APPENDIX A MERGING AIR RELEASE SOURCES INTO FOUR VIRTUAL SOURCES

The report addressing Phase II of the Savannah River Site (SRS) Dose Reconstruction Project identified approximately 15 major locations for actual sources of radionuclide release to air (1).[1] To make the computational work for this Phase III effort more tractable, Advanced Technologies and Laboratories International, Inc. (ATL) represented appropriate groups of individual sources by a set of four virtual sources. This appendix summarizes the thought processes that were used when performing this merger and the effects that the merger had on the precision and accuracy of the Phase III study.

A.1 Description of the Problem

Like most dose assessments, radiation doses received by a set of hypothetical humans were calculated for Phase III of the SRS Dose Reconstruction Project by summing up incremental doses from various sources, radionuclides, years, exposure pathways, and exposure locations. If this assessment had been performed in a direct fashion without combining sources, the total number of incremental doses that would have been calculated, written to a computer file, and summed up was estimated to be between 100,000 and 10,000,000. This large amount of data created several potential problems related to 1) data handling and processing; 2) computer run time, both for generating the doses and processing the results; and 3) quality assurance and quality control of the raw data output and its processing.

Figure A-1 shows approximately 15 separate, major sources for air release identified in the Phase II report (SRL is the Savannah River Laboratory, CS Area is the Central Shops Area, and CMX-TNX is a complex used to test equipment and chemical processes). For Phase III, an analysis was performed to determine a way to combine several of these sources. This would proportionally reduce the size of the computational problem and its attendant disadvantages in a manner that preserved the integrity of the assessment. Reducing the number of sources from 15 to 4 reduced the computational size to 27 percent of the original size (i.e., 4/15 = 0.27).

Table A-1 lists the main sources for air releases at the SRS. These sources each emitted a mix of radionuclides, and emission rates of the various radionuclides varied with time. For the Phase III study, these time variations were accounted for by analyzing on an annual basis the release of the radionuclides to air over the 39-year span of nuclear material production.

For any given exposure location (e.g., the residence of one of the hypothetical families), the concentration of a given radionuclide was calculated as the sum of the concentrations induced at that location by each of the separate sources. For short time periods (e.g., 30 minutes), the concentration induced by a source at a given exposure location depends upon the following factors:

- The release rate of the contaminant (e.g., curies per year).
- The height of the release (stack height).
- Wind speed.
- Wind direction.
- Atmospheric stability class.
- Distance from the source to the exposure location.

[1]The actual number of sources of radionuclide release into the air depends on how the larger and smaller sources of release are grouped.

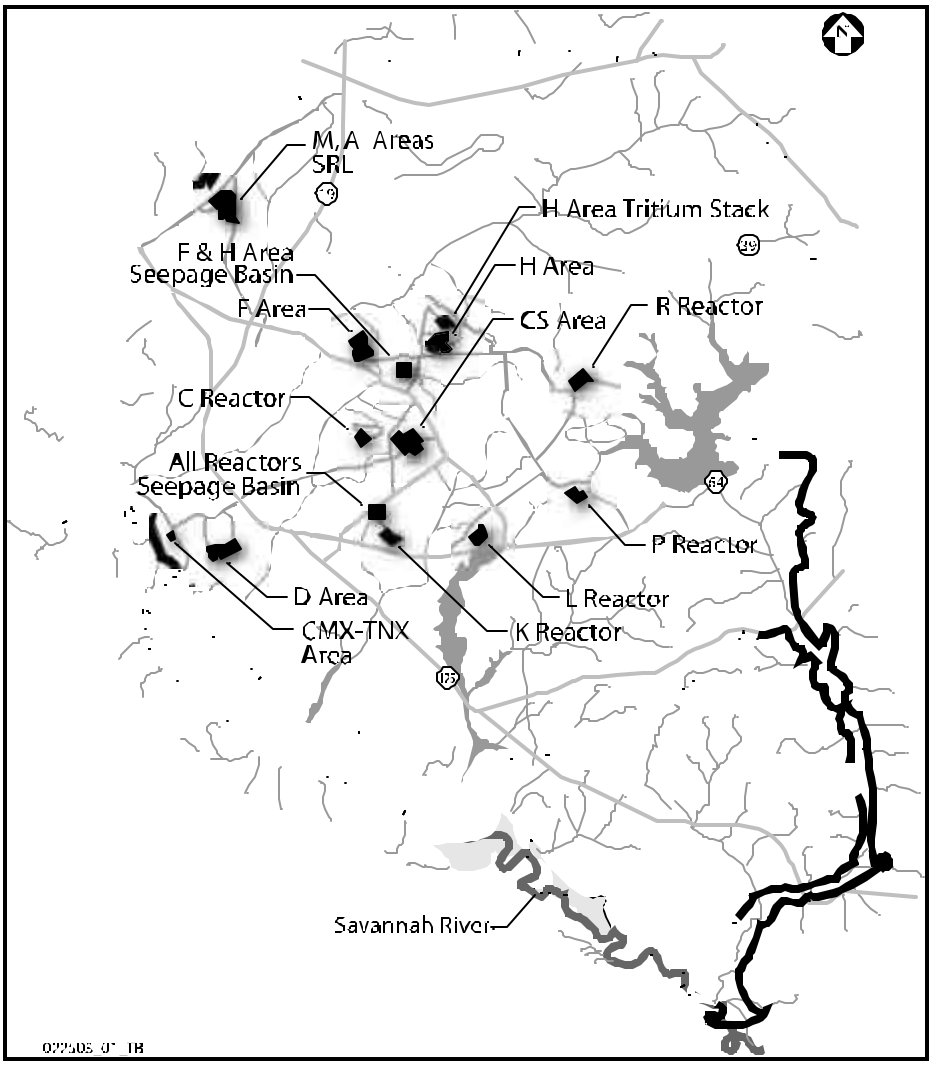

Figure A-1 Major Sources for Air Releases

For the long-term, annual releases of interest in this study, an appropriate model—the sector average approximation—was used to estimate the concentrations induced by each source at the exposure locations. This probabilistic approach sums up the concentrations produced by each wind speed, wind direction,[2] and stability class weighted by the frequency with which these conditions occur (the joint frequency distribution). This calculation obtains an average concentration produced by the source at the exposure location of interest over a long time period. The resulting formula for concentration is based on the standard Gaussian plume model (2).

The joint frequency distribution is a set of data for a specific location that represents a summary of meteorological conditions over a specified period of time such as a year. The joint frequency distribution is computed by compiling meteorological data, usually determined and recorded for each hour, over an

[2] Wind direction is usually determined in terms of either 16 or 36 sectors. Each sector represents a pie-shaped slice of an imaginary circle surrounding the source. In the older 16-sector approximation, each pie-shaped wedge describes a 22.5^{o} arc (360°/16 sectors) corresponding to the 16 major compass directions (N, NE, NNE, E, etc.). In the newer 36-sector approximation, each pie-shaped wedge describes a 10° arc (360°/36 sectors).

Table A-1 Main Sources for Air Releases of Radionuclides at SRS

Facility Type	Designation	Principal Radionuclides Released			
		Tritium	ß-Emitters	a-Emitters	Activation Products
Reactors	C	X	X		X
	K	X	X		X
	L	X	X		X
	P	X	X		X
	R	X			X
Separations Facilities	F-Canyon	X	X	X	X
	H-Canyon	X	X	X	X
	H Tritium Stack	X			
Waste Facilities	All Reactors Seepage Basin Evaporation*	X			
	CMX-TNX	X			
	D-Area	X			
	F & H Seepage Basin Evaporation†	X			
Other Facilities	A-Area	X	X	X	X
	M-Area	X		X	
	SRL	X‡	X‡	X‡	

*The "All Reactors Seepage Basin Evaporation" is already a virtual source. Each reactor had its own seepage basin. The location of this virtual source was chosen to be close to the centers of the locations of the reactors.
†The "F & H Seepage Basin Evaporation" is already a virtual source, but the seepage basins for F and H are only about one mile apart.
‡Releases from the SRL may have been included with A-Area releases for at least some years.

appropriate time interval and computing the frequency of occurrence of each joint frequency category. Each joint frequency category represents a band of wind speeds, directions, and stability conditions.

Because this Phase III study is concerned with annual releases, it was preferable to use the joint frequency distribution computed for each year. However, because the meteorological data tower has only been operational at the SRS since the early 1970's, no annual data were available for about 20 of the early years (3). In addition, the historical meteorological data from the on-site tower was made available for this study as five-year averages. Therefore, a 20-year average was used to represent the joint frequency distribution for all 39 years. This appeared reasonable in light of the general practice used by the SRS for estimating environmental consequences. For example, the SRS Environmental Report for 1991 (4) states that the meteorological measurements made over the five-year period (1982-1986) were used and that comparisons with other time periods "show very little change in dispersion conditions."

The 20-year average joint frequency distribution that was obtained from the SRS was provided in terms of 16 sectors, where each sector describes a 22.5-degree arc around the circumference of the SRS meteorological data tower.

A.2 Description of the Analyses

The central issue was whether combining separate sources at an artificial location (a virtual source) would provide sufficient accuracy. This issue was addressed in two ways due to the different characteristics of the source groups. For strong sources (e.g., the separations facilities and reactors), it was important to show that the concentrations estimated for offsite exposure locations did not have large errors due to sources being consolidated within a particular source group and represented by a virtual source. For weak sources (e.g., the seepage basins and waste facilities), the precision of the concentration estimate (and hence, the dose estimate) based on representing the weak release at a virtual source was not as significant due to the small contribution from the weak sources compared to the contribution from the strong sources.

An underlying assumption for this analysis was that radionuclide concentration was a suitable surrogate for individual dose in determining whether coalescence of sources was acceptable. Because some of the exposure pathways depend on radionuclides deposited on soil or vegetation, consideration of radionuclides deposited from the contaminant plume may be important. However, the quantity of radionuclide deposited depends on the air concentration of the radionuclide. If the deposition rate is moderate (which is the case for our assumed values of particle size and density), then plume depletion will not be a major factor and the air concentration will be a good surrogate for individual dose.

Approximating a group of actual sources by a virtual source reduces the precision of the analysis. However, in evaluating this apparent lack of *precision*, one should bear in mind the great difficulty in achieving *accuracy* (i.e., correspondence between calculated doses and doses actually received). The following factors limit the accuracy of the dose reconstruction in general and the doses from air releases:

- The released quantities of radionuclides are estimated with substantial uncertainties (e.g., Figure 1-7 in the Phase II report shows uncertainty bands around annual iodine-131 releases that range up to a factor of 10) (1).
- The receptors and their behavior are hypothetical, chosen to provide realistic dose estimates that have a good chance of bounding doses actually received.
- Many of the model parameters are not known precisely (e.g., radionuclide uptake rates by biota); furthermore, these parameters may have significant variability in time and across the region modeled.
- The site history is known to include many acute releases; doses from large acute releases may deviate significantly from doses calculated on the basis of average annual releases.

Because of these and other factors, a high degree of precision (i.e., correspondence between the calculated concentrations based on multiple separate sources and those calculated based on virtual sources) in the air dispersion modeling was not warranted due to other factors which limited the overall accuracy of the analysis.

A.2.1 The Initial Analysis

Initially, four virtual sources were evaluated with each virtual source corresponding to the types of facilities listed in Table A-1. Table A-2 lists the groups of facilities comprising these four original virtual sources. Each of these virtual sources was placed approximately at the centers of the locations of the constituent sources.

Table A-2 Definitions of Original Virtual Source Groupings

Original Group	Facilities in Group
Group $1_{original}$	A-Area, M-Area, SRL
Group $2_{original}$ (Separation Facilities)	F-Canyon, H-Canyon, H Tritium Stack
Group $3_{original}$ (Reactors)	C-, K-, L-, P- and R-Reactors
Group $4_{original}$ (Seepage Basins and Other Facilities)	All Reactors Seepage Basin Evaporation, CMX-TNX, D Area F & H Seepage Basin Evaporation

The waste facility group (Group $4_{original}$) was a set of sources cited in the Phase II report and in references (e.g., [5]) on which the Phase II report was based. However, these sources were not included in the Phase II estimates of release. For completeness, these sources were added to the Phase III assessment even though they are not major sources.

To determine how precisely the virtual sources represented the actual sources, concentrations induced by the actual and virtual source locations were compared with unit source strengths at each location. Because air dispersion was approximated using averaged meteorological conditions, the relationship between the release rate of a source and the concentration induced at an exposure location was fixed. This relationship can be represented by a *dilution factor* (e.g., units of y/m^3), which is the ratio of the concentration at the exposure location divided by a unit release rate. In air-transport modeling, it is often represented as the relationship ?/Q, where ? is the concentration at the exposure location (e.g., curies per cubic meter) and Q is the release rate (e.g., curies per year).

The initial analysis determined the concentrations induced at each of 9 offsite exposure locations by each of the 15 individual sources. Figure A-2 shows the nine offsite exposure locations. These concentrations were expressed as 135 (135 = 9 x 15) dilution factors assuming unit release rates (e.g., 1 curie per year) from each source. These dilution factors were obtained using Version 2 of the GENII code.[3] In addition to the 135 dilution factors from the original sources, 36 additional dilution factors were determined for the 4 original virtual source locations.

In considering the initial analysis, it was determined that, because Group $3_{original}$ (reactors) and Group $4_{original}$ (seepage basins and other areas) were comprised of sources dispersed widely around the site, the original virtual sources did not represent all constituent sources with sufficient precision for all of the exposure locations. This lack of precision occasioned a reexamination of the initial grouping of virtual sources.

In rethinking the analysis, the following four facts were noted and corresponding adjustments made to the source groupings:

[3]All further reference to the GENII code is to Version 2 of the code. The original version of GENII was created by members of Pacific Northwest National Laboratory in the late 1980's. Version 2 incorporates improved transport models, exposure options, dose and risk estimates, and user interfaces. It implements dosimetry models recommended by the International Commission on Radiological Protection and is designed to function within the Framework for Risk Analysis Multimedia Environmental Systems (FRAMES) (6).

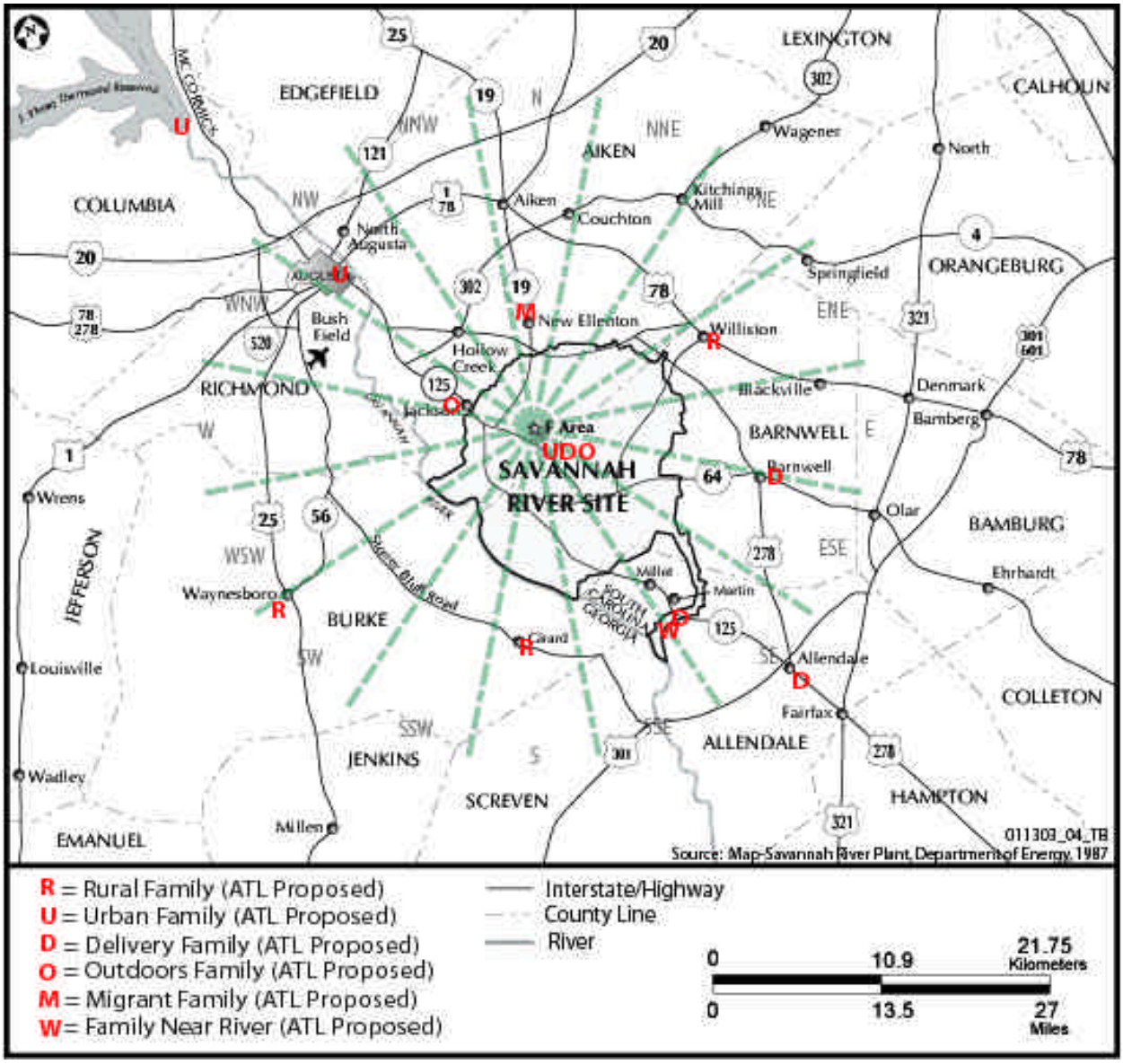

Figure A-2 Exposure Locations

1. The initial grouping for reactors was abandoned; the reactors were instead represented by two virtual sources—one for P- and R-Reactors, and one for C-, K-, and L-Reactors.
2. Because the releases from the R-Reactor occurred only for a short time, the virtual source location for the P- and R-Reactors was weighted toward the P-Reactor location. The weighting factor is approximately 0.85. Purely geometric considerations determined the remainder of the virtual source locations.
3. Although no releases are tabulated separately in the Phase II database for the Savannah River Laboratory, site history and recent environmental reports verify that releases actually occurred from this location. For this reason, coordinates for this location were used to calculate the location of the virtual source for that group.

