Drinking water containing residual radioactivity from a well.

The conceptual model for this case assumes that residual radioactive materials are contained in the saturated zone and all sources that contributed to this contamination have since been removed. Groundwater, from a contaminated portion of the saturated zone, is withdrawn via a well and used for irrigation and drinking water. This groundwater serves as the source from which the critical group is exposed via the pathways described above.

The RESRAD code was originally designed to estimate radiation doses from residual radioactive material contained in a solid phase source above the water table rather than a liquid phase source in the groundwater itself. It was therefore necessary to modify the input to RESRAD to reflect the conceptual model for this scenario, which considers dose contributions from water-dependent pathways only. This was accomplished by turning off the water-independent pathways. It was also necessary to set the values of certain parameters (livestock soil intake, mass loading for foliar deposition, depth of roots) to zero to eliminate water-independent dose contributions associated with a source above the water table. An arbitrary radionuclide concentration in groundwater of 9.97 pCi/l was established in RESRAD by setting the source concentration to 1 pCi/g, the distribution coefficient to 100 cm^3/g, the time since placement of material to 1 year, the number of unsaturated zone strata to zero, and the water transport option to mass balance. The resulting groundwater concentration is consistent with that in equilibrium with the source under saturated conditions, which can be derived using the principals of the linear sorption theory (3, 4) and calculated from

$$C = \frac{1000 S_0 \rho_b}{\left[1 + \left(K_d \rho_b / n\right)\right] n}$$ (Eq. 1)

where C is the equilibrium groundwater concentration (pCi/l), S_o is the initial principal radionuclide concentration in the contaminated zone (pCi/g), ρ_b is the bulk density of the contaminated zone (g/cm^3), K_d is the distribution coefficient of contaminated zone (cm^3/g), and n is the total porosity of the contaminated zone (cm^3/cm^3). It should be noted the methodology used to establish the groundwater concentration and associated dose produces results that are valid only when the peak dose occurs at zero years (i.e., at the time of site release). Dose contributions from the in-growth of progeny are not considered.

Following the parameter selection process described previously and establishing the abovementioned parameters, sensitivity analyses were performed on priority 1 and 2 physical parameters relevant to the water-dependent dose calculations. These included:

- Wet weight crop yield for non-leafy vegetables;
- Weathering removal constant for vegetation;
- Wet foliar interception fraction for leafy vegetables;
- Plant transfer factors;
- Meat transfer factors; and
- Milk transfer factors.

The above parameters were treated as stochastic variables and assigned probability density functions as described previously. A sensitivity analyses was then conducted using RESRAD, Version 6.1 following the same process as was used for the soil DCGLs. Using the |PRCC| ≥ 0.25 criterion, the dose was found to be sensitive to a number of the parameters listed above. Complete sensitivity analysis results can be found in the LTP. The most sensitive parameters identified for each of the radionuclides are highlighted below:

9

- Weathering removal constant for vegetation: Mn-54, Nb-94, Eu-152, Eu-154, Eu-155, Pu-238, Pu-239, Pu-241, Am-241, Cm-243
- Meat transfer factors: Fe-55, Co-60
- Milk transfer factors: Ni-63, Sr-90, Ag-108m, Cs-134, Cs-137
- Plant transfer factors: Tc-99

For H-3 and C-14, the dose exhibited no sensitivity to any of the above parameters (|PRCC| = 0.00). These results were confirmed using RESRAD, Version 5.91 by perturbing the parameters individually and comparing the peak doses, which remained the same irrespective of parameter values.

With the sensitive parameters identified, conservative values were assigned as discussed in the parameter selection process. Deterministic RESRAD, Version 5.91 (3) was then run to calculate the well water concentration (RESRAD groundwater) and associated peak dose for each of the radionuclides. The groundwater DCGLs were calculated by scaling the well water concentrations against the peak dose to determine the concentration that would give a TEDE of 25 mrem/year. To account for dose contributions from the in-growth of progeny, a separate analysis was performed using RESRAD, Version 5.91 to model the decay of 1 pCi/l of parent radionuclide and in-growth of progeny over 1000 years. Effective dose conversion factors were used to convert the resulting groundwater concentrations into dose, which were then summed to determine total dose as a function of time. These results were then used to determine the time to the peak dose. For those radionuclides for which the peak dose occurred at a time greater than zero, the initial parent radionuclide concentration of 1 pCi/l was scaled against the peak total dose to obtain a concentration yielding a TEDE of 25 mrem/yr. Table II summarizes the groundwater DCGLs, identifies the time of the peak dose, and quantifies the dose contributions from the various water-dependent pathways.