4. Representation of the Group 4 original minor sources by a single virtual source did not provide a satisfactory overall level of precision. Nevertheless, inclusion of these sources was deemed appropriate (even if accomplished in an approximate fashion) because a fundamental component of the Phase III approach was to recognize and model the spatial distribution of the various sources. Because these are minor sources, another way to represent them was available. First, this waste facility group primarily released tritium into the air. Second, these releases were a small percentage of their respective facility releases. For example, the total tritium releases from the reactor seepage basins when compared to total tritium releases from the reactors on a yearly basis were, at most, 6.39 percent. This occurred in 1976 (5). Releases from the F&H Area seepage basin equaled, at most, 4.91 percent of the total tritium releases for the F-Canyon, H-Canyon, and H- Tritium Stack, also in 1976 (5). Furthermore, the ratio of annual tritium releases from the entire waste facility group to the annual total site release of tritium was a small fraction; the maximum value of the ratio was 7.14 percent, also in 1976 (5). Finally, the ratio of the average annual tritium release from the waste facility group to the average annual tritium release from the entire site was small—2.36 percent (average taken from 1957-1990).[4]

To mitigate any reduced precision resulting from consideration of these sources, the tritium source terms from these minor sources were incorporated into the four virtual sources as follows:

- Incorporate tritium releases from F & H seepage basin evaporation into the F & H Canyon virtual source.
- Incorporate the D-Area releases and the CMX-TNX releases in the virtual source for C-, K-, and L-Reactors (closest neighbor).
- Partition tritium releases from the all-reactor seepage basin evaporation between the virtual sources for the C-, K-, L-Reactors and the P- and R-Reactors according to the ratio of their respective reactor releases.

In addition to these adjustments for tritium releases, releases of alpha and beta-gamma activity from the D-Area were added to the virtual source for the C-, K, and L-Reactors. These releases are documented for the years 1986-92 and are small compared to releases in these categories for the site as a whole (4, 5, 7, 8).

The use of the 16-sector joint frequency distribution for SRS presented some modeling concerns. Comparisons of concentrations produced by actual versus virtual sources were made more difficult because of the discontinuous behavior of the sector average approximation. Because the sector average approximation treats each 22.5-degree sector as having a uniform concentration within the sector at a given radius, the transition between sectors can show a substantial discontinuity. Figure A-3 shows this discontinuity schematically. However, this calculated discontinuity in concentration is a modeling artifact and does not represent actual conditions. If smaller and smaller sectors were chosen for the analysis (e.g., one degree), then the magnitude of any discontinuities would become quite small.

The GENII code models sources at different locations by centering a polar coordinate grid over each source. This coordinate grid is then used to calculate concentrations at various exposure locations. However, when the coordinate grid is moved between two nearby sources, the concentrations at exposure locations near a radial grid line may change substantially—not because of any physical phenomenon, but because the exposure location moves from one sector to another as the grid moves from one source to another. For example, when the center of the grid was moved between the virtual source for Group $2_{original}$ and the F-Canyon, Waynesboro changed from the sector centered on 247.5 degrees (WSW) to the sector

[4] References used for calculating this average were (5) and (7).

centered on 225 degrees (SW). This produced a difference in calculated concentrations of about 31%. When the center of the grid was moved between the virtual source for Group $2_{original}$ and the H-Canyon, the sector for Waynesboro remained 247.5° (WSW). This produced a difference in concentrations of only 3.8%. Since the F-Canyon and H-Canyon sources are approximately equidistant from the virtual source, this difference in behavior is related to the coarseness of the sector average approximation and does not represent a real physical difference in behavior.

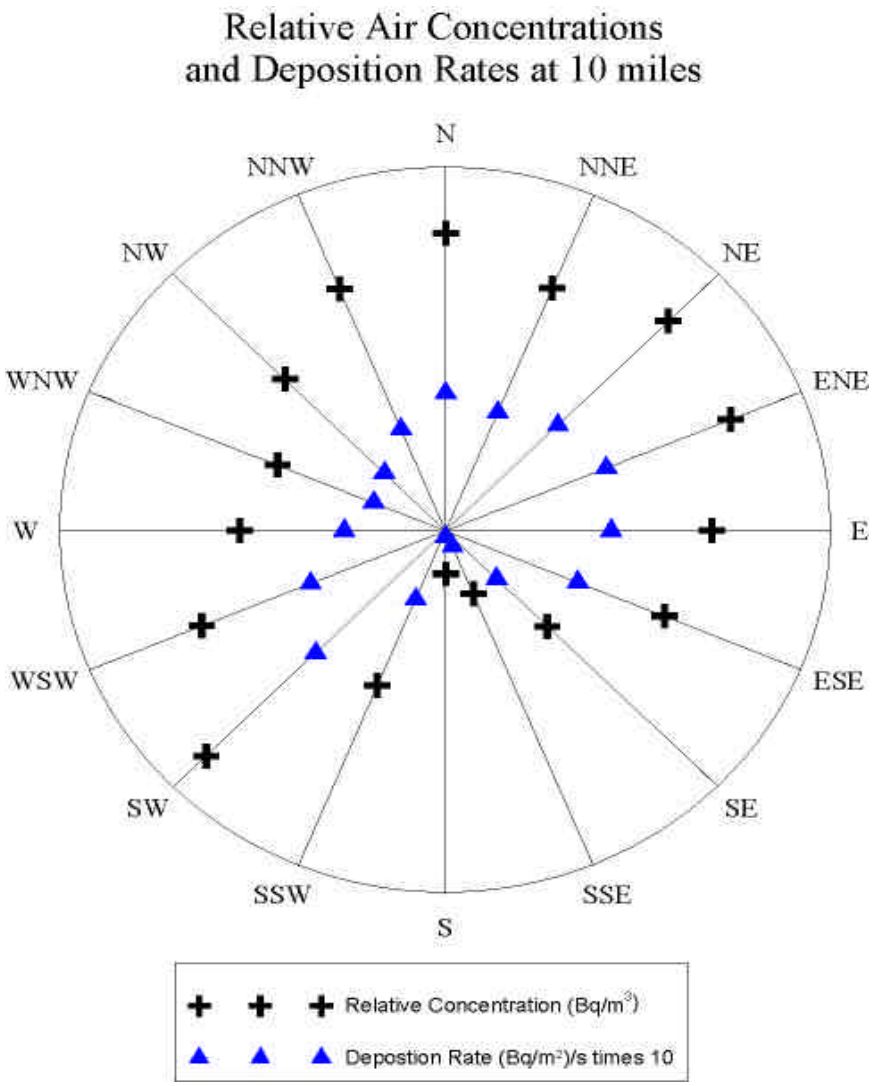

Figure A-3 Plot, in Polar Coordinates, of Concentrations and Deposition Rates for a Source Located on the SRS

The radii correspond to the center of the sectors modeled. Note the large concentration gradients while traversing from the SW radius toward S. This means there is a substantial change in estimated concentration if one moves from the sector centered on SSW to either S or SW. A movement on the grid of a few meters could induce such a change; however, the estimated change is due to the coarseness of the grid, not physical reality. Also note that the deposition rate tracks proportionally to the concentration.

Similarly, the exposure location for Girard, Georgia, was originally assumed to be at the actual site of the town. Assuming a radial grid over a source located in the rough center of the SRS, the boundary between the 202.5-degree (SSW) and 180-degree (S) sectors runs very close to the actual site of the town. By moving the center of the source only slightly in one direction or the other, the sector which modeled radiation concentrations at Girard shifted between the SSW sector and the S sector. Figure 6-5 shows this shift between sectors resulted in large apparent changes in radionuclide concentrations that were due more to the coarseness of the grid than physical reality.

To make the Phase III analysis easier to interpret, the coordinates of two exposure locations, Waynesboro and Girard, were adjusted slightly to minimize this modeling artifact. For Waynesboro, the location was moved from the city center to the actual location of the present high school (2-3 kilometers to the southeast). For Girard, the location was moved from the town center to a spot further to the east along Stony Bluff Road, about 3 miles west of the Savannah River.

A.2.2 The Second Analysis

From the perspectives gained in the first analysis, the number of separate sources to be analyzed was reduced from 15 to 11 because the 4 waste facility sources (Group $4_{original}$) were subsumed into other sources. The second analysis proceeded in two parts: Part 1, a comparison of concentrations produced by actual and virtual sources within redefined groups (Section A.2.2.1); and Part 2, a quantitative confirmation of the qualitative argument that a weak source can be moved to a virtual location with little effect on concentration and dose (Section A.2.2.2).

A.2.2.1 Part 1: Comparison of Concentrations

In this analysis, the concentration induced at each offsite exposure location by each source in a group was compared to the concentration induced by the virtual source representing that group, assuming a unit release rate for the individual sources and virtual source. If the virtual source concentration differed from the original source concentration by no more than 25 percent for every original source, then the virtual source was considered acceptable.

Given all the uncertainties in the dose reconstruction project, 25 percent was a relatively stringent criterion that was intuitively appealing. If no individual source in the group differed from the virtual source by more than 25 percent, the combination of several individual sources would differ by no more than 25 percent from the equivalent virtual source. This behavior was examined on a hypothetical basis by comparing the concentrations induced by a combination of n sources to the concentration induced by a virtual source representing the n sources, assuming each source had a concentration of 1/n.

A.2.2.1.1 Description of the Basic Computations

The GENII code was run multiple times to estimate the concentrations at 9 offsite exposure locations for the 11 actual sources and 4 virtual sources for a total of 135 dilution factors (9 x [11 + 4]). All sources were assumed to have a unit concentration of a contaminant that did not degrade by radioactive decay, deposition, chemical reaction, or any other depleting physicochemical process. Appropriate stack heights were used for actual sources and for the virtual sources derived from them.

A.2.2.1.2 Definition of Groups and Virtual Sources

Table A-3 defines the groupings for the second analysis.

Table A-3 Definitions of Final Virtual Source Groupings

Final Group	Facilities in Group
Group 1	A-Area, M-Area, SRL
Group 2	F-Canyon, H-Canyon, H Tritium Stack, F&H Seepage Basins
Group 3	C-Reactor, K-Reactor, L-Reactor, Reactor Seepage Basin release attributable to C, K, and L-Reactors, D-Area, CMX-TNX
Group 4	P-Reactor, R-Reactor, Reactor Seepage Basin release attributable to P- and R-Reactors

The coordinates of the virtual sources were chosen to be at the approximate centers of the actual sources in the group. But for Group 4, the virtual source location was shifted heavily toward P-Reactor because it operated over a much longer time period than R-Reactor.

Table A-4 lists the Universal Transverse Mercator (UTM) coordinates of the actual sources, the virtual sources, and the exposure locations.

Table A-4 Rectangular Coordinates (UTM) of Sources and Exposure Locations

Location	X UTM (m)*	Y UTM (m)*	Release Height (m)*
Source Locations			
A-Area	431,683	3,689,063	10
C-Reactor	436,947	3,679,014	61
D-Area	431,034	3,673,822	0
F-Canyon	436,755	3,683,149	61
H-Canyon	440,168	3,683,317	61
F+H Seepage Basin Evap.	438,774	3,682,115	0
K-Reactor	438,077	3,674,736	61
L-Reactor	441,899	3,674,615	61
M-Area	431,250	3,688,966	10
P-Reactor	445,841	3,676,587	61
R-Reactor	446,034	3,681,659	61
SRL	431,346	3,689,543	10
H (Tritium Stack)	439,880	3,683,221	61
All Reactors – Seepage Basin	437,764	3,675,000	0
CMX-TNX Area	429,183	3,674,784	0
Virtual Source Locations			
Group 1	431,467	3,689,255	10
Group 2	438,459	3,683,233	61
Group 3	438,990	3,676,350	61

Location	X UTM (m)*	Y UTM (m)*	Release Height (m)*
Source Locations			
Group 4	446,010	3,679,087	61
Offsite Exposure Locations			
Girard, GA	442,700	3,653,500	
Waynesboro, GA	406,000	3,660,100	
Augusta, GA	411,800	3,703,350	
Jackson, SC	426,900	3,687,700	
New Ellenton, SC	436,150	3,697,250	
Barnwell, SC	466,650	3,678,500	
Martin, SC	455,350	3,659,300	
Allendale, SC	471,100	3,652,200	
Williston, SC	460,800	3,695,850	

*m = meters.

A.2.2.1.3 Comparison of Concentrations from Actual and Virtual Sources

Tables A-5 through A-8 show the results of the quantitative analysis. Columns with headings that include "% Delta" show percentage differences (percent error) between dilution factors for actual and virtual sources. The percent error was computed to show the direction of the deviation between concentrations predicted by the virtual and actual sources:

$$\text{Actual Source \% error} = [(D_V - D_A)/D_A] \times 100$$

Where D_V is the dilution factor for the virtual source and a particular exposure location, D_A is the dilution factor for the actual source and the same exposure location. The actual source is assumed to be the baseline (i.e., a negative value in the table means the virtual source is underestimating the release, while a positive number means the virtual source is overestimating the release).

In Table A-5, the first three columns list the dilution factors for each of the actual sources— A-Area, M-Area, and SRL, respectively. The fourth column lists the dilution factors for the Group 1 virtual source. The next three columns, marked A % Delta, M % Delta, and SRL% Delta, provide the percent error involved when the virtual source is used instead of the actual source. The next column, marked Sum: A, M, SRL, is a dilution factor that represents the concentrations that would result if each actual source had a magnitude of 1/3; in other words, the combined source strength of the three sources is unity. The next column, marked Sum % Delta, lists the percent error between that produced by the virtual source and the combined effect of the actual sources assuming each has equal strengths that sum to unity. Other tables in this group follow the same format.

The deviations shown in Tables A-5 through A-8 are frequently quite small. For Group 1, the maximum deviation is -9 percent for the exposure location Jackson and the M-Area source. For Group 2, the maximum deviation is -15 percent for the exposure location Jackson and the F-Canyon source. For Group 3, the maximum deviation is -27 percent for the exposure location Jackson and the C Reactor source. For Group 4, the maximum deviation is +17 percent for the exposure location Augusta and the R-Reactor

Table A-5 Comparison of Dilution Factors for Group 1 Individual Sources and Virtual Source

Exposure Location	A-Area	M-Area	SRL	Virtual Source	A % Delta	M % Delta	SRL % Delta	Sum: A, M, SRL	Sum % Delta
Girard, GA	7.881E-06	7.872E-06	7.761E-06	7.827E-06	-0.69	-0.58	0.84	7.838E-06	-0.14
Waynesboro, GA	1.687E-05	1.704E-05	1.681E-05	1.687E-05	0.00	-1.01	0.36	1.691E-05	-0.22
Augusta, GA	2.196E-05	2.225E-05	2.252E-05	2.225E-05	1.29	-0.01	-1.23	2.224E-05	0.01
Jackson, SC	1.320E-04	1.502E-04	1.381E-04	1.377E-04	4.14	-9.08	-0.29	1.401E-04	-1.74
New Ellenton, SC	6.377E-05	6.129E-05	6.595E-05	6.430E-05	0.82	4.68	-2.57	6.367E-05	0.98
Barnwell, SC	1.171E-05	1.158E-05	1.155E-05	1.162E-05	-0.80	0.32	0.57	1.161E-05	0.03
Martin, SC	8.530E-06	8.484E-06	8.394E-06	8.463E-06	-0.79	-0.24	0.82	8.469E-06	-0.07
Allendale, SC	5.919E-06	5.891E-06	5.855E-06	5.887E-06	-0.55	-0.07	0.54	5.888E-06	-0.03
Williston, SC	1.749E-05	1.721E-05	1.735E-05	1.739E-05	-0.59	1.02	0.21	1.735E-05	0.21

Table A-6 Comparison of Dilution Factors for Group 2 Individual Sources and Virtual Source

Exposure Location	F-Canyon	H-Canyon	H Tritium Stack	Virtual Source	F % Delta	H % Delta	H Tritium Stack % Delta	Sum: F, H, H Tritium Stack	Sum % Delta
Girard, GA	7.36E-06	6.49E-06	6.51E-06	6.467E-06	-13.80	-0.38	-0.61	6.785E-06	-4.93
Waynesboro, GA	1.18E-05	1.10E-05	1.11E-05	1.141E-05	-3.80	3.57	2.86	1.131E-05	0.88
Augusta, GA	1.10E-05	1.01E-05	1.02E-05	1.054E-05	-4.14	3.92	3.45	1.043E-05	1.07
Jackson, SC	2.73E-05	2.09E-05	2.13E-05	2.372E-05	-15.20	12.03	10.38	2.315E-05	2.40
New Ellenton, SC	2.74E-05	2.45E-05	2.45E-05	2.716E-05	-0.72	9.69	9.80	2.546E-05	6.26
Barnwell, SC	1.34E-05	1.51E-05	1.50E-05	1.421E-05	5.70	-6.47	-5.42	1.450E-05	-2.06
Martin, SC	8.45E-06	7.84E-06	7.82E-06	8.733E-06	3.27	10.27	10.52	8.033E-06	8.02
Allendale, SC	5.47E-06	5.77E-06	5.75E-06	5.613E-06	2.62	-2.74	-2.40	5.660E-06	-0.84
Williston, SC	1.41E-05	1.59E-05	1.57E-05	1.494E-05	5.91	-6.60	-5.26	1.524E-05	-1.99

NOTE: I thought we decided that computer printout abbreviations for exponents were not to be used in tables or text.

Table A-7 Comparison of Dilution Factors for Group 3 Individual Sources and Virtual Source

Exposure Location	C-Reactor	K-Reactor	L-Reactor	Virtual Source	C % Delta	K % Delta	L % Delta	Sum of All Reactors	Sum % Delta
Girard, GA	8.52E-06	1.03E-05	9.17E-06	8.373E-06	-1.76	-22.89	-9.50	9.327E-06	-11.39
Waynesboro, GA	8.97E-06	9.24E-06	8.43E-06	8.843E-06	-1.43	-4.43	4.72	8.877E-06	-0.38
Augusta, GA	1.01E-05	9.14E-06	8.52E-06	9.157E-06	-9.76	0.15	6.92	9.239E-06	-0.90
Jackson, SC	2.67E-05	2.04E-05	1.81E-05	2.107E-05	-26.56	3.29	14.06	2.172E-05	-3.07
New Ellenton, SC	2.09E-05	1.65E-05	1.46E-05	1.781E-05	-17.07	7.19	17.91	1.733E-05	2.68
Barnwell, SC	1.37E-05	1.41E-05	1.63E-05	1.466E-05	6.89	3.89	-11.26	1.468E-05	-0.16
Martin, SC	9.52E-06	1.12E-05	1.28E-05	1.094E-05	12.99	-2.16	-17.06	1.117E-05	-2.08
Allendale, SC	5.83E-06	6.34E-06	6.90E-06	6.310E-06	7.64	-0.51	-9.27	6.355E-06	-0.71
Williston, SC	1.30E-05	1.22E-05	1.33E-05	1.294E-05	-0.21	5.97	-3.06	1.283E-05	0.90

Table A-8 Comparison of Dilution Factors for Group 4 Individual Sources and Virtual Source

Exposure Location	P-Reactor	R-Reactor	Virtual Source	P % Delta	R % Delta	Sum of P & R	Sum % Delta
Girard, GA	8.32E-06	6.85E-06	7.515E-06	-10.70	8.90	7.583E-06	-0.90
Waynesboro, GA	7.55E-06	7.15E-06	7.345E-06	-2.79	2.65	7.350E-06	-0.07
Augusta, GA	8.18E-06	7.01E-06	8.455E-06	3.22	17.13	7.595E-06	10.17
Jackson, SC	1.30E-05	1.43E-05	1.368E-05	4.75	-4.75	1.368E-05	0.00
New Ellenton, SC	1.50E-05	1.89E-05	1.669E-05	10.16	-13.10	1.693E-05	-1.47
Barnwell, SC	1.98E-05	1.98E-05	2.000E-05	1.25	1.05	1.977E-05	1.15
Martin, SC	1.14E-05	9.21E-06	1.022E-05	-11.25	9.85	1.029E-05	-0.70
Allendale, SC	7.24E-06	6.56E-06	6.900E-06	-4.91	4.93	6.900E-06	0.01
Williston, SC	1.57E-05	1.89E-05	1.721E-05	8.83	-9.82	1.730E-05	-0.49

source. Although the maximum deviation for Group 3 is slightly in excess of the 25-percent target criterion, it is not considered to be a serious concern because the excess is only 2 percent.

Recall that a positive ("+") percent error means the virtual source predicts a higher concentration than is predicted by the actual source (i.e., an over-prediction); a negative ("-") percent error means the virtual source underestimates concentration. Because the virtual source locations were chosen to be approximately at the centers of the group of individual actual sources and because the exposure locations are widely distributed around the site, the direction of the error tends to be evenly distributed between overprediction and underprediction. For example, the column labeled "L % Delta" in Table A-7 has five negative entries (underestimates) and four positive entries (overestimates). Furthermore, the sum of the

column is –6.5 percent, even though the largest entry is +17.9 percent. This implies that overestimates in some exposure locations are approximately balanced by underestimates at other locations. One may also look at the rows corresponding to an exposure location in each of Tables A-5 through A-8. Of the 36 rows (9 locations x 4 virtual sources), only 5 have all the errors in the same direction; all the rest have a mix.

However, there may be a bias for large errors. Out of the four maximum errors in the tables describing the four virtual sources, three are negative. This indicates that the virtual source underpredicted the concentration induced by the actual source for three out of the four maximum errors. A conjecture that could explain this apparent bias is related to the fact that the maximum error is expected for those exposure locations closest to the site. Consider a hypothetical situation where the virtual source is located in the middle of a line connecting two actual sources, A and B. Further suppose that the exposure location is at a point on the same line, but to the left of A. The increase in concentration at the exposure location induced by changing from the virtual source to source A is larger than the decrease in concentration induced by changing from the virtual source to source B, even though the change in distances are the same. This is because the dependence of concentration on distance is nonlinear. This is the suspected reason why the maximum errors, where small distances are involved, are biased toward underestimation.

In addition to this comparison of the concentration induced by each actual source to the concentration induced by the virtual source, the combined effect of a unit release at every source was compared to the effect of the virtual source with its strength equal to the combined strength of all actual sources. That is, if there were n sources in the group, each with a unit release, the strength of the virtual source was assumed to be n. This is a particular example of what may actually occur. In general, the individual sources in a group represented by a virtual source have strengths that vary in time. To analyze the error involved in such a situation would be complex. However, the error is capped by the comparisons made above where the virtual source was compared to each individual source in turn (i.e., the percent error from an entire group can never be larger than the maximum error exhibited by any single individual source).

Because it was not feasible to evaluate all possible permutations of source strength, the condition of all sources having the same strength was chosen as an example. Although this choice of source strengths was but one of an infinite number of choices, it did demonstrate (as expected) that a virtual source would represent a group of sources more precisely than an individual source. This is because underestimates for some sources were often balanced by overestimates for others. As can be seen in Tables A-5 through A-8, the columns marked “Sum” provide the dilution factors induced by the combination of the actual sources. The columns marked “Sum % Delta” indicate the percentage deviations between the combination of actual sources and the virtual source.

These deviations are also very small. For Group 1, the maximum deviation is 2 percent for the exposure location Jackson. For Group 2, the maximum deviation is 8 percent for the exposure location Martin. For Group 3, the maximum deviation is 11 percent for the exposure location Girard. For Group 4, the maximum deviation is 10 percent for the exposure location Augusta. As expected, the concentrations from the combined actual sources are closer to those of the equivalent virtual sources because underestimates and overestimates in concentrations using the virtual source to represent each actual source tended to cancel each other. This led to a more precise estimate for the group than for many of the individual sources taken separately.

Figures A-4 through A-7 illustrate graphically the concentration comparisons discussed above. The dilution factors for the actual and virtual sources are plotted on the y-axis for each of the exposure locations shown on the x-axis. With few exceptions, the concentrations implied by these dilution factors would all be very close.