The results show that for all the radionuclides, except Pu-241, the peak dose occurs at zero years (i.e., at the time of site release), and that the dose contributions come primarily from the ingestion of drinking water. For Pu-241, the peak dose is expected to occur at 50 years, and with most of the dose contribution also coming primarily from the ingestion of drinking water.

Table II. Dose Modeling Results and Base Case DCGLs for Groundwater Based on the Resident Farmer Scenario

Radionuclide	DCGL (pCi/l)	Time to Peak Dose (years)	Dose Fraction From Water Dependent Pathways (%)			
			Water	Plant	Meat	Milk
H-3	6.52E+05	0	77.53	0.02	4.42	18.03
C-14	9.01E+03	0	35.98	33.63	16.77	13.61
Mn-54	2.42E+04	0	87.79	8.52	1.38	2.30
Fe-55	6.54E+04	0	66.88	5.77	25.61	1.74
Co-60	1.14E+03	0	55.02	3.83	31.58	9.58
Ni-63	3.15E+04	0	34.57	2.39	3.10	59.95
Sr-90	2.51E+02	0	72.51	7.09	9.26	11.14
Nb-94	6.75E+03	0	92.03	7.96	-	0.01
Tc-99	2.64E+04	0	73.75	18.91	0.08	7.26
Ag-108m	4.24E+03	0	61.51	4.74	1.94	31.82
Cs-134	3.42E+02	0	40.70	2.80	25.94	30.56
Cs-137	4.31E+02	0	40.70	2.80	25.94	30.56
Eu-152	7.33E+03	0	88.44	7.63	3.40	0.53
Eu-154	5.05E+03	0	88.65	7.65	3.41	0.29
Eu-155	3.25E+04	0	88.65	7.65	3.41	0.29
Pu-238	1.51E+01	0	91.97	7.93	0.09	-
Pu-239	1.36E+01	0	91.97	7.93	0.09	0.00
Pu-241	4.60E+02	50	91.96	7.94	0.09	0.01
Am-241	1.32E+01	0	92.01	7.94	0.04	0.01
Cm-243	1.94E+01	0	92.03	7.94	0.02	0.01

DCGLs for Concrete

<u>Buildings Left Standing</u>

The DCGLs for concrete left standing were calculated using the building occupancy scenario. The average member of the critical group is an adult engaged in light industrial work within the buildings following decommissioning of the site. This adult occupies a commercial facility in a normal manner without deliberately disturbing the sources of residual radioactivity. The potential pathways used to estimate human radiation exposure resulting from residual radioactivity in the building include the following:

- Direct exposure to external radiation from
  - Residual radioactivity remaining on the room surfaces
  - Material deposited on the floor (dust)
  - Submersion in the airborne dust
- Internal dose from inhalation of airborne radionuclides; and
- Internal dose from inadvertant ingestion of radionuclides from the room surfaces.

The conceptual model for this case consists of a single-room building. Residual radioactivity is assumed to be uniformly distributed over the surfaces of the room, including the floor, ceiling, and four walls. The size of the room was assumed to be 10 m by 10 m by 2.5 m high, typical of a room at the HNP. The receptor is located at the center of the room at a height of 1 m. Removal of a fraction of the residual radioactivity from the building surfaces occurs over time and causes both an airborne source and deposition of material onto the floor.

Two cases were considered for the source type: area (surface) sources and volume sources. Area sources consisted of a thin-layer of residual radioactivity on the surface (2). Volume sources consisted of 0.305 m (12 inches) of concrete to account for the possibility of volumetrically contaminated sources, either by migration of radioactive material into the depth of the source or by neutron activation.

Behavioral, metabolic and physical parameters were assigned as described previously. The priority 1 and 2 physical parameters retained for the sensitivity analysis included the following:

- Deposition velocity;
- Resuspension rate;
- Time for source removal (area sources); and
- Erosion rate (volume sources).

Each of the above quantities were treated as stochastic variables and assigned probability density functions as described previously. Probabilistic RESRAD-BUILD Version 3.1 (5) was then used to sample these distributions using the Latin Hypercube Sampling technique to generate vectors of input parameters for Monte Carlo simulation. To ensure that the statistics of the ensuing simulations would be stable, 300 simulations were performed for each of the 20 radionuclides of interest. The statistical post-processing facilities of RESRAD-BUILD Version 3.1 were then used to evaluate the statistical correlations between the values of the input parameters and the calculated magnitude of the peak of the mean dose. Using the $|PRCC| \geq 0.10$ criterion, the dose was found to be sensitive to each of the priority 1 and 2 physical parameters. Complete sensitivity analysis results can be found in the LTP. The most sensitive parameters identified for each of the radionuclides, as measured by the magnitude of the PRCC, are highlighted below.

- Deposition velocity: Fe-55, Nb-94, Ag-108m, Eu-152
- Resuspension rate: Fe-55, Nb-94, Ag-108m, Eu-152
- Time for source removal: All 20 radionuclides were sensitive to this parameter
- Erosion rate: All 20 radionuclides were sensitive to this parameter

With the sensitive parameters identified, conservative values were assigned as discussed in the parameter selection process. Deterministic RESRAD-BUILD Version 2.37 (6) was then run to calculate the annual dose from a unit

source. DCGLs were determined by proportioning the concentrations so that a TEDE of 25 mrem/year was achieved.

Table III summarizes the DCGLs for both cases of area and volume sources and quantifies the dose contributions from the various pathways. The peak dose for all radionuclides is expected to occur at zero years (i.e., the time of site release). For the building area DCGLs, the dominant dose contributions are from the external or ingestion pathways and for the volume source DCGLs, the dominant dose contributions are from the external or inhalation pathways.

Table III. Dose Modeling Results and Base Case DCGLs for Concrete Left Standing Based on the Building Occupancy Scenario

Radio-nuclide	Buildings with Area (Surface) Sources						Buildings with Volume Sources					
	DCGL	Dose Fraction by Pathway (%)					DCGL	Dose Fraction by Pathway (%)				
	(dpm/100 cm^2)	Ext.	Deposit.	Immer.	Inhal.	Ingest.	(pCi/g)	Ext.	Deposit.	Immer.	Inhal.	Ingest.
H-3	3.15E+08	-	-	-	6	94	1.47E+03	-	-	-	100	-
C-14	1.03E+07	-	-	-	-	100	1.18E+08	-	-	-	95	5
Mn-54	3.21E+04	100	-	-	-	-	9.06E+00	100	-	-	-	-
Fe-55	3.49E+07	-	-	-	1	98	9.54E+07	-	-	-	99	1
Co-60	1.11E+04	99	-	-	-	1	2.90E+00	100	-	-	-	-
Ni-63	3.60E+07	-	-	-	3	97	4.11E+07	-	-	-	100	-
Sr-90	1.27E+05	7	-	-	2	90	2.38E+03	99	-	-	1	-
Nb-94	1.71E+04	99	-	-	-	1	4.83E+03	100	-	-	-	-
Tc-99	1.45E+07	-	-	-	2	98	3.09E+07	-	-	-	99	1
Ag-108m	1.65E+04	99	-	-	-	1	4.84E+00	100	-	-	-	-
Cs-134	1.65E+04	94	-	-	-	6	4.93E+00	100	-	-	-	-
Cs-137	4.30E+04	90	-	-	-	10	1.37E+01	100	-	-	-	-
Eu-152	2.34E+04	99	-	-	-	1	6.70E+00	100	-	-	-	-
Eu-154	2.19E+04	99	-	-	-	1	6.11E+00	100	-	-	-	-
Eu-155	4.37E+05	97	-	-	-	3	3.23E+02	100	-	-	-	-
Pu-238	4.87E+03	-	-	-	27	72	6.61E+02	-	-	-	100	-
Pu-239	4.44E+03	-	-	-	27	73	6.02E+02	-	-	-	100	-
Pu-241	2.29E+05	-	-	-	27	73	3.12E+04	1	-	-	99	-
Am-241	4.27E+03	1	-	-	27	72	4.16E+02	29	-	-	71	-
Cm-243	6.07E+03	3	-	-	27	71	7.53E+01	91	-	-	9	-

Buildings Demolished

Concrete debris generated from the demolition of HNP buildings is expected to be placed in building basements. As discussed previously, the concrete debris may have come in contact with radioactive liquids or have been subject to neutron activation.