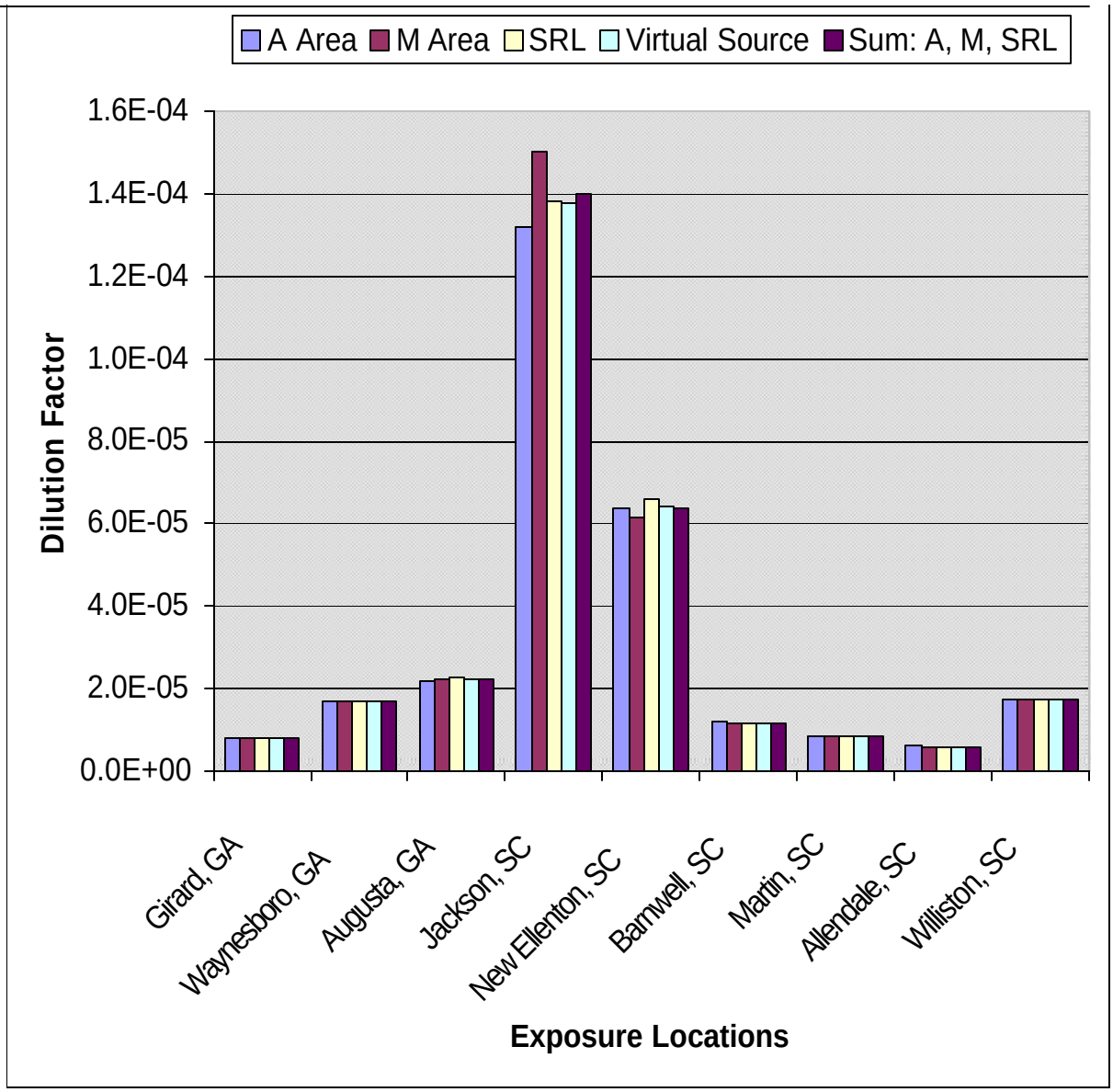

Figure A-4 Group 1 Comparisons

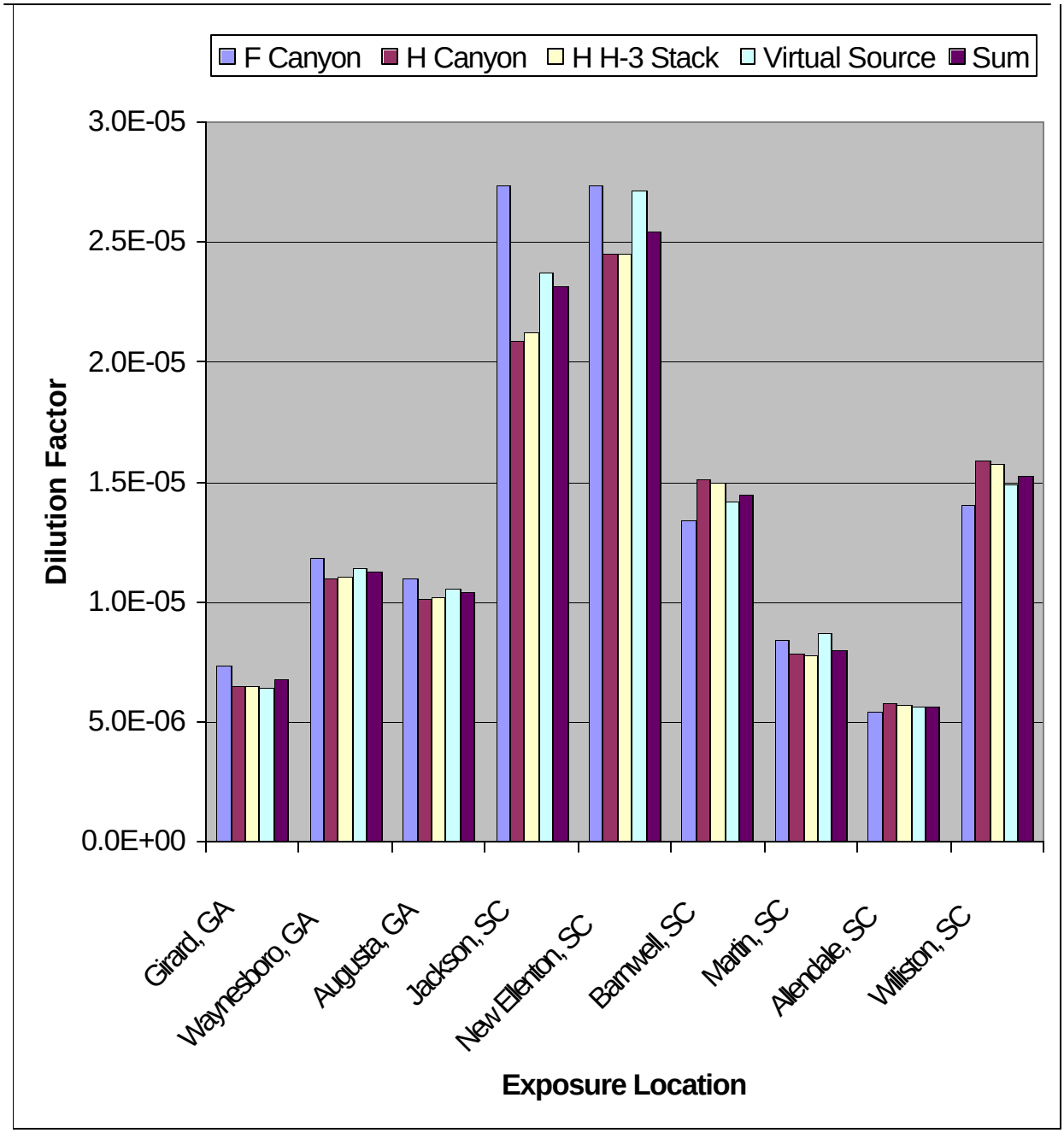

Figure A-5 Group 2 Comparisons

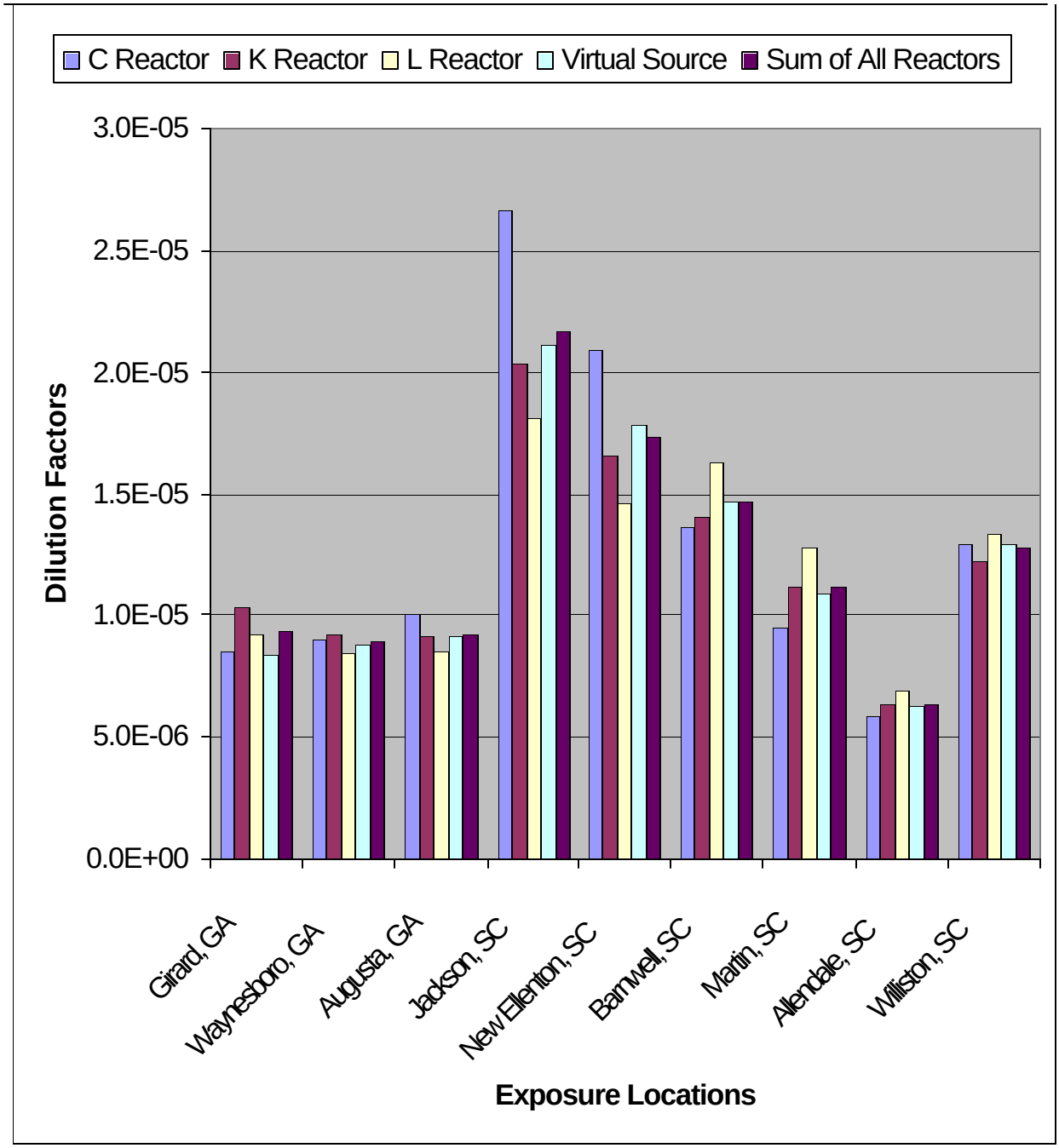

Figure A-6 Group 3 Comparisons

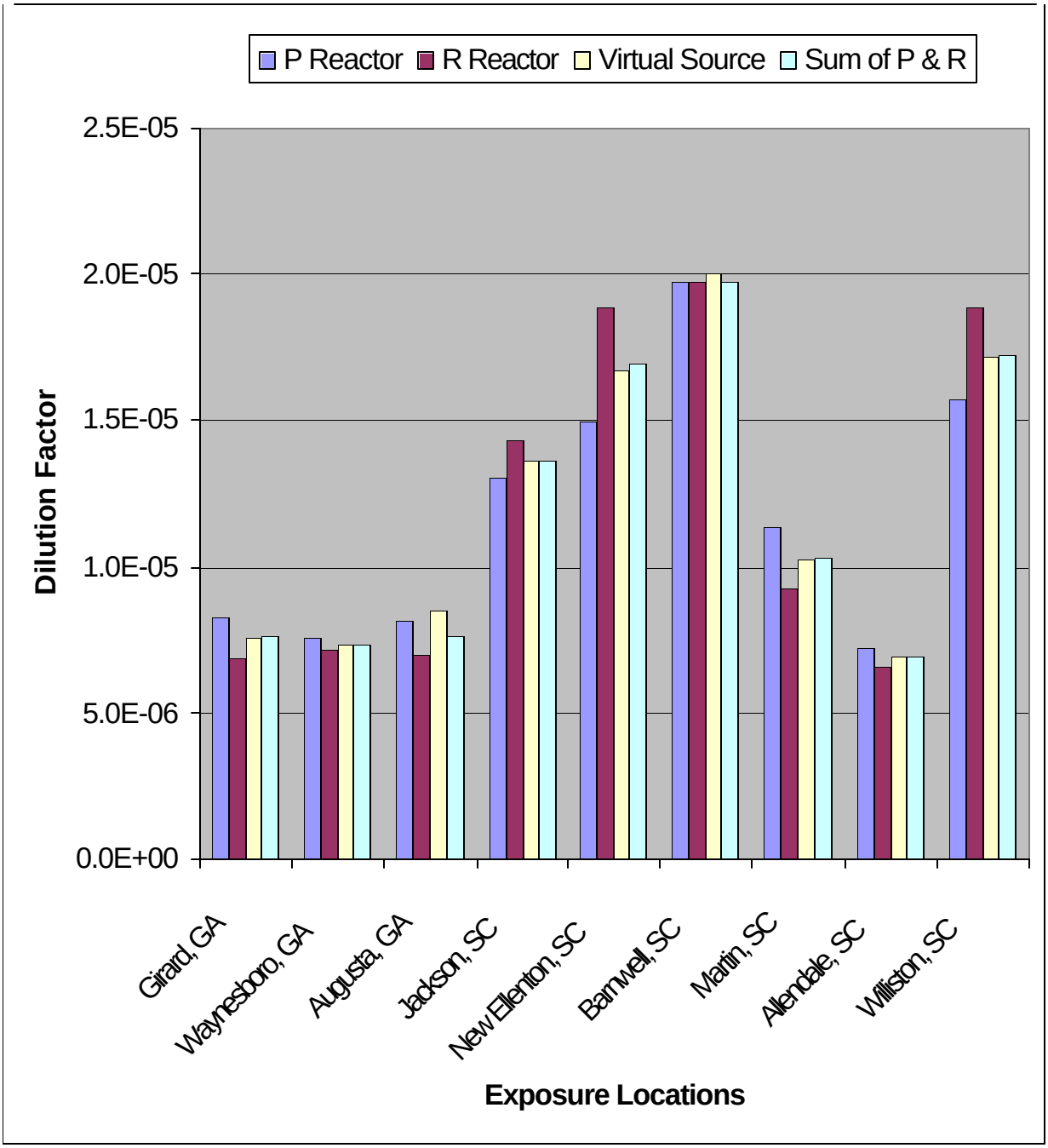

Figure A-7 Group 4 Comparisons

A.2.2.2 Part 2: Analysis of Weak Sources

This discussion expands and quantifies the qualitative discussion in Section A.2.1, item 4. Consider the effect of source strength on the concentrations induced by individual sources compared to concentrations induced by their representative virtual source. To analyze this problem, consider two actual sources represented by a virtual source. Then,

$$C_V = (S_1 + S_2)\, D_V \qquad \text{(A-1)}$$

and

$$C_1 = S_1 D_1 \qquad \text{(A-2)}$$
$$C_2 = S_2 D_2 \qquad \text{(A-3)}$$

Where,

C is the concentration induced at an exposure location;

D is the dilution factor; and

S is the source strength.

The subscripts V, 1, and 2, represent the virtual source, source 1, and source 2, respectively, where source 1 is a strong source and source 2 is a weak source.

The actual concentration, C_A, is:

$$C_A = C_1 + C_2 = S_1D_1 + S_2D_2 \qquad \text{(A-4)}$$

The fractional error, F, is given by:

$$F = (C_V - C_A)/ C_A = [\{(S_1 + S_2)\, D_V\}/(S_1D_1 + S_2D_2)] - 1 \qquad \text{(A-5)}$$

Recall that Source 1 is a strong source and Source 2 is a weak source. Therefore, it is convenient, with some manipulation, to express the fractional error in this form:

$$F = \frac{D_V / D_1}{\frac{S_1}{S_1 + S_2}\left(1 + \frac{S_2}{S_1} \times \frac{D_2}{D_1}\right)} - 1 \qquad \text{(A-6)}$$

If it is assumed that $S_2 < S_1$ (i.e., the relative strength of S_2 is very small), then $S_1/(S_1+S_2) \approx 1$. If it is further assumed that $S_2D_2 < S_1D_1$ (i.e., the small size of S_2 is sufficient to more than compensate for the fact that source 2 may be closer to the exposure location, causing D_2 to be larger than D_1), this analytic approximation may be used (9):

$$(1 + x)^{-1} = 1 - x + x^2 - x^3 + x^4 - \ldots \qquad (-1<X<1) \qquad \text{(A-7)}$$

to obtain:

$$F \approx \left[\frac{D_V}{D_1}\left(1 - \frac{S_2}{S_1} \times \frac{D_2}{D_1}\right)\right] - 1 \qquad \text{(A-8)}$$

This means that the fractional error for the combined strong and weak individual sources is equal approximately to the ratio of the dilution factors of the virtual and strong sources (D_V/D_1) multiplied by a factor depending on the characteristics of the strong and weak sources, minus 1. Note that if $S_2 = 0$, the error is just the ratio of the dilution factors for the virtual and strong sources, minus 1.

The ratio S_2/S_1 limits the magnitude of the error induced by the weak source. That is, even if the dilution factors for sources 2 and 1 are not very close, their ratio will be multiplied by the relative strengths of sources 2 and 1. Suppose source 2 induces 10 times the concentration at the exposure location (an extremely large difference) compared to source 1. If the relative strength of source 2 is 0.01 of source 1 (1 percent), then the error induced by the weak source only amounts to 10 percent of the error that would be present from the strong source alone. This quantifies why a weak source with a strength that is only a few percent of a nearby larger source may be subsumed into that larger source. For modeling of air sources at the SRS, this implies that weak, ground-level sources could be combined with nearby elevated virtual sources. This was done as indicated in Section A.2.1, item 4.

A.3 Conclusions

The analysis shows very good agreement between the virtual sources and individual actual source locations. The largest error was 27 percent. This was the only case where the error exceeded 25 percent, and then by only 2 percent. This error was for a single-source/exposure-location combination, which is considered to be a stringent comparison. Comparisons between virtual sources and the combined effects of several actual sources, each assumed to have unit strength, showed even better agreement. The maximum error was 11 percent, with most values lower. Although the direction of the errors for the virtual source compared to various actual sources was generally balanced between positive and negative, for the larger errors the virtual sources appeared to underestimate the concentration that would be induced by the actual sources. This appears to be linked to the nonlinear behavior of the air-dispersion relations. However, even the maximum errors are not considered to be excessive.

Given that this choice of virtual sources provides an excellent portrayal of the concentrations induced by the actual sources, the four virtual sources defined in Table A-3 were used for Phase III.

A.4 References

1. Till JE, et al. Savannah river site environmental dose reconstruction project phase II: source term calculation and ingestion pathway data retrieval. Neeses SC, Risk Assessment Corporation. April 30, 2001.

2. International Atomic Energy Agency (IAEA). Generic models for the use in assessing the impact of discharges of radioactive substances to the environment. Safety Reports Series No. 19. IAEA. Vienna, Austria. 2001.

3. Weber AH, et al. The creation of an historical meteorological database for dose reconstruction. WSRC-TR-2001-00275. Westinghouse Savannah River Company. Aiken, South Carolina. 2001.

4. Arnett MW, et al. Savannah River Site environmental report for 1991. WSRC-TR-92-186. Westinghouse Savannah River Company. Aiken, South Carolina. 1992.

5. Cummins CL, Hetrick CS, and Martin DK. Radioactive releases at the Savannah River Site 1954–1989. WSRC-RP-91-684. 1991.

6. Napier BA, Peloquin RA, Strenge DL, and Ramsdell JV. GENII—the Hanford Environmental Radiation Dosimetry System. 11/10/1999. [Internet citation 7/14/2003] Available at URL: http://www.pnl.gov/eshs/software/genii.html.

7. Cummins CL, Martin DK, Todd JL. Savannah River Site environmental report for 1990 (U). WSRC-IM-91-28. Westinghouse Savannah River Company, Environmental Monitoring Section. Savannah River Site. Aiken, South Carolina. 1991.

8. Arnett MW, Karapatakis LK, Mamatey AR. Savannah River Site environmental report for 1992. WSRC-TR-93-075. Westinghouse Savannah River Company, Environmental Monitoring Section. Savannah River Site. Aiken, South Carolina. 1993.

9. Abramowitz M, Stegun, IA. Handbook of mathematical functions. New York: Dover Publications, Inc. 1965.

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APPENDIX B RADIONUCLIDE SOURCE TERMS USED FOR PHASE III ANALYSIS

This appendix lists the source term that was used for Phase III of the Savannah River Site (SRS) Dose Reconstruction Project. It contains tables of the annual quantities of radionuclides that were released into air and surface during the 39 years of production of nuclear materials at SRS – i.e., 1954 through 1992.

The first four of the tables lists the annual quantities (units of Curies[1]) of sixteen radionuclides released into the air at SRS from four virtual sources. These four virtual sources were derived as discussed in detail in Appendix A. The table citations and the SRS facilities comprising these four virtual sources are:

- Table B-1 -- A-Area, M-Area, Savannah River Laboratory (SRL)
- Table B-2 -- F-Canyon, H-Canyon, H-Tritium Stack, F&H Seepage Basins
- Table B-3 -- C-Reactor, K-Reactor, L-Reactor, Reactor Seepage Basin release attributable to C-, K-, and L-Reactors, D-Area, CMX-TNX
- Table B-4 -- P-Reactor, R-Reactor, Reactor Seepage Basin release attributable to P- and R-Reactors.

The next two tables list those radionuclides released into surface water. Table B-5 lists the annual concentrations (units of picoCuries per milliliter, or pCi/ml)[2] of twenty-two radionuclides discharged into the Savannah River from all SRS surface water sources. Table B-6 lists the annual concentrations (again, units of pCi/ml) of three radionuclides discharged into Lower Three Runs Creek. The concentrations represent average annual concentrations as they were assumed to exist in either the Savannah River or Lower Three Runs Creek for purposes of the exposure assessment.

In these tables, the following nomenclature is used for specific radionuclides:

- H-3 – tritium (T) released in an oxide form (i.e., as HTO).
- H-3EL – tritium released in elemental form (HT).
- I-129E – I-129 in elemental form (I_2).
- I-129O – I-129 in organic form (e.g., CH_3).
- I-131E – I-131 in elemental form (I_2).
- I-131O - I-131 in organic form (e.g., CH_3).

[1] Where one Curie (Ci) equals 3.7E+10 Becquerels (Bq), and 1 Bq equals one nuclear disintegration per second.
[2] Where 10^{12} picoCuries (pCi) equals 1 Ci, and 1000 milliliters (ml) equals 1 liter.

Table B-1 Radionuclides Released to Air from A-Area, M-Area, and SRL (Ci)

Radio-nuclide	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963
Am-241	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ar-41	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C-14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cs-137	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H-3	0.00	0.00	0.00	0.00	0.00	6260	5500	2670	382	0.00
H-3EL	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-129E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-129O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-131E	0.00	0.00	0.00	0.00	2.93	0.10	0.018	0.35	0.12	0.009
I-131O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pu-238	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pu-239	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.20×10^{-04}	3.00×10^{-04}	2.42×10^{-04}
Ru-106	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr-89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr-90	0.00	0.00	0.00	0.00	0.01	0.49	0.08	0.09	0.22	0.18
U-234	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-235	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-236	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-238	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table B-1 Radionuclides Released to Air from A-Area, M-Area, and SRL (Ci) (continued)

Radio-nuclide	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973
Am-241	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ar-41	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C-14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cs-137	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H-3	197	60.0	380	110	120	120	120	289	220	733
H-3EL	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-129E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-129O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-131E	1.65	0.73	0.018	0.17	0.019	0.0038	0.088	0.018	0.025	0.031
I-131O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pu-238	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pu-239	0.00	0.00	0.00	0.00	5.00×10^{-04}	4.60×10^{-04}	6.10×10^{-04}	6.60×10^{-04}	0.00	1.90×10^{-05}
Ru-106	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr-89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr-90	0.050	0.090	0.005	0.012	0.0016	0.010	0.0059	0.0014	6.70×10^{-04}	7.00×10^{-06}
U-234	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-235	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-236	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-238	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table B-1 Radionuclides Released to Air from A-Area, M-Area, and SRL (Ci) (continued)

Radio-nuclide	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983
Am-241	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ar-41	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C-14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cs-137	0.00	0.00	0.00	0.00	0.00	0.0026	0.00	0.00	0.00	0.00
H-3	527	603	77.7	4.0	0.00	0.00	0.00	15.0	5.00	0.00
H-3EL	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-129E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-129O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-131E	0.026	0.0077	0.013	0.0050	0.0087	0.0032	0.0042	0.0032	0.0020	0.0027
I-131O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pu-238	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pu-239	$6.78x10^{-05}$	$1.02x10^{-05}$	$8.7x10^{-06}$	$1.85x10^{-05}$	$1.35x10^{-05}$	$9.94x10^{-06}$	$1.47x10^{-05}$	$7.11x10^{-07}$	$8.64x10^{-06}$	$7.21x10^{-06}$
Ru-106	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr-89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr-90	$3.50x10^{-05}$	$3.10x10^{-05}$	$2.30x10^{-05}$	$7.00x10^{-06}$	0.00	0.00	$3.60x10^{-05}$	$1.00x10^{-05}$	$1.90x10^{-05}$	$1.85x10^{-04}$
U-234	0.00	$1.66x10^{-06}$	$1.21x10^{-06}$	$9.07x10^{-06}$	$1.12x10^{-06}$	$1.11x10^{-06}$	$4.36x10^{-08}$	0.00	$1.45x10^{-06}$	$2.24x10^{-06}$
U-235	0.00	$7.56x10^{-08}$	$5.51x10^{-08}$	$4.12x10^{-07}$	$5.11x10^{-08}$	$5.05x10^{-08}$	$1.98x10^{-09}$	0.00	$6.6x10^{-08}$	$1.02x10^{-07}$
U-236	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-238	0.00	$1.62x10^{-06}$	$1.18x10^{-06}$	$8.84x10^{-06}$	$1.1x10^{-06}$	$1.08x10^{-06}$	$4.25x10^{-08}$	0.00	$1.41x10^{-06}$	$2.18x10^{-06}$

Table B-1 Radionuclides Released to Air from A-Area, M-Area, and SRL (Ci) (continued)