The DCGLs for concrete debris were calculated using the resident farmer scenario. The average member of the critical group is the resident farmer that lives on the plant site, grows all or a portion of his/her diet onsite and drinks from the groundwater source onsite. The potential pathways used to estimate human radiation exposure resulting from residual radioactivity contained in the concrete debris include the following:

- Direct exposure to external radiation from the concrete debris containing residual radioactivity,
- Internal dose from inhalation of airborne radionuclides, and
- Internal dose from ingestion of
  - Plant foods grown in the soil cover and irrigated with water containing residual radioactivity,
  - Meat and milk from livestock fed with fodder and water containing residual radioactivity,
  - Drinking water containing residual radioactivity from a well, and
  - Concrete debris containing residual radioactivity.

The conceptual model for this case includes a contaminated zone, comprised of concrete debris that extends both above and below the water table. Concrete debris is placed to a depth of 1 m (3 ft) below the ground surface and covered with 1 m (3 ft) of clean soil fill. The resident farmer constructs their home over the debris, and drills and completes a well in the same area that supplies water for drinking, crop irrigation and for the livestock. The

contaminated zone, comprised of concrete debris, serves as the source from which the critical group is exposed via the pathways described above.

As indicated previously, the RESRAD code is designed to estimate radiation doses from a source above the water table. In the present scenario, the source consists of concrete debris that extends both above and below the water table. It was therefore necessary to provide the appropriate the input to RESRAD to reflect this conceptual model. This was accomplished in RESRAD by setting the contaminated zone thickness equal to the water table depth, the number of unsaturated zone strata to zero, and the water transport option to mass balance. The groundwater concentrations calculated by RESRAD for these conditions were then checked against the values calculated by Eq. 1 as a function of time for an assumed source concentration of 1 pCi/g. Values calculated from Eq. 1 represent the liquid phase radionuclide concentration that is in equilibrium with the solid phase concentration in the absence of any dilution, which is the theoretical upper bound for groundwater in contact with a concrete debris source below the water table. In all cases the RESRAD calculated groundwater concentrations were greater than or equal to the Eq. 1 calculated values, which ensured that the source below the water table was represented correctly in the dose model.

Key physical parameters in this scenario are the distribution coefficients that define the affinity of radionuclides for concrete debris. Because the geochemical conditions in concrete are markedly different from those of soil, concrete-water distribution coefficients were expected to differ from soil-water distribution coefficients that are relatively well-documented in the literature. Site-specific tests were therefore conducted using concrete cores taken from several HNP buildings and site groundwater to determine the concrete-water distribution coefficients for the radionuclides of interest (10). Associated plant transfer factors for plants whose roots would come in contact with the concrete debris were established using the relationship given by (7).

Following the parameter selection process described previously and establishing the abovementioned parameters, sensitivity analyses were performed on priority 1 and 2 physical parameters considered relevant to the dose calculations. These included:

- Distribution coefficients for the contaminated zone;
- Cover material depth, density and erosion rate;
- Contaminated zone density, total porosity, hydraulic conductivity, and soil "b" parameter;
- Mass loading for inhalation;
- Indoor dust filtration factor;
- External gamma shielding factor;
- Depth of soil mixing layer;
- Depth of roots;
- Wet weight crop yield for non-leafy vegetables;
- Weathering removal constant for vegetation;
- Wet foliar interception fraction for leafy vegetables;
- C-14 evasion layer thickness in soil; and
- Plant, meat, milk and fish transfer factors.

The above parameters were treated as stochastic and assigned probability density functions as described previously. The sensitivity analyses performed on these parameters using RESRAD, Version 6.1 are consistent with the analyses described previously. Using the |PRCC| ≥ 0.25 criterion, the dose was found to be sensitive to a number of the parameters listed above. Complete sensitivity analysis results can be found in the LTP. The most sensitive parameters identified for each of the radionuclides are highlight below:

- Cover depth: H-3, Mn-54, Co-60, Sr-90, Ag-108m, Cs-134, Cs-137, Eu-152, Eu-154, Eu-155, Cm-243
- Depth of roots: C-14, Fe-55, Ni-63, Tc-99
- External gamma shielding factor: Nb-94
- Distribution coefficients in the contaminated zone: Pu-238, Pu-239, Pu-241, Am-241

With the sensitive parameters identified, conservative values were assigned as discussed in the parameter selection process. Deterministic RESRAD Version 5.91 (3) was then run to calculate the concrete debris DCGLs. Table IV

summarizes the DCGLs, identifies the time to the peak dose, and quantifies the dose contributions from the various water independent and water dependent pathways. The results show the peak dose occurs at zero years (i.e., at the time of site release) for most of the radionuclides. The peak dose occurs at times greater than zero for Cs-137, Pu-238, Am-241, Pu-241, Pu-239, Nb-94, and Ag-108m. Note that Table IV includes a surface DCGL in addition to the volumetric DCGL calculated by RESRAD. The reader is referred to the LTP (1) for a description of the methodology used to determine the surface DCGL as a function of the volumetric DCGL, as it is beyond the scope of this paper.

The results also indicate that, with the exception of H-3, Pu-238, Pu-239, Pu-241 and Am-241, the dose contributions are predominantly from the water independent pathways, primarily from external radiation and the ingestion of plant foods. For H-3, Pu-238, Pu-239, Pu-241 and Am-241, the dose contributions come primarily from the ingestion of drinking water.

Table IV. Dose Modeling Results and Base Case DCGLs for Concrete Demolish Based on the Resident Farmer Scenario

Radio-nuclide	DCGL (pCi/g)	DCGL (dpm/100 cm²)	Time to Peak Dose (years)	Dose Fraction From Water Independent Pathways (%)						Dose Fraction From Water Dependent Pathways (%)			
				Ground	Inhal.	Plant	Meat	Milk	Soil	Water	Plant	Meat	Milk
H-3	9.05E+01	1.17E+06	0	-	-	6.67	0.15	1.09	-	73.44	15.76	0.50	2.40
C-14	2.05E+01	2.64E+05	0	-	-	89.32	4.56	4.77	-	1.10	0.19	0.03	0.03
Mn-54	5.51E+01	7.10E+05	0	6.84	-	87.03	0.18	0.44	-	5.21	0.30	-	0.01
Fe-55	8.96E+01	1.15E+06	0		-	86.61	5.27	0.44	-	6.86	0.66	0.15	0.01
Co-60	9.07E+01	1.17E+06	0	98.36	-	0.14	0.01	-	-	1.42	0.03	0.03	0.01
Ni-63	1.29E+02	1.66E+06	0	-	-	61.57	0.62	33.35	-	3.77	0.21	0.01	0.46
Sr-90	3.77E-01	4.86E+03	0	-	-	84.71	1.72	2.87	-	9.74	0.81	0.07	0.08
Nb-94	7.74E+00	9.97E+04	82.7	99.47	-	0.20	-	-	-	0.32	0.01	-	-
Tc-99	2.85E+01	3.67E+05	0	-	-	92.23	0.02	1.56	-	5.54	0.63	-	0.02
Ag-108m	2.59E+01	3.34E+05	177.3	99.89	-	0.01	-	0.02	-	0.08	-	-	-
Cs-134	3.21E+02	4.13E+06	0	75.69	-	2.73	0.28	0.46	-	19.08	0.44	0.64	0.68
Cs-137	6.45E+02	8.31E+06	0.1001	59.10	-	4.35	0.44	0.74	-	32.34	0.75	1.11	1.17
Eu-152	2.27E+02	2.92E+06	0	89.54	-	5.98	0.02	0.01	-	4.34	0.10	0.01	-
Eu-154	1.94E+02	2.50E+06	0	87.02	-	7.43	0.03	0.01	-	5.38	0.12	0.01	-
Eu-155	9.53E+03	1.23E+08	0	0.96	-	56.73	0.23	0.06	-	41.01	0.95	0.06	0.01
Pu-238	1.14E+01	1.47E+05	0.1182	-	-	19.43	-	-	-	77.91	2.65	0.01	-
Pu-239	1.00E+01	1.29E+05	82.8	-	0.26	19.92	0.04	-	1.97	75.23	2.56	0.01	-
Pu-241	1.49E+02	1.92E+06	68.8	-	0.04	30.08	0.01	-	0.31	67.99	1.57	-	-
Am-241	4.42E+00	5.69E+04	0.1182	-	-	29.56	-	-	-	68.84	1.59	-	-
Cm-243	3.83E+00	4.93E+04	0	0.01	-	55.91	-	-	-	43.07	1.00	-	-