Radio-nuclide	1984	1985	1986	1987	1988	1989	1990	1991	1992
Am-241	0.00	0.00	0.00	0.00	0.00	0.00	2.38x10-07	0.00	$2.34x10^{-08}$
Ar-41	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C-14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cs-137	0.00	0.00	0.00	0.00	0.00	0.00	$1.19x10^{-06}$	$6.73x10^{-06}$	$3.94x10^{-06}$
H-3	0.00	33.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H-3EL	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-129E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-129O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-131E	0.0021	0.0011	0.0025	0.0043	0.0021	$3.34x10^{-04}$	$1.24x10^{-04}$	$2.96x10^{-05}$	$5.75x10^{-05}$
I-131O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pu-238	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pu-239	$5.77x10^{-06}$	$9.28x10^{-06}$	$2.19x10^{-05}$	$2.79x10^{-05}$	$1.23x10^{-05}$	$8.18x10^{-06}$	$3.52x10^{-0}5$	$5.24x10^{-05}$	$5.78x10^{-05}$
Ru-106	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr-89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr-90	$5.10x10^{-05}$	$1.60x10^{-05}$	$2.60x10^{-05}$	$3.20x10^{-05}$	$3.40x10^{-05}$	$1.00x10^{-06}$	$1.18x10^{-04}$	$2.59x10^{-04}$	$5.26x10^{-05}$
U-234	0.00	$5.64x10^{-06}$	$4.84x10^{-05}$	$1.1x10^{-05}$	$1.38x10^{-06}$	$4.17x10^{-07}$	$9.9x10^{-06}$	$6.19x10^{-05}$	$2.54x10^{-06}$
U-235	0.00	$2.57x10^{-07}$	$2.2x10^{-06}$	$4.99x10^{-07}$	$6.28x10^{-08}$	$1.9x10^{-08}$	$4.5x10^{-07}$	$2.81x10^{-06}$	$1.15x10^{-07}$
U-236	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-238	0.00	$5.5x10^{-06}$	$4.72x10^{-05}$	$1.07x10^{-05}$	$1.35x10^{-06}$	$4.07x10^{-07}$	$9.65x10^{-06}$	$6.03x10^{-05}$	$2.47x10^{-06}$

Table B-2 Radionuclides Released to Air from F-Canyon, H-Canyon, H-Tritium Stack, and F&H Seepage Basins (Ci)

Radio-nuclide	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963
Am-241	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ar-41	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C-14	0.00	35.0	35.0	35.0	35.0	56.0	56.0	56.0	56.0	56.0
Cs-137	0.00	1.35	0.24	0.063	0.026	0.14	0.12	0.048	0.037	0.025
H-3	0.00	$1.47x10^{+04}$	$2.20x10^{+05}$	$5.69x10^{+05}$	$1.13x10^{+06}$	$4.14x10^{+05}$	$3.43x10^{+05}$	$3.50x10^{+05}$	$3.82x10^{+05}$	$3.94x10^{+05}$
H-3EL	0.00	$1.47x10^{+04}$	$2.20x10^{+05}$	$5.68x10^{+05}$	$1.13x10^{+06}$	$4.52x10^{+05}$	$3.44x10^{+05}$	$3.43x10^{+05}$	$4.24x10^{+05}$	$3.98x10^{+05}$
I-129E	0.00	0.013	0.022	0.032	0.054	0.030	0.034	0.042	0.030	0.074
I-129O	0.00	0.050	0.088	0.13	0.22	0.12	0.14	0.17	0.12	0.30
I-131E	0.00	273	6437	1311	79.3	737	29.9	385	3.80	1.10
I-131O	0.00	1140	27352	5432	325	3065	124	1565	15.25	4.42
Pu-238	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pu-239	0.00	12.5	0.049	0.065	0.032	0.036	0.11	0.018	0.015	0.0047
Ru-106	0.00	25.1	6.34	1.24	0.62	9.99	8.85	3.91	2.78	3.89
Sr-89	0.00	0.32	0.043	0.016	0.018	0.24	0.040	0.031	0.025	0.027
Sr-90	0.00	34.0	8.44	1.68	0.0059	0.079	0.013	0.010	0.0083	0.0089
U-234	0.00	0.81	0.030	$9.53x10^{-04}$	0.0023	$5.72x10^{-04}$	0.0011	0.0046	0.0032	0.018
U-235	0.00	0.023	0.0073	$1.24x10^{-04}$	$9.74x10^{-05}$	$3.80x10^{-04}$	0.0011	$5.64x10^{-04}$	$3.98x10^{-04}$	0.0015
U-236	0.00	0.057	0.0021	$6.70x10^{-05}$	$1.61x10^{-04}$	$4.02x10^{-05}$	$8.04x10^{-05}$	$3.22x10^{-04}$	$2.22x10^{-04}$	0.0013
U-238	0.00	0.54	0.52	0.0082	0.0041	0.029	0.081	0.037	0.026	0.086

Table B-2 Radionuclides Released to Air from F-Canyon, H-Canyon, H-Tritium Stack, and F&H Seepage Basins (Ci) (continued)

Radio-nuclide	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973
Am-241	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ar-41	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C-14	46.0	46.0	46.0	46.0	36.0	36.0	36.0	36.0	36.0	36.0
Cs-137	0.067	0.018	0.048	0.018	0.040	0.085	0.042	0.0093	0.024	0.0026
H-3	$5.13x10^{+05}$	$1.79x10^{+05}$	$1.82x10^{+05}$	$1.55x10^{+05}$	$2.28x10^{+05}$	$1.54x10^{+05}$	$1.48x10^{+05}$	$2.08x10^{+05}$	$2.70x10^{+05}$	$1.76x10^{+05}$
H-3EL	$5.05x10^{+05}$	$1.71x10^{+05}$	$1.71x10^{+05}$	$1.89x10^{+05}$	$2.41x10^{+05}$	$1.49x10^{+05}$	$1.39x10^{+05}$	$2.02x10^{+05}$	$2.90x10^{+05}$	$1.74x10^{+05}$
I-129E	0.10	0.10	0.038	0.046	0.042	0.048	0.038	0.018	0.016	0.026
I-129O	0.40	0.40	0.15	0.18	0.17	0.19	0.15	0.074	0.063	0.10
I-131E	2.29	3.95	7.12	4.39	5.00	7.77	7.34	5.24	0.58	0.40
I-131O	9.18	15.96	28.43	17.61	20.38	31.12	29.70	21.17	2.36	1.61
Pu-238	0.00	0.00	0.00	$3.49x10^{-04}$	0.0013	1.89	0.028	0.029	0.022	0.030
Pu-239	0.0075	0.092	0.041	0.014	0.0076	0.20	0.012	0.011	0.0051	0.0019
Ru-106	2.62	2.76	4.59	0.42	20.1	13.73	0.68	5.69	7.32	3.19
Sr-89	0.030	0.015	0.016	0.011	0.026	0.087	0.042	0.027	0.10	0.011
Sr-90	0.0099	0.0049	0.0053	0.0035	0.0085	0.029	0.014	0.0091	0.033	0.0035
U-234	0.041	0.0022	0.0035	0.0027	0.053	0.10	0.0088	0.0076	0.0079	0.0047
U-235	0.0026	0.0022	$9.04x10^{-04}$	$8.37x10^{-04}$	0.0014	0.0035	$7.64x10^{-04}$	$2.65x10^{-04}$	$3.76x10^{-04}$	$2.46x10^{-04}$
U-236	0.0029	$1.53x10^{-04}$	$2.50x10^{-04}$	$1.91x10^{-04}$	0.0037	0.0071	$6.21x10^{-04}$	$5.34x10^{-04}$	$5.54x10^{-04}$	$3.33x10^{-04}$
U-238	0.14	0.17	0.065	0.061	0.032	0.12	0.046	0.0091	0.017	0.012

Table B-2 Radionuclides Released to Air from F-Canyon, H-Canyon, H-Tritium Stack, and F&H Seepage Basins (Ci) (continued)

Radio-nuclide	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983
Am-241	0.00	0.00	0.00	$3.39x10^{-04}$	0.0012	$3.55x10^{-04}$	0.0011	$4.94x10^{-04}$	$4.98x10^{-04}$	$2.57x10^{-04}$
Ar-41	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C-14	33.0	27.0	28.0	26.0	23.0	23.0	27.0	28.0	33.0	37.0
Cs-137	0.0013	0.0011	0.0013	0.0019	0.0020	0.0027	0.0026	0.0031	0.0010	0.0010
H-3	$1.10x10^{+05}$	$8.67x10^{+04}$	$7.00x10^{+04}$	$9.64x10^{+04}$	$7.65x10^{+04}$	$8.29x10^{+04}$	$8.56x10^{+04}$	$1.53x10^{+05}$	$1.41x10^{+05}$	$2.04x10^{+05}$
H-3EL	$5.84x10^{+05}$	$2.63x10^{+05}$	$8.34x10^{+04}$	$1.13x10^{+05}$	$1.35x10^{+05}$	$9.19x10^{+04}$	$8.16x10^{+04}$	$1.19x10^{+05}$	$1.41x10^{+05}$	$2.34x10^{+05}$
I-129E	0.034	0.028	0.030	0.028	0.026	0.026	0.032	0.028	0.012	0.0082
I-129O	0.14	0.11	0.12	0.11	0.10	0.10	0.13	0.11	0.047	0.033
I-131E	0.41	0.026	0.033	0.013	0.014	0.018	0.0054	0.010	0.023	0.018
I-131O	1.65	0.11	0.13	0.053	0.056	0.073	0.022	0.041	0.091	0.073
Pu-238	0.0064	0.0027	0.022	0.0067	0.0093	0.0018	0.0037	0.0061	0.0054	0.0035
Pu-239	0.0039	$6.98x10^{-04}$	$3.22x10^{-04}$	$1.40x10^{-04}$	$3.03x10^{-04}$	$5.36x10^{-04}$	0.0017	0.0038	0.0023	$9.67x10^{-04}$
Ru-106	0.15	0.04	0.28	0.16	32.9	0.059	0.061	0.091	0.24	0.10
Sr-89	0.0083	0.0038	0.0035	0.0031	0.0029	0.0018	0.0019	0.0022	0.0017	0.0020
Sr-90	0.0028	0.0014	0.0012	0.0011	0.0016	$7.33x10^{-04}$	0.0012	$9.26x10^{-04}$	0.0010	$7.64x10^{-04}$
U-234	$1.86x10^{-04}$	$9.3x10^{-05}$	$3.10x10^{-04}$	$9.92x10^{-04}$	0.0016	0.0012	0.0018	0.0055	0.0020	$6.76x10^{-04}$
U-235	$3.73x10^{-04}$	$2.03x10^{-04}$	$2.15x10^{-04}$	$7.22x10^{-05}$	$1.40x10^{-04}$	$1.11x10^{-04}$	$1.83x10^{-04}$	$2.92x10^{-04}$	$4.04x10^{-04}$	$1.95x10^{-04}$
U-236	$1.31x10^{-05}$	$6.54x10^{-06}$	$2.18x10^{-05}$	$6.97x10^{-05}$	$1.14x10^{-04}$	$8.41x10^{-05}$	$1.30x10^{-04}$	$3.85x10^{-04}$	$1.43x10^{-04}$	$4.75x10^{-05}$
U-238	0.029	0.016	0.016	0.0041	0.0085	0.0068	0.011	0.014	0.028	0.014

Table B-2 Radionuclides Released to Air from F-Canyon, H-Canyon, H-Tritium Stack, and F&H Seepage Basins (Ci) (continued)

Radio-nuclide	1984	1985	1986	1987	1988	1989	1990	1991	1992
Am-241	$1.42x10^{-04}$	$4.26x10^{-04}$	$1.54x10^{-04}$	$2.04x10^{-04}$	$1.18x10^{-04}$	$2.01x10^{-04}$	$1.28x10^{-04}$	$1.53x10^{-04}$	$1.13x10^{-04}$
Ar-41	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C-14	34.0	31.0	25.0	17.0	13.0	18.0	0.67	0.62	0.0031
Cs-137	0.0019	0.0052	0.0029	1.07	0.0018	0.0010	0.0021	$3.20x10^{-04}$	$2.16x10^{-04}$
H-3	$3.10x10^{+05}$	$2.05x10^{+05}$	$1.66x10^{+05}$	$1.72x10^{+05}$	$1.69x10^{+05}$	$9.78x10^{+04}$	$9.68x10^{+04}$	$6.21x10^{+04}$	$5.31x10^{+04}$
H-3EL	$2.43x10^{+05}$	$2.04x10^{+05}$	$1.24x10^{+05}$	$3.26x10^{+05}$	$1.87x10^{+05}$	$9.67x10^{+04}$	$7.77x10^{+04}$	$6.29x10^{+04}$	$5.58x10^{+04}$
I-129E	0.0070	0.013	0.017	0.014	0.013	0.010	0.0026	0.0020	$7.00x10^{-04}$
I-129O	0.028	0.052	0.070	0.058	0.050	0.042	0.010	0.0081	0.0028
I-131E	0.060	0.013	0.0056	0.0027	$1.05x10^{-04}$	$7.82x10^{-05}$	$3.12x10^{-08}$	$4.68x10^{-09}$	$8.20x10^{-06}$
I-131O	0.24	0.052	0.023	0.011	$4.28x10^{-04}$	$3.14x10^{-04}$	$1.25x10^{-07}$	$1.87x10^{-08}$	$3.28x10^{-05}$
Pu-238	0.0018	$7.30x10^{-04}$	0.0027	0.0026	0.0011	0.0012	$4.50x10^{-04}$	$3.54x10^{-04}$	$5.94x10^{-04}$
Pu-239	$6.18x10^{-04}$	$6.67x10^{-04}$	$4.09x10^{-04}$	$4.98x10^{-04}$	$9.64x10^{-04}$	0.0022	0.0039	$4.67x10^{-04}$	$9.21x10^{-04}$
Ru-106	0.17	0.054	0.062	0.047	0.031	0.0033	0.0012	$4.44x10^{-04}$	$1.81x10^{-06}$
Sr-89	0.0026	0.0013	$6.90x10^{-04}$	$4.60x10^{-04}$	$7.82x10^{-04}$	$4.05x10^{-04}$	0.00	0.00	$2.06x10^{-04}$
Sr-90	$9.53x10^{-04}$	$6.96x10^{-04}$	$2.30x10^{-04}$	$1.62x10^{-04}$	$4.93x10^{-04}$	$4.87x10^{-04}$	0.0074	0.0028	0.0014
U-234	0.0012	0.0012	$7.04x10^{-04}$	$3.60x10^{-04}$	$3.38x10^{-04}$	$4.59x10^{-04}$	$8.06x10^{-04}$	$3.97x10^{-04}$	$2.32x10^{-04}$
U-235	$1.01x10^{-04}$	$1.15x10^{-04}$	$6.71x10^{-05}$	$3.67x10^{-04}$	$6.48x10^{-05}$	$2.19x10^{-04}$	$2.28x10^{-04}$	$1.12x10^{-04}$	$6.69x10^{-05}$
U-236	$8.61x10^{-05}$	$8.70x10^{-05}$	$4.95x10^{-05}$	$2.53x10^{-05}$	$2.38x10^{-05}$	$3.23x10^{-05}$	$5.67x10^{-05}$	$2.79x10^{-05}$	$1.63x10^{-05}$
U-238	0.0060	0.0071	0.0042	0.028	0.0045	0.016	0.016	0.0081	0.0049

Table B-3 Radionuclides Released to Air from C-Reactor, K-Reactor, L-Reactor, Reactor Seepage Basin Release Attributable to C-, K-, and L-Reactors, D-Area, and CMX-TNX (Ci)

Radio-nuclide	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963
Am-241	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ar-41	0.00	$8.00x10^{+04}$	$1.50x10^{+05}$	$1.70x10^{+05}$	$2.00x10^{+05}$	$2.60x10^{+05}$	$2.40x10^{+05}$	$2.40x10^{+05}$	$2.50x10^{+05}$	$2.70x10^{+05}$
C-14	0.00	27.0	28.0	28.0	28.0	48.0	48.0	48.0	48.0	48.0
Cs-137	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H-3	0.00	3800	$1.49x10^{+04}$	$4.13x10^{+04}$	$6.33x10^{+04}$	$1.19x10^{+05}$	$1.66x10^{+05}$	$1.19x10^{+05}$	$1.69x10^{+05}$	$2.33x10^{+05}$
H-3EL	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-129E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-129O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-131E	0.18	2.06	15.8	35.7	26.7	25.9	9.92	16.1	6.10	7.33
I-131O	0.076	0.88	6.76	15.3	11.5	11.1	4.25	6.91	2.62	3.14
Pu-238	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pu-239	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ru-106	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr-89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr-90	0.00	0.00	0.00	0.00	0.00	0.00	0.0032	0.0052	0.019	0.033
U-234	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-235	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-236	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-238	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table B-3 Radionuclides Released to Air from C-Reactor, K-Reactor, L-Reactor, Reactor Seepage Basin Release Attributable to C-, K-, and L-Reactors, D-Area, and CMX-TNX (Ci) (continued)

Radio-nuclide	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973
Am-241	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ar-41	$2.20x10^{+05}$	$2.10x10^{+05}$	$2.10x10^{+05}$	$2.40x10^{+05}$	$1.50x10^{+05}$	$1.00x10^{+05}$	$7.33x10^{+04}$	$8.20x10^{+04}$	$1.10x10^{+05}$	$1.15x10^{+05}$
C-14	42.0	48.0	48.0	48.0	37.0	34.0	35.0	34.0	34.0	34.0
Cs-137	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H-3	$3.68x10^{+05}$	$3.25x10^{+05}$	$2.73x10^{+05}$	$2.98x10^{+05}$	$2.65x10^{+05}$	$1.60x10^{+05}$	$1.79x10^{+05}$	$1.65x10^{+05}$	$2.12x10^{+05}$	$1.82x10^{+05}$
H-3EL	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-129E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-129O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-131E	4.35	2.48	1.49	7.24	4.89	7.32	2.82	0.62	0.43	0.10
I-131O	1.87	1.06	0.64	3.10	2.10	3.14	1.21	0.27	0.19	0.043
Pu-238	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pu-239	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	$7.33x10^{-06}$
Ru-106	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr-89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr-90	0.0077	0.0040	0.0069	0.0012	0.0014	$7.91x10^{-04}$	$3.45x10^{-04}$	$8.00x10^{-05}$	$2.50x10^{-04}$	$4.67x10^{-04}$
U-234	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-235	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-236	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-238	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table B-3 Radionuclides Released to Air from C-Reactor, K-Reactor, L-Reactor, Reactor Seepage Basin Release Attributable to C-, K-, and L-Reactors, D-Area, and CMX-TNX (Ci) (continued)