Operational DCGLS

As discussed in the sections above, DCGLs, representing a TEDE dose of 25 mrem/year, were developed for soil, groundwater, and concrete for each radionuclide of interest at the site. In reality, exposures at the HNP site can be due to more than one medium, and this total exposure, by regulation, must still be no greater than 25 mrem/year. For example, the HNP site can be postulated to be occupied by an individual who farms the soil and obtains drinking and irrigation water from a well installed in the concrete debris-filled basement of a former building. In this case, the occupant would be receiving dose not only from contaminated soil but from contaminated groundwater as well. Additionally, the dose from groundwater would not only be affected by the existing contamination in the groundwater but would be also affected by the contamination in the concrete debris leaching into the groundwater. As the total dose to the individual from this scenario must be below the 25 mrem/year TEDE, a means of accounting for dose to a site occupant from all of the media present is needed. Simplistically, the total dose from all of the media present can be represented as:

$$H_{Total} = H_{Soil} + H_{Existing\,GW} + H_{FutureGW} \qquad\qquad \text{(Eq. 2)}$$

For each of these media (i), the dose (H^i) depends upon the concentration of contamination present (C^i) as compared to the calculated DCGL for that medium ($DCGL^i$). For soil and existing groundwater contamination, this relationship can be shown as:

$$H^i = 25 * \frac{C^i}{DCGL^i}$$

(Eq. 3)

Note that for $H_{FutureGW,}$ only the contribution to groundwater from contaminated concrete is added. To account for this, the formula above is modified accordingly by multiplying the right side of the equation above by the fraction of dose from water-dependent pathways, f, as determined by RESRAD:

$$H^{FutureGW} = 25 * f * \frac{C^{concrete}}{DCGL^{concrete}}$$

(Eq. 4)

Using the formulas provided above to account for the different the different media, the total dose (25 mrem/year) is given as:

$$25 = 25 * \frac{C^{soil}}{DCGL^{soil}} + 25 * \frac{C^{ExitingGW}}{DCGL^{ExistingGW}} + 25 * f * \frac{C^{FutureGW}}{DCGL^{FutureGW}}$$

(Eq. 5)

The numerator in each of the above terms is the limit for the amount of contamination that can exist at the time of final status survey, otherwise referred to as an "operational DCGL." To differentiate the "operational DCGLs" from the DCGLs representing 25 mrem/yr TEDE dose, the terminology "base DCGLs" is applied to the later. Restating the above equation in terms of "operational DCGLs" and "base DCGLs" and dividing all terms by 25, we find:

$$1 = \frac{DCGL_{OP-Soil}}{DCGL_{Base-Soil}} + \frac{DCGL_{OP-ExistingGW}}{DCGL_{Base-ExistingGW}} + f \frac{DCGL_{OP-ConcreteDebris}}{DCGL_{Base-ConcreteDebris}}$$

(Eq. 6)

The use of this equation requires that only one variable be unknown. In the case of the HNP, the values for the first and second terms on the right hand side of Eq. 6 were selected in order to calculate the operational DCGL for concrete.

As noted previously, the "base DCGLs" are calculated on a per radionuclide basis, and likewise the "operational DCGLs" are calculated on a per radionuclide basis. If a site has contamination that includes a mixture of radionuclides, as is the case at the HNP, the sum of fractions is used.

DISCUSSION

Site-specific DCGLs were developed for the HNP site as part of the NRC license termination process for four media: soil, groundwater, concrete from buildings left standing, and concrete from buildings demolished. These DCGLs were developed to meet the radiological criteria for unrestricted use as defined in 10 CFR 20.1402, which requires that the TEDE to an average member of the critical group does not exceed 25 mrem/year, including that from groundwater sources. It was necessary to develop site-specific DCGLs for the HNP site because the NRC interim screening values for soils are not applicable to sites with subsurface and/or groundwater contamination. Similarly, NRC screening values for building surfaces do not consider the possibility of using demolished concrete as backfill.