Radio-nuclide	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983
Am-241	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ar-41	$5.55x10^{+04}$	$4.19x10^{+04}$	$5.61x10^{+04}$	$4.67x10^{+04}$	$3.55x10^{+04}$	$3.65x10^{+04}$	$4.73x10^{+04}$	$4.22x10^{+04}$	$3.62x10^{+04}$	$1.62x10^{+04}$
C-14	31.4	26.5	28.0	25.0	22.7	22.0	26.0	27.0	31.0	35.3
Cs-137	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H-3	$1.70x10^{+05}$	$9.86x10^{+04}$	$1.03x10^{+05}$	$1.32x10^{+05}$	$1.12x10^{+05}$	$1.11x10^{+05}$	$1.16x10^{+05}$	$9.52x10^{+04}$	$1.24x10^{+05}$	$1.48x10^{+05}$
H-3EL	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-129E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-129O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-131E	0.0048	$9.83x10^{-04}$	$6.96x10^{-04}$	0.0012	$6.14x10^{-04}$	$9.56x10^{-04}$	0.0011	0.0034	0.0047	0.0026
I-131O	0.0021	$4.21x10^{-04}$	$2.98x10^{-04}$	$4.97x10^{-04}$	$2.63x10^{-04}$	$4.10x10^{-04}$	$4.55x10^{-04}$	0.0015	0.0020	0.0011
Pu-238	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pu-239	$5.05x10^{-06}$	$9.96x10^{-06}$	$7.10x10^{-06}$	$4.49x10^{-06}$	$2.50x10^{-06}$	$1.34x10^{-06}$	$3.56x10^{-06}$	$7.62x10^{-06}$	$2.37x10^{-06}$	$5.22x10^{-06}$
Ru-106	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr-89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr-90	$1.87x10^{-04}$	$2.21x10^{-04}$	$5.49x10^{-04}$	$3.59x10^{-04}$	$1.21x10^{-04}$	$1.21x10^{-04}$	0.0012	$7.52x10^{-04}$	$6.05x10^{-04}$	0.0016
U-234	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-235	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-236	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-238	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table B-3 Radionuclides Released to Air from C-Reactor, K-Reactor, L-Reactor, Reactor Seepage Basin Release Attributable to C-, K-, and L-Reactors, D-Area, and CMX-TNX (Ci) (continued)

Radio-nuclide	1984	1985	1986	1987	1988	1989	1990	1991	1992
Am-241	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ar-41	$1.25x10^{+04}$	$2.05x10^{+04}$	$3.01x10^{+04}$	$4.88x10^{+04}$	$1.17x10^{+04}$	0.0	0.0	0.0	251
C-14	33.0	30.0	10.3	16.0	7.5	0	0	0	0.14
Cs-137	0.00	0.00	0.00	0.00	0.00	0.00	$2.11x10^{-05}$	0.00	$3.05x10^{-05}$
H-3	$1.78x10^{+05}$	$2.23x10^{+05}$	$8.62x10^{+04}$	$4.55x10^{+04}$	$5.21x10^{+04}$	$4.10x10^{+04}$	$6.62x10^{+04}$	$6.33x10^{+04}$	$4.59x10^{+04}$
H-3EL	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-129E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-129O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-131E	$6.96x10^{-04}$	$8.88x10^{-04}$	0.0023	0.0013	$6.88x10^{-04}$	0.00	0.00	$5.46x10^{-08}$	$7.46x10^{-07}$
I-131O	$2.98x10^{-04}$	$3.81x10^{-04}$	$9.71x10^{-04}$	$5.67x10^{-04}$	$2.95x10^{-04}$	0.00	0.00	$2.34x10^{-08}$	$3.20x10^{-07}$
Pu-238	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pu-239	$6.00x10^{-06}$	$3.4x10^{-06}$	$6.15x10^{-06}$	$5.76x10^{-06}$	$7.81x10^{-06}$	$2.27x10^{-05}$	$2.41x10^{-05}$	$2.36x10^{-05}$	$5.32x10^{-07}$
Ru-106	0.00	0.00	0.00	0.00	0.00	0.00	$2.03x10^{-05}$	0.00	0.00
Sr-89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr-90	$3.05x10^{-04}$	$2.99x10^{-04}$	$5.61x10^{-04}$	$4.15x10^{-04}$	0.0017	$2.05x10^{-04}$	$3.58x10^{-04}$	$2.38x10^{-04}$	$1.92x10^{-04}$
U-234	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-235	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-236	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-238	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table B-4 Radionuclides Released to Air from P-Reactor, R-Reactor, and Reactor Seepage Basin Release Attributable to P- and R-Reactors (Ci)

Radio-nuclide	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963
Am-241	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ar-41	$5.00x10^{+04}$	$6.00x10^{+04}$	$1.00x10^{+05}$	$1.20x10^{+05}$	$1.40x10^{+05}$	$1.80x10^{+05}$	$1.60x10^{+05}$	$1.80x10^{+05}$	$1.80x10^{+05}$	$1.80x10^{+05}$
C-14	0.00	21.0	21.0	21.0	21.0	34.0	34.0	34.0	34.0	34.0
Cs-137	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H-3	0.00	2800	$1.47x10^{+04}$	$2.26x10^{+04}$	$3.77x10^{+04}$	$5.28x10^{+04}$	$9.25x10^{+04}$	$7.13x10^{+04}$	$1.36x10^{+05}$	$1.03x10^{+05}$
H-3EL	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-129E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-129O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-131E	0.18	1.37	10.5	23.8	17.8	17.2	10.8	10.7	73.5	32.4
I-131O	0.076	0.59	4.50	10.2	7.64	7.39	4.64	4.59	31.5	13.9
Pu-238	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pu-239	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ru-106	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr-89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr-90	0.00	0.00	0.00	0.00	0.00	0.00	$5.10x10^{-04}$	0.0030	0.074	0.0058
U-234	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-235	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-236	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-238	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table B-4 Radionuclides Released to Air from P-Reactor, R-Reactor, and Reactor Seepage Basin Release Attributable to P- and R-Reactors (Ci) (continued)

Radio-nuclide	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973
Am-241	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ar-41	$1.50x10^{+05}$	$6.00x10^{+04}$	$7.00x10^{+04}$	$8.00x10^{+04}$	$7.00x10^{+04}$	$4.00x10^{+04}$	$3.67x10^{+04}$	$5.90x10^{+04}$	$5.62x10^{+04}$	$6.96x10^{+04}$
C-14	22.0	16.0	16.0	16.0	14.0	17.0	17.0	17.0	17.0	17.0
Cs-137	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H-3	$1.36x10^{+05}$	$6.95x10^{+04}$	$4.88x10^{+04}$	$4.64x10^{+04}$	$2.87x10^{+04}$	$3.31x10^{+04}$	$4.66x10^{+04}$	$4.64x10^{+04}$	$4.95x10^{+04}$	$6.72x10^{+04}$
H-3EL	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-129E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-129O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-131E	0.18	0.033	0.0099	0.040	1.10	1.97	0.070	0.099	0.061	0.044
I-131O	0.076	0.014	0.0043	0.017	0.47	0.84	0.030	0.042	0.026	0.019
Pu-238	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pu-239	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	$1.59x10^{-06}$
Ru-106	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr-89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr-90	0.0017	0.0025	$9.00x10^{-04}$	$1.30x10^{-05}$	0.0011	$3.75x10^{-04}$	$3.18x10^{-04}$	$6.00x10^{-05}$	$9.10x10^{-05}$	$1.32x10^{-04}$
U-234	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-235	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-236	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-238	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table B-4 Radionuclides Released to Air from P-Reactor, R-Reactor, and Reactor Seepage Basin Release Attributable to P- and R-Reactors (Ci) (continued)

Radio-nuclide	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983
Am-241	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ar-41	$5.21x10^{+04}$	$2.30x10^{+04}$	$2.67x10^{+04}$	$1.84x10^{+04}$	$1.74x10^{+04}$	$1.65x10^{+04}$	$2.24x10^{+04}$	$1.97x10^{+04}$	$2.40x10^{+04}$	$2.46x10^{+04}$
C-14	15.7	12.5	13.0	12.0	11.3	11.0	13.0	14.0	16.0	17.7
Cs-137	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H-3	$7.21x10^{+04}$	$6.85x10^{+04}$	$4.68x10^{+04}$	$4.00x10^{+04}$	$3.61x10^{+04}$	$4.71x10^{+04}$	$3.36x10^{+04}$	$2.74x10^{+04}$	$2.78x10^{+04}$	$3.25x10^{+04}$
H-3EL	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-129E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-129O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-131E	0.0024	$4.84x10^{-04}$	$3.43x10^{-04}$	0.0016	$2.50x10^{-04}$	0.0086	0.0071	0.0053	0.018	0.0081
I-131O	0.0010	$2.08x10^{-04}$	$1.47x10^{-04}$	$6.73x10^{-04}$	$1.07x10^{-04}$	0.0037	0.0031	0.0023	0.0079	0.0035
Pu-238	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pu-239	$1.16x10^{-06}$	$4.18x10^{-06}$	$4.36x10^{-06}$	$2.40x10^{-06}$	$8.30x10^{-07}$	$4.00x10^{-07}$	$3.50x10^{-07}$	$1.07x10^{-06}$	$4.50x10^{-07}$	$4.00x10^{-07}$
Ru-106	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr-89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr-90	$5.80x10^{-05}$	$1.23x10^{-04}$	$1.39x10^{-04}$	$1.09x10^{-04}$	$2.70x10^{-05}$	$3.90x10^{-05}$	$1.70x10^{-04}$	$1.53x10^{-04}$	$2.60x10^{-05}$	$4.70x10^{-05}$
U-234	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-235	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-236	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-238	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table B-4 Radionuclides Released to Air from P-Reactor, R-Reactor, and Reactor Seepage Basin Release Attributable to P- and R-Reactors (Ci) (continued)

Radio-nuclide	1984	1985	1986	1987	1988	1989	1990	1991	1992
Am-241	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ar-41	$2.35x10^{+04}$	$3.12x10^{+04}$	$5.31x10^{+04}$	$3.89x10^{+04}$	$1.78x10^{+04}$	0.00	0.00	0.00	0.00
C-14	16.0	15.0	10.3	8.00	3.52	0.00	0.00	0.00	0.046
Cs-137	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H-3	$5.47x10^{+04}$	$4.18x10^{+04}$	$4.62x10^{+04}$	$5.44x10^{+04}$	$5.71x10^{+04}$	$8.93x10^{+04}$	$1.21x10^{+04}$	$1.16x10^{+04}$	438
H-3EL	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-129E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-129O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-131E	0.019	0.014	0.0014	0.015	$3.39x10^{-04}$	0.00	0.00	$1.82x10^{-08}$	$2.49x10^{-07}$
I-131O	0.0081	0.0059	$6.20x10^{-04}$	0.0064	$1.45x10^{-04}$	0.00	0.00	$7.80x10^{-09}$	$1.07x10^{-07}$
Pu-238	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pu-239	$6.30x10^{-07}$	$1.60x10^{-06}$	$2.84x10^{-06}$	$2.77x10^{-06}$	$1.94x10^{-06}$	$3.79x10^{-06}$	$7.95x10^{-06}$	$7.60x10^{-06}$	$1.69x10^{-09}$
Ru-106	0.00	0.00	0.00	0.00	0.00	0.00	$1.02x10^{-05}$	0.00	0.00
Sr-89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr-90	$7.40x10^{-05}$	$1.11x10^{-04}$	$3.82x10^{-04}$	$2.98x10^{-04}$	$2.59x10^{-04}$	$4.10x10^{-05}$	$1.17x10^{-04}$	$7.43x10^{-05}$	$5.93x10^{-05}$
U-234	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-235	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-236	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U-238	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table B-5 Radionuclides Discharged into Savannah River From All SRS Surface Water Sources (pCi/ml)

Radio-nuclide	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963
Ce-144	0.00	0.00	0.00	0.00	0.00	0.00	0.0079	0.0033	0.0024	0.0041
Co-60	$9.63x10^{-06}$	$7.44x10^{-06}$	$3.70x10^{-06}$	$4.24x10^{-06}$	$1.06x10^{-05}$	$2.96x10^{-05}$	$5.12x10^{-04}$	$2.85x10^{-04}$	$8.78x10^{-04}$	$2.97x10^{-04}$
Cs-134	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cs-137	$2.13x10^{-05}$	$4.96x10^{-05}$	$1.96x10^{-04}$	$1.56x10^{-04}$	$9.65x10^{-04}$	$4.13x10^{-04}$	$6.48x10^{-04}$	0.0011	0.0020	0.0017
H-3	1.16	2.47	2.66	2.91	2.93	7.23	5.94	8.50	6.85	9.74
I-129E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-129O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-131E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-131O	0.00	0.00	0.00	0.0084	0.00	0.00	0.0024	0.0030	0.0083	0.0047
Nb-95	0.00	0.00	0.00	0.00	0.00	0.00	0.0084	0.0021	0.0022	0.0035
P-32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pu-238	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pu-239	$3.18x10^{-07}$	$7.10x10^{-06}$	$3.89x10^{-05}$	$8.38x10^{-08}$	$5.07x10^{-06}$	$5.62x10^{-06}$	$4.55x10^{-06}$	$8.51x10^{-06}$	$1.29x10^{-05}$	$5.72x10^{-06}$
Ru-106	$7.22x10^{-06}$	$4.69x10^{-04}$	$1.45x10^{-04}$	$7.21x10^{-05}$	$1.59x10^{-04}$	0.0013	0.011	0.0027	0.0085	0.0069
S-35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0069	0.048	0.016
Sr-89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	$5.00x10^{-04}$	0.0024	0.0020
Sr-90	$1.93x10^{-05}$	$3.74x10^{-05}$	$7.49x10^{-05}$	$2.08x10^{-04}$	$8.65x10^{-05}$	$2.16x10^{-04}$	0.0020	$5.78x10^{-04}$	$9.03x10^{-04}$	0.0012
Tc-99	$2.23x10^{-04}$	$6.20x10^{-04}$	$4.18x10^{-04}$	$1.91x10^{-04}$	$1.49x10^{-04}$	$2.06x10^{-04}$	$1.44x10^{-04}$	$1.54x10^{-04}$	$1.40x10^{-04}$	$1.48x10^{-04}$
U-234	0.00	$9.45x10^{-07}$	$9.45x10^{-06}$	$4.83x10^{-08}$	$6.49x10^{-07}$	$9.51x10^{-07}$	$3.31x10^{-07}$	$2.73x10^{-06}$	$1.53x10^{-06}$	$5.91x10^{-07}$
U-235	0.00	$1.14x10^{-07}$	$9.52x10^{-07}$	$2.35x10^{-09}$	$6.85x10^{-08}$	$9.84x10^{-08}$	$1.80x10^{-07}$	$1.72x10^{-07}$	$3.07x10^{-07}$	$4.66x10^{-07}$
U-236	0.00	$6.64x10^{-08}$	$6.64x10^{-07}$	$3.39x10^{-09}$	$4.57x10^{-08}$	$6.68x10^{-08}$	$2.33x10^{-08}$	$1.92x10^{-07}$	$1.07x10^{-07}$	$4.15x10^{-08}$
U-238	0.00	$7.40x10^{-06}$	$5.97x10^{-05}$	$1.10x10^{-07}$	$4.34x10^{-06}$	$6.21x10^{-06}$	$1.35x10^{-05}$	$9.26x10^{-06}$	$2.16x10^{-05}$	$3.53x10^{-05}$
Zn-65	0.00	0.00	0.00	0.00	0.00	0.00	$2.73x10^{-04}$	$9.05x10^{-04}$	0.0022	0.0017
Zr-95	0.00	0.00	0.00	0.00	0.00	0.00	0.0038	$9.79x10^{-04}$	0.0010	0.0017

Table B-5 Radionuclides Discharged into Savannah River From All SRS Surface Water Sources (pCi/ml) (continued)

Radio-nuclide	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973
Ce-144	0.0052	0.0030	0.0018	0.0015	0.0049	$6.47x10^{-04}$	$9.99x10^{-04}$	$7.68x10^{-04}$	$4.57x10^{-04}$	$9.25x10^{-04}$
Co-60	$2.54x10^{-04}$	$4.84x10^{-04}$	$3.90x10^{-04}$	$1.47x10^{-04}$	$2.57x10^{-04}$	$5.76x10^{-05}$	$4.86x10^{-05}$	$6.48x10^{-04}$	$3.37x10^{-05}$	$1.26x10^{-05}$
Cs-134	0.00	$9.76x10^{-05}$	$4.33x10^{-05}$	$8.26x10^{-05}$	0.00	0.00	0.00	$2.68x10^{-05}$	$8.61x10^{-06}$	$3.82x10^{-06}$
Cs-137	0.0028	0.0021	0.0027	0.0040	0.0024	0.0011	0.0014	$1.77x10^{-04}$	$6.25x10^{-05}$	$3.44x10^{-05}$
H-3	6.58	9.31	9.58	9.27	9.74	7.82	5.80	4.65	4.65	4.74
I-129E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-129O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-131E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-131O	$4.90x10^{-04}$	$3.91x10^{-04}$	$2.18x10^{-04}$	0.0012	$8.67x10^{-04}$	$4.98x10^{-04}$	$1.90x10^{-04}$	$1.59x10^{-04}$	$7.11x10^{-05}$	$8.44x10^{-06}$
Nb-95	0.0053	0.0012	0.0023	0.0027	0.0013	$4.94x10^{-04}$	0.0017	$6.33x10^{-04}$	0.0014	0.0025
P-32	$1.34x10^{-04}$	0.0020	0.0091	$9.97x10^{-04}$	$1.68x10^{-04}$	$2.61x10^{-05}$	$5.63x10^{-05}$	$1.17x10^{-04}$	$4.57x10^{-05}$	$2.70x10^{-05}$
Pu-238	0.00	0.00	0.00	$8.36x10^{-06}$	$1.76x10^{-05}$	$2.27x10^{-05}$	$1.74x10^{-05}$	$6.13x10^{-06}$	$3.08x10^{-06}$	$9.87x10^{-07}$
Pu-239	$4.54x10^{-06}$	$2.43x10^{-05}$	$3.48x10^{-05}$	$4.77x10^{-05}$	$2.27x10^{-05}$	$3.00x10^{-05}$	$4.75x10^{-05}$	$2.02x10^{-05}$	$2.29x10^{-06}$	$1.90x10^{-06}$
Ru-106	0.011	0.0053	0.0072	0.0048	0.0070	0.0020	0.0039	0.0050	0.0054	0.0070
S-35	0.0051	0.0062	0.0087	0.014	0.033	0.014	0.0038	0.0015	$1.88x10^{-04}$	$1.02x10^{-04}$
Sr-89	0.0028	$3.16x10^{-04}$	$4.93x10^{-04}$	0.0010	0.0020	0.0020	0.0034	$6.83x10^{-04}$	$4.23x10^{-04}$	$3.60x10^{-04}$
Sr-90	$7.01x10^{-04}$	$6.06x10^{-04}$	0.0039	0.010	$7.30x10^{-04}$	$4.30x10^{-04}$	$8.37x10^{-04}$	$5.82x10^{-04}$	$2.41x10^{-04}$	$2.66x10^{-04}$
Tc-99	$8.29x10^{-05}$	$1.07x10^{-04}$	$1.06x10^{-04}$	$1.31x10^{-04}$	$1.34x10^{-04}$	$1.46x10^{-04}$	$1.29x10^{-04}$	$1.53x10^{-04}$	$1.12x10^{-04}$	$8.02x10^{-05}$
U-234	$2.17x10^{-06}$	$2.45x10^{-06}$	$1.05x10^{-06}$	$7.75x10^{-07}$	$6.33x10^{-06}$	$1.62x10^{-06}$	$8.69x10^{-07}$	$3.10x10^{-07}$	0.00	$9.07x10^{-08}$
U-235	$6.49x10^{-07}$	$7.47x10^{-07}$	$3.21x10^{-06}$	$4.92x10^{-06}$	$2.15x10^{-06}$	$6.49x10^{-07}$	$8.43x10^{-07}$	$1.28x10^{-07}$	$5.38x10^{-08}$	$2.38x10^{-08}$
U-236	$1.52x10^{-07}$	$1.72x10^{-07}$	$7.35x10^{-08}$	$5.45x10^{-08}$	$1.71x10^{-07}$	$3.62x10^{-08}$	$6.11x10^{-08}$	$2.18x10^{-08}$	0.00	$6.37x10^{-09}$
U-238	$4.72x10^{-05}$	$5.43x10^{-05}$	$2.48x10^{-04}$	$3.82x10^{-04}$	$1.54x10^{-04}$	$4.68x10^{-05}$	$6.43x10^{-05}$	$9.47x10^{-06}$	$4.18x10^{-06}$	$1.71x10^{-06}$
Zn-65	$8.74x10^{-04}$	$3.61x10^{-04}$	$5.50x10^{-04}$	$5.65x10^{-04}$	$5.75x10^{-04}$	$7.51x10^{-05}$	$3.73x10^{-05}$	$2.26x10^{-04}$	0.00	0.00
Zr-95	0.0025	$5.73x10^{-04}$	0.0011	0.0013	$6.55x10^{-04}$	$2.32x10^{-04}$	$8.20x10^{-04}$	$5.97x10^{-04}$	0.0011	0.0021

Table B-5 Radionuclides Discharged into Savannah River From All SRS Surface Water Sources (pCi/ml) (continued)

Radio-nuclide	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983
Ce-144	0.0011	$1.75x10^{-04}$	$1.15x10^{-04}$	$8.23x10^{-05}$	$7.15x10^{-05}$	$4.87x10^{-04}$	$1.15x10^{-04}$	$2.15x10^{-04}$	$5.93x10^{-05}$	$5.68x10^{-05}$
Co-60	$2.00x10^{-04}$	$5.00x10^{-05}$	$9.34x10^{-05}$	$7.85x10^{-05}$	$5.31x10^{-06}$	$1.00x10^{-05}$	$6.13x10^{-05}$	$1.21x10^{-05}$	$2.33x10^{-05}$	$3.37x10^{-05}$
Cs-134	$6.11x10^{-06}$	$2.26x10^{-06}$	$6.56x10^{-07}$	$1.01x10^{-06}$	$7.76x10^{-07}$	$1.61x10^{-06}$	$2.57x10^{-07}$	$5.39x10^{-07}$	$2.33x10^{-07}$	$1.81x10^{-07}$
Cs-137	$7.07x10^{-05}$	$2.63x10^{-05}$	$1.17x10^{-05}$	$2.36x10^{-05}$	$1.11x10^{-05}$	$8.75x10^{-06}$	$6.53x10^{-06}$	$1.96x10^{-05}$	$1.31x10^{-05}$	$7.02x10^{-06}$
H-3	5.46	3.59	3.73	3.87	3.77	2.40	2.54	4.27	4.82	2.93
I-129E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-129O	0.00	0.00	0.00	0.00	0.00	0.00	$2.15x10^{-05}$	$3.25x10^{-05}$	$4.59x10^{-05}$	$2.17x10^{-05}$
I-131E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-131O	$1.36x10^{-06}$	0.00	$1.02x10^{-07}$	$1.05x10^{-06}$	$7.27x10^{-08}$	0.00	0.00	0.00	0.00	0.00
Nb-95	0.0020	$1.07x10^{-04}$	$6.92x10^{-04}$	$2.42x10^{-04}$	$4.82x10^{-05}$	$2.74x10^{-05}$	$5.33x10^{-04}$	$3.07x10^{-04}$	$3.60x10^{-04}$	$4.82x10^{-04}$
P-32	$1.46x10^{-05}$	$1.16x10^{-06}$	$5.17x10^{-06}$	$4.45x10^{-06}$	$1.18x10^{-07}$	$1.18x10^{-07}$	$5.15x10^{-07}$	$2.78x10^{-07}$	$6.05x10^{-07}$	$2.35x10^{-06}$
Pu-238	$8.50x10^{-07}$	$5.21x10^{-07}$	$1.15x10^{-07}$	$2.36x10^{-07}$	$6.85x10^{-08}$	$4.90x10^{-08}$	$4.69x10^{-08}$	$4.10x10^{-07}$	$1.27x10^{-07}$	$7.58x10^{-08}$
Pu-239	$1.02x10^{-06}$	$1.86x10^{-07}$	$3.13x10^{-08}$	$8.26x10^{-08}$	$2.49x10^{-08}$	$3.57x10^{-08}$	$8.33x10^{-08}$	$4.51x10^{-07}$	$1.91x10^{-07}$	$4.23x10^{-08}$
Ru-106	0.010	$7.62x10^{-04}$	0.0030	0.0014	$6.48x10^{-04}$	$3.43x10^{-04}$	0.0058	0.0018	$7.85x10^{-04}$	$4.62x10^{-04}$
S-35	$5.54x10^{-04}$	$2.38x10^{-05}$	$3.33x10^{-05}$	$5.66x10^{-05}$	$2.84x10^{-06}$	$5.78x10^{-05}$	$7.81x10^{-07}$	$8.02x10^{-06}$	$2.71x10^{-05}$	$7.38x10^{-06}$
Sr-89	$1.83x10^{-04}$	$4.80x10^{-05}$	$3.91x10^{-05}$	$4.53x10^{-05}$	$1.12x10^{-05}$	$1.63x10^{-06}$	$1.24x10^{-05}$	$9.07x10^{-06}$	$5.96x10^{-06}$	$1.30x10^{-05}$
Sr-90	$2.37x10^{-04}$	$1.29x10^{-04}$	$1.54x10^{-04}$	$1.14x10^{-04}$	$8.39x10^{-05}$	$7.31x10^{-05}$	$2.00x10^{-04}$	$1.19x10^{-04}$	$8.61x10^{-05}$	$6.41x10^{-05}$
Tc-99	$1.43x10^{-04}$	$1.03x10^{-04}$	$7.50x10^{-05}$	$1.24x10^{-04}$	$1.48x10^{-04}$	$7.82x10^{-05}$	$1.06x10^{-04}$	$1.59x10^{-04}$	$2.25x10^{-04}$	$1.06x10^{-04}$
U-234	$4.68x10^{-08}$	$5.52x10^{-09}$	$1.70x10^{-08}$	$1.54x10^{-08}$	$9.41x10^{-09}$	$1.19x10^{-08}$	$3.52x10^{-08}$	$9.06x10^{-08}$	$3.95x10^{-08}$	$7.06x10^{-09}$
U-235	$5.08x10^{-08}$	$2.49x10^{-08}$	$1.05x10^{-08}$	$9.29x10^{-09}$	$3.29x10^{-09}$	$4.34x10^{-09}$	$2.20x10^{-08}$	$8.03x10^{-08}$	$2.37x10^{-08}$	$1.30x10^{-08}$
U-236	$3.29x10^{-09}$	$3.87x10^{-10}$	$1.19x10^{-09}$	$1.08x10^{-09}$	$6.59x10^{-10}$	$8.37x10^{-10}$	$2.48x10^{-09}$	$6.21x10^{-09}$	$2.71x10^{-09}$	$4.97x10^{-10}$
U-238	$3.87x10^{-06}$	$1.92x10^{-06}$	$7.91x10^{-07}$	$6.99x10^{-07}$	$2.41x10^{-07}$	$3.19x10^{-07}$	$1.66x10^{-06}$	$6.10x10^{-06}$	$1.78x10^{-06}$	$1.00x10^{-06}$
Zn-65	$3.64x10^{-04}$	$6.60x10^{-05}$	$8.70x10^{-05}$	$8.31x10^{-05}$	$1.72x10^{-06}$	$1.57x10^{-06}$	$3.86x10^{-05}$	$5.58x10^{-06}$	$8.11x10^{-06}$	$1.40x10^{-05}$
Zr-95	0.0018	$1.15x10^{-04}$	0.0011	$3.55x10^{-04}$	$6.69x10^{-05}$	$4.68x10^{-05}$	$8.54x10^{-04}$	$4.23x10^{-04}$	$5.58x10^{-04}$	$5.57x10^{-04}$

Table B-5 Radionuclides Discharged into Savannah River From All SRS Surface Water Sources (pCi/ml) (continued)

Radio-nuclide	1984	1985	1986	1987	1988	1989	1990	1991	1992
Ce-144	$3.71x10^{-05}$	$5.84x10^{-05}$	$1.92x10^{-04}$	$1.31x10^{-04}$	$1.01x10^{-04}$	$1.36x10^{-07}$	0.00	0.00	0.00
Co-60	$1.05x10^{-04}$	$6.04x10^{-05}$	$6.07x10^{-05}$	$1.17x10^{-05}$	$1.01x10^{-06}$	0.00	0.00	0.00	$5.04x10^{-09}$
Cs-134	$2.98x10^{-07}$	$8.73x10^{-08}$	$1.13x10^{-07}$	$1.97x10^{-07}$	$7.60x10^{-07}$	$2.47x10^{-08}$	0.00	0.00	$1.68x10^{-09}$
Cs-137	$1.07x10^{-05}$	$8.03x10^{-06}$	$9.99x10^{-06}$	$2.47x10^{-05}$	$6.08x10^{-05}$	$2.56x10^{-05}$	$4.05x10^{-06}$	$2.46x10^{-06}$	$7.96x10^{-06}$
H-3	2.83	3.45	4.01	2.55	3.78	2.47	1.45	2.54	1.22
I-129E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-129O	$2.37x10^{-05}$	$3.04x10^{-05}$	$2.66x10^{-05}$	$2.79x10^{-05}$	$7.88x10^{-05}$	$1.87x10^{-04}$	$1.21x10^{-05}$	0.00	$1.34x10^{-05}$
I-131E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I-131O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nb-95	0.0019	0.0018	$4.46x10^{-04}$	$1.49x10^{-04}$	$3.04x10^{-05}$	$3.59x10^{-09}$	0.00	0.00	0.00
P-32	$1.19x10^{-06}$	$1.27x10^{-07}$	$3.93x10^{-08}$	$1.01x10^{-08}$	$1.22x10^{-08}$	$4.42x10^{-07}$	$3.13x10^{-07}$	0.00	0.00
Pu-238	$4.20x10^{-08}$	$3.35x10^{-08}$	$2.21x10^{-08}$	$2.03x10^{-08}$	$5.37x10^{-08}$	0.00	0.00	0.00	$9.82x10^{-10}$
Pu-239	$9.37x10^{-08}$	$4.50x10^{-08}$	$1.10x10^{-06}$	$1.63x10^{-07}$	$4.07x10^{-07}$	$1.74x10^{-06}$	$1.92x10^{-06}$	$1.88x10^{-06}$	$1.26x10-^{06}$
Ru-106	$6.57x10^{-04}$	0.0018	0.0039	$7.82x10^{-04}$	$2.28x10^{-04}$	$9.84x10^{-06}$	0.00	0.00	0.00
S-35	$1.16x10^{-06}$	$4.38x10^{-06}$	$2.40x10^{-06}$	$2.14x10^{-06}$	$6.40x10^{-07}$	$1.33x10^{-07}$	$2.60x10^{-05}$	0.00	$1.99x10^{-08}$
Sr-89	$6.48x10^{-06}$	$2.85x10^{-06}$	$4.93x10^{-06}$	$7.15x10^{-06}$	$3.44x10^{-05}$	0.00	0.00	0.00	0.00
Sr-90	$2.66x10^{-04}$	$1.90x10^{-04}$	$1.83x10^{-04}$	$2.38x10^{-04}$	$1.04x10^{-04}$	$2.06x10^{-04}$	$5.11x10^{-05}$	$1.09x10^{-05}$	$8.32x10^{-05}$
Tc-99	$1.16x10^{-04}$	$1.49x10^{-04}$	$1.31x10^{-04}$	$1.37x10^{-04}$	$3.87x10^{-04}$	$9.17x10^{-04}$	$8.13x10^{-04}$	$3.53x10^{-04}$	$9.00x10^{-04}$
U-234	$4.83x10^{-09}$	$3.55x10^{-09}$	$1.69x10^{-09}$	$2.12x10^{-08}$	$1.45x10^{-09}$	0.00	0.00	0.00	$6.15x10^{-11}$
U-235	$4.06x10^{-09}$	$2.80x10^{-09}$	$1.35x10^{-08}$	$1.29x10^{-09}$	$3.34x10^{-09}$	$6.60x10^{-10}$	$1.50x10^{-09}$	$3.84x10^{-09}$	$1.89x10^{-09}$
U-236	$3.39x10^{-10}$	$2.50x10^{-10}$	$1.19x10^{-10}$	$1.49x10^{-09}$	$9.59x10^{-11}$	0.00	0.00	0.00	$4.32x10^{-12}$
U-238	$3.08x10^{-07}$	$2.12x10^{-07}$	$1.04x10^{-06}$	$6.83x10^{-08}$	$2.57x10^{-07}$	$5.13x10^{-08}$	$1.17x10^{-07}$	$2.99x10^{-07}$	$1.46x10^{-07}$
Zn-65	$3.94x10^{-06}$	$6.22x10^{-07}$	$2.40x10^{-05}$	$1.66x10^{-05}$	$5.87x10^{-06}$	0.00	0.00	0.00	0.00
Zr-95	0.0028	0.0021	$3.93x10^{-04}$	$1.07x10^{-04}$	$2.32x10^{-05}$	$3.18x10^{-08}$	0.00	0.00	0.00

Table B-6 Annual Radionuclide Concentrations for Exposure Pathways Involving Lower Three Runs Creek (pCi/ml)

	1954	**1955**	**1956**	**1957**	**1958**	**1959**	**1960**	**1961**	**1962**	**1963**
Cs-137	0.0028	0.0057	0.0070	0.042	0.073	0.018	0.010	0.0075	0.011	0.036
H-3	4.35	4.79	4.48	6.26	6.60	22.5	26.5	20.5	35.5	55.5
Sr-90	0.0023	0.0047	0.0057	0.035	0.059	0.014	0.0075	0.0065	0.010	0.015
	1964	**1965**	**1966**	**1967**	**1968**	**1969**	**1970**	**1971**	**1972**	**1973**
Cs-137	0.041	0.017	0.013	0.012	0.0095	0.0060	0.0065	0.0070	0.0040	0.0025
H-3	85.5	23.0	14.5	14.0	5.75	1.50	2.00	8.50	5.50	8.00
Sr-90	0.019	0.0080	0.0045	0.0040	0.0040	0.0040	0.0040	0.0045	0.0015	0.0040
	1974	**1975**	**1976**	**1977**	**1978**	**1979**	**1980**	**1981**	**1982**	**1983**
Cs-137	0.0045	0.0087	0.0028	0.0039	0.0051	0.0055	0.0012	0.0013	0.0010	0.0016
H-3	7.77	12.6	5.00	6.00	5.80	5.90	4.00	3.10	3.60	3.50
Sr-90	0.0023	0.0017	0.0016	2.10×10^{-04}	1.20×10^{-04}	1.10×10^{-04}	0.0011	8.80×10^{-04}	1.90×10^{-04}	4.40×10^{-04}
	1984	**1985**	**1986**	**1987**	**1988**	**1989**	**1990**	**1991**	**1992**	
Cs-137	9.30×10^{-04}	0.0014	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	
H-3	3.70	3.30	3.70	2.60	2.70	2.10	1.08	1.20	0.86	
Sr-90	2.10×10^{-04}	6.00×10^{-05}	4.00×10^{-04}	2.20×10^{-04}	5.90×10^{-04}	4.70×10^{-04}	5.20×10^{-04}	4.06×10^{-04}	1.86×10^{-04}	

APPENDIX C SUPPLEMENTAL INFORMATION FOR CREATION OF RADIONUCLIDE SOURCE TERMS

This appendix presents supplemental and background information pertaining to preparation of a source term for Phase III of the Savannah River Site (SRS) dose reconstruction project. This appendix is composed of five sections:

- **Section C.1:** Summary of Phase II Screening Analysis.
- **Section C.2:** Phase III Assumptions for Partitioning Mixed Isotopic Activity.
- **Section C.3:** Phase III Adjustment Factors for Surface Water Transport.
- **Section C.4:** Comparison of Phase II and Phase III Source Terms for Air Release.
- **Section C.5:** Comparison of Phase II and Phase III Source Terms for Water Release.