An integral part of the process in determining the site-specific DCGLs were the use of dose models and the assignment of model parameters. Dose models were constructed using the RESRAD and RESRAD-BUILD codes, which were then used to relate the residual radioactivity in site media to the dose received by a future resident or occupant of the site. Dose models require the assignment of a large number of parameters. Some of these parameters significantly influence the calculated dose. Many of these parameters are difficult to quantify and are not known

with certainty. It is also a requirement that the parameter values be assigned in such a way that the dose model overestimates rather than underestimates the dose. To meet this requirement and to ensure that the same level of conservatism is applied across all media and all radionuclides, it is necessary to establish a structured parameter assignment process that identifies the model parameters that influence the dose and account for the uncertainty in these parameters. The authors believe that the parameter assignment process described in this paper and illustrated in Figure 2 meets the requirements stated above.

The process developed to assign the parameters necessary to model dose and establish radiological criteria for site release comprises three components. First, parameters are categorized as behavioral, metabolic, or physical. Population means are assigned to the behavioral and metabolic parameters, which is appropriate because the TEDE requirements established in 10 CFR 20.1402 apply to the average member of the critical group. Second, physical parameters that significantly affect the modeled dose are established through formal sensitivity analysis. Third, once the sensitive parameters are identified, conservative values are established for each parameter at a fixed quantile of the parameter's cumulative distribution function. In this case, the 25% quantile was used to assign conservative values for parameters negatively correlated with dose, while the 75% quantile was used for parameters positively correlated with dose. This parameter assignment process was applied uniformly across all four media and all twenty radionuclides. In doing this, there is assurance that the conservatism associated with the resultant DCGLs is uniform across all media and all radionuclides.

In the course of completing the sensitivity analysis and dose modeling, results were obtained that may be of interest to other decommission projects. For the three media considered under the resident farmer scenario, the sensitivity analysis indicated that the dose was most sensitive to the depth of roots, external gamma shielding factor, food transfer factors, weathering removal constant for vegetation, cover depth, and contaminated zone distribution coefficients. For the concrete in buildings left standing, the deposition velocity, resuspension rate, time for source removal, and erosion rate were found be the sensitive parameters under the building occupancy scenario. Dose modeling results produced by RESRAD and RESRAD-BUILD include the dose contribution by pathway. Water-independent pathways for soils dominated the dose contributions under the resident farmer scenario, while the dominant pathways were radionuclide-specific in the case of concrete from buildings demolished. External radiation and inhalation were the dominant pathways for concrete from buildings left standing under the building occupancy scenario. Also, the peak dose was predicted to occur relatively early in the 1,000 year time period required for analysis by 10 CFR 20.1402 for all media and radionuclides, with the peak dose for most radionuclides occurring at the time of site release.

To place the values of the site-specific DCGLs developed for the HNP site into context, it is useful to compare their magnitudes against the interim screening values published by the NRC in the Federal Register for selected radionuclides. The site-specific soil DCGLs for H-3, C-14, Mn-54, Fe-55, Co-60, Ni-63, Sr-90, Tc-99 and Cs-137 were 374%, 47%, 116%, 274%, 100%, 34%, 91%, 66% and 72% of the interim screening values, respectively. Also for soils, the site-specific DCGLs ranged from about 100 to 1200% of the interim screening values for transuranic radionuclides. Similarly, the site-specific DCGLs for concrete in building left standing for H-3, C-14, Mn-54, Fe-55, Co-60, Ni-63, Sr-90, Tc-99 and Cs-137 were 263%, 278%, 100%, 7756%, 156%, 2000%, 1460%, 1115% and 154% of the interim screening values, respectively. These results indicate that DCGLs determined by site-specific dose modeling can differ significantly from the interim screening values.

Lastly, it is noted that the HNP site is the first power-reactor decommissioning project to have site-specific DCGLs accepted by the NRC. Their acceptance was contingent upon the successful development and implementation of the parameter selection process described in this paper.

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