Appendix B lists the source term used for Phase III. This appendix contains tables of the annual quantities of radionuclides that were released into air and surface water during the 39 years of production of nuclear materials at the SRS (i.e., 1954 through 1992).

Annual quantities of 16 radionuclides released into the air are provided in terms of 4 virtual sources. Appendix A discusses the derivation of these four virtual sources. The four virtual sources consist of releases to air from the following groups of SRS facilities:

1. A-Area, M-Area, Savannah River Laboratory (SRL).
2. F-Canyon, H-Canyon, H-Tritium Stack, F&H Seepage Basins.
3. C-Reactor; K-Reactor; L-Reactor; Reactor Seepage Basin release attributable to C-, K-, and L-Reactors; D-Area; CMX-TNX.
4. P-Reactor, R-Reactor, Reactor Seepage Basin release attributable to P- and R-Reactors.

Two additional tables in Appendix B list the radionuclides released into surface water. One table lists the annual concentrations (units of picocuries per milliliter, or pCi/mL) of 22 radionuclides discharged into the Savannah River from all SRS surface-water sources. The second table lists annual concentrations (pCi/mL) of three radionuclides discharged into the Lower Three Runs Creek.

The Phase III derivation of the source term is addressed in Chapter 5 for release of radionuclides to air, and in Chapter 7 for release of radionuclides to surface water.

C.1 Summary of Phase II Screening Analysis

This appendix section summarizes the screening analysis that was performed for Phase II of the SRS Dose Reconstruction Project. A master list of radionuclides that had been released into the air and surface water was identified from SRS records, interviews, and workshops. In addition, estimates were made of the average annual radionuclide release rates. However, the master list of radionuclides was too large for efficient analysis, and a screening assessment was performed to identify smaller lists of key radionuclides that were the dominant contributors to radiation dose and cancer risk. This screening assessment was performed using a two-step method recommended by the National Council on Radiation Protection and Measurements (NCRP) (1,2). This two-step method featured, for both air and water, 1) a screening considering the summation of six exposure pathways, and 2) a screening considering each of the exposure pathways plus the sum total of all six pathways (1,2,3).

C.1.1 Screening Calculations

To apply both steps of the NCRP method, it was first necessary to determine the concentration of the radionuclide of interest in the transporting medium (air or water). The concentration in air was estimated by a simple dilution equation (3):

$$C_a = f\ Q/V \qquad \text{(Eqn. C1-1)}$$

Where:

C_a = The atmospheric concentration of the radionuclide (becquerels per cubic meter [Bq/m^3]).
Q = The release rate from the facility (becquerels per second [Bq/s]).
V = The volumetric flow rate of the exhaust vent (cubic meters per second [m^3/s]).
f = The fraction of time the wind blows toward the receptor (dimensionless).

The release rate, Q, for each radionuclide was based in Phase II on estimates of the quantity released during a one-year period. An average annual release was used that was calculated from compilations of SRS references. Conservative assumptions were made concerning the flow rate from the exhaust vent (0.3 cubic meter per second) and the fraction of time the wind blew toward a receptor (25 percent) (3). In effect, it was assumed for Phase II that all radionuclides were released into the air from a single SRS stack.

The concentration in surface water was estimated as (3):

$$C_w = W_O / Q_O \qquad \text{(Eqn. C1-2)}$$

Where:

C_w = The radionuclide concentration in the receiving surface water (Bq/m^3).
Q_O = The flow rate of an effluent discharge at the point of release (m^3/s).
W_O = The radionuclide release rate at the point of release (Bq/s).

The volume of contaminated water released to all site streams was assumed to be $7.7 \times 10^{+09}$ m^3 per year, based on site reports (3).

After the concentration of each radionuclide (i) in air or water ($C_{a\ or\ w}$) was determined, the screening value (SV_i) for each radionuclide was determined as (3):

$$SV_i = C_{i(a\ or\ w)}\ SF_{i(a\ or\ w)} \qquad \text{(Eqn. C1-3)}$$

Where:

SV_i = The screening value for radionuclide (i) (sievert [Sv] or millirem [mrem]).
$C_{i(a\ or\ w)}$ = The concentration of radionuclide (i) in air or water (Bq/m^3).
$SF_{i(a\ or\ w)}$ = The screening factor for radionuclide (i) in air or water (Sv per Bq/m^3).

The screening factors were those provided in Tables B-1 and C-1 of NCRP Report No. 123 (2) for air and surface water. For Step One of the screening assessment, the screening factor was a term representing the sum of the effective doses received from a set of exposure pathways associated with radionuclides released to air or to surface water. The following six exposure pathways were for release to air (3):

- Inhalation of contamination in air.
- Inhalation of contamination resuspended from soil.
- Immersion in a plume of air.
- Eating produce after deposition of radionuclides on the ground (including plant surfaces).
- Eating meat after deposition of the radionuclides on the ground (including plant surfaces).
- Drinking milk from local cows after deposition of radionuclides on the ground (including plant surfaces.)

The following six exposure pathways were for release to surface water (3):

- Drinking from the surface water.
- Eating fish caught in the surface water.
- Drinking milk produced on land that had been irrigated with the surface water.
- Eating produce produced on land that had been irrigated with the surface water.
- Eating meat produced on land that had been irrigated with the surface water.
- External exposure to radionuclides deposited from the surface water to the ground (e.g., as from irrigation).

Table C-1 lists some of the Phase II assumptions that were used in these exposure pathway assessments (3).

Table C-1 Selected Assumptions Used in Screening Assessments

Exposure Pathway	Selected Parameters	Assumed Value
Inhalation	Breathing rate	8,000 m^3/y
	Resuspension factor	$2x10^{-8}$ m^{-1}
External exposure	Annual exposure to contaminated ground surface	8,000 h/y
Ingestion	Vegetables, fruit, and grain consumption	100 kg/y
	Water consumption	800 L/y
	Fish consumption	20 kg/y
	Milk consumption	300 L/y
	Soil ingestion	0.25 g/d

Source: Phase II (3).

For Step Two of the screening assessment, two sets of screening factors were considered for air and for water. Each set represented the effective dose received from each of the six exposure pathways as well as the sum of the effective dose from all six of the exposure pathways (3).

The product of the average concentration of each radionuclide with the screening factor for that radionuclide was a term called the *screening value* (units of Sv). In Step One, a single screening value for release to air and a single screening value for release to water were calculated for each radionuclide. In Step Two, seven screening values were calculated for air and seven screening values were calculated for water for each radionuclide representing each of the applicable exposure pathways plus their respective summations. Both screening steps included the following significant simplifications:

- Releases were averaged over 36 years (from 1954 to 1989).
- Concentrations at the point of release were used rather than concentrations plausibly at the locations of individuals.
- Standard human behavior patterns (e.g., consumption rates of foods) were assumed.
- Adult rather than age-dependent dose conversion factors were used (3).

For these and other reasons, the screening values thus calculated were not plausible representations of doses to actual humans. Rather, the screening values were highly conservative estimates meant only to identify those radionuclides that should be considered in further analyses.[1]

C.1.2 Screening Results for Step One of the Phase II Screening Analysis

After the calculations described in Section C.1.1 were performed, total screening values were determined for air and water. The total screening values are the sums of the screening values determined for each radionuclide. Each radionuclide was ranked in importance for air and surface-water pathways by dividing the screening value determined for each radionuclide by the total screening value (for air or for water) and multiplying by 100 (percent). Those radionuclides that contributed more than 0.1 percent of the total screening values for air or for water were identified as key radionuclides for further analysis. Table C-2 and C-3 document the results of Step One of the Phase II screening analysis for release to air and water, respectively (3).[2]

Table C-2 Results from Step One of Phase II Screening Assessment for Air

Radionuclide	Estimated Annual Air Release (Bq/y)	Concentration at Point of Release (Bq/m^3)†	All Pathways Screening Factor (Sv/y)	Screening Value (Sv/y)	Percent of Total Screening Value (%)
Americium-241	$2.07x10^{+08}$	$2.19x10^{+01}$	1.00	5.48	0.15
Argon-41	$6.58x10^{+15}$	$6.95x10^{+08}$	$1.50x10^{-06}$	$2.61x10^{+02}$	7.12
Bromine-82	$4.11x10^{+07}$	4.35	$2.30x10^{-04}$	$2.50x10^{-04}$	<0.01
Carbon-14	$3.08x10^{+12}$	$3.26x10^{+05}$	$2.60x10^{-04}$	$2.12x10^{+01}$	0.58
Cerium-141,144*	$4.34x10^{+09}$	$4.58x10^{+02}$	$5.20x10^{-03}$	$5.96x10^{-01}$	0.02
Cesium-134	$4.73x10^{+07}$	5.00	$1.30x10^{-01}$	$1.60x10^{-01}$	<0.01
Cesium-137	$3.60x10^{+09}$	$3.80x10^{+02}$	$2.20x10^{-01}$	$2.09x10^{+01}$	0.57
Cobalt-60	$9.25x10^{+07}$	9.78	$1.70x10^{-01}$	$4.10x10^{-01}$	0.01

[1]The report describing the NCRP screening method notes: "The assumptions and methods incorporated into all of the screening procedures presented in this Report are such that actual doses should not be underestimated by more than one order of magnitude. In most situations, the actual dose will be significantly less than the values calculated for screening" [NCRP 1991, p. 4]. This reference is not included at the end.

[2] The results in these tables were obtained from an Excel spreadsheet (Rad-Screening.xls) that is linked to the electronic version of the Phase II report. For both air and water, the results of Step One of the screening assessment as presented in this Excel spreadsheet are somewhat different from those results presented in Tables 3A-2a and 3A-3a of Chapter 3 of the Phase II report (3).

Radionuclide	Estimated Annual Air Release (Bq/y)	Concentration at Point of Release (Bq/m^3)†	All Pathways Screening Factor (Sv/y)	Screening Value (Sv/y)	Percent of Total Screening Value (%)
Curium-242	$2.36x10^{+06}$	$2.50x10^{-01}$	$4.00x10^{-02}$	$2.46x10^{-03}$	<0.01
Curium-244	$9.20x10^{+07}$	9.72	$5.40x10^{-01}$	1.29	0.04
Europium-154	$2.41x10^{+07}$	2.54	$4.20x10^{-07}$	$2.63x10^{-07}$	<0.01
Europium-155	$6.03x10^{+06}$	$6.37x10^{-01}$	$1.70x10^{-08}$	$2.67x10^{-09}$	<0.01
Hydrogen-3	$2.52x10^{+16}$	$2.66x10^{+09}$	$1.90x10^{-06}$	$1.25x10^{+03}$	34.05
Iodine-129	$5.86x10^{+09}$	$6.19x10^{+02}$	$5.60x10^{-01}$	$8.54x10^{+01}$	2.33
Iodine-131	$2.57x10^{+12}$	$2.68x10^{+05}$	$2.80x10^{-02}$	$1.87x10^{+03}$	51.20
Iodine-133	$3.70x10^{+08}$	$3.85x10^{+01}$	$2.20x10^{-04}$	$2.12x10^{-03}$	<0.01
Iodine-135	$4.81x10^{+09}$	$5.01x10^{+02}$	$2.50x10^{-05}$	$3.13x10^{-03}$	<0.01
Krypton-85	$1.54x10^{+16}$	$1.63x10^{+09}$	$2.80x10^{-09}$	1.14	0.03
Krypton-85m	$1.54x10^{+14}$	$1.63x10^{+07}$	$2.00x10^{-07}$	$8.15x10^{-01}$	0.02
Krypton-87	$2.57x10^{+13}$	$2.72x10^{+06}$	$1.00x10^{-06}$	$6.79x10^{-01}$	0.02
Krypton-88	$1.03x10^{+13}$	$1.09x10^{+06}$	$5.40x10^{-06}$	1.47	0.04
Molybdenum-99	$2.36x10^{+10}$	$2.46x10^{+03}$	$2.30x10^{-04}$	$1.42x10^{-01}$	<0.01
Niobium-95	$1.13x10^{+09}$	$1.18x10^{+02}$	$1.20x10^{-03}$	$3.53x10^{-02}$	<0.01
Osmium-185	$1.85x10^{+06}$	$1.93x10^{-01}$	$2.80x10^{-03}$	$1.35x10^{-04}$	<0.01
Plutonium-239, 240*	$3.60x10^{+09}$	$3.80x10^{+02}$	1.00	$9.51x10^{+01}$	2.60
Plutonium-238	$1.03x10^{+09}$	$1.09x10^{+02}$	$8.90x10^{-01}$	$2.42x10^{+01}$	0.66
Ruthenium-103,106*	$1.75x10^{+09}$	$1.85x10^{+02}$	$9.60x10^{-03}$	$4.43x10^{-01}$	0.01
Antimony-125	$2.14x10^{+07}$	2.23	$1.00x10^{-08}$	$5.57x10^{-09}$	<0.01
Selenium-75	$1.95x10^{+05}$	$2.03x10^{-02}$	$1.40x10^{-02}$	$7.12x10^{-05}$	<0.01
Strontium-89,90	$1.58x10^{+09}$	$1.67x10^{+02}$	$1.90x10^{-01}$	7.95	0.22
Technicium-99	$1.04x10^{+11}$	$1.10x10^{+04}$	$1.30x10^{-11}$	$3.56x10^{-08}$	<0.01
Uranium-235,238*	$1.03x10^{+09}$	$1.09x10^{+02}$	$3.40x10^{-01}$	9.23	0.25
Xenon-131m	$1.13x10^{+13}$	$1.19x10^{+06}$	$1.10x10^{-08}$	$3.29x10^{-03}$	<0.01
Xenon-133	$5.14x10^{+14}$	$5.43x10^{+07}$	$4.30x10^{-08}$	$5.84x10^{-01}$	0.02
Xenon-135	$2.06x10^{+14}$	$2.17x10^{+07}$	$3.00x10^{-07}$	1.63	0.04
Zirconium,Niobium-95*	$3.25x10^{+09}$	$3.43x10^{+02}$	$4.10x10^{-03}$	$3.52x10^{-01}$	0.01
Total annual screening value from radionuclides released to air:				$3.66x10^{+03}$	100

*Cerium-141,144 screened as cerium-144; plutonium-239,240 screened as plutonium-239; ruthenium-103,106 screened as ruthenium-106; uranium-235,238 screened as uranium-235; zirconium,niobium-95 screened as zirconium-95.
†Before multiplication by the 0.25 wind direction frequency factor.
Source: Phase II (3).

Table C-3 Results from Step One of Phase II Screening Assessment for Surface Water

Radionuclide	Estimated Annual Surface Water Release (Bq)	Estimated Concentration at Point of Release (Bq/m^3)	Screening Factor for Surface Water Pathway (Sv per Bq/m^3)	Estimated Screening Value (Sv/y)	Percent of Total Screening Value
Americium-241	$1.03x10^{+07}$	$1.33x10^{-03}$	$2.00x10^{-06}$	$2.67x10^{-09}$	$7.0x10^{-04}$
Barium,Lanthanum-140*	$2.26x10^{+11}$	$2.94x10^{+01}$	$9.50x10^{-09}$	$2.79x10^{-07}$	0.07
Cerium-141,144*	$7.19x10^{+11}$	$9.34x10^{+01}$	$3.70x10^{-08}$	$3.46x10^{-06}$	0.91
Curium-244	$8.22x10^{+08}$	$1.07x10^{-01}$	$9.00x10^{-07}$	$9.61x10^{-08}$	0.03
Cesium-134	$1.39x10^{+10}$	1.80	$1.10x10^{-06}$	$1.98x10^{-06}$	0.52
Cesium-137	$2.00x10^{+12}$	$2.60x10^{+02}$	$1.10x10^{-06}$	$2.86x10^{-04}$	75.23
Cobalt-58	$2.81x10^{+09}$	$3.64x10^{-01}$	$1.80x10^{-08}$	$6.56x10^{-09}$	$1.7x10^{-03}$
Cobalt-60	$8.63x10^{+10}$	$1.12x10^{+01}$	$6.10x10^{-07}$	$6.84x10^{-06}$	1.80
Chromium-51	$5.14x10^{+12}$	$6.67x10^{+02}$	$3.70x10^{-10}$	$2.47x10^{-07}$	0.06
Hydrogen-3	$1.54x10^{+15}$	$2.00x10^{+05}$	$1.40x10^{-11}$	$2.80x10^{-06}$	0.74
Iodine-131	$3.11x10^{+11}$	$4.04x10^{+01}$	$8.60x10^{-08}$	$3.48x10^{-06}$	0.91
Iodine-129	$1.23x10^{+09}$	$1.60x10^{-01}$	$1.40x10^{-06}$	$2.24x10^{-07}$	0.06
Neptunium-239	$1.48x10^{+12}$	$1.92x10^{+02}$	$1.20x10^{-09}$	$2.31x10^{-07}$	0.06
Phosphorus-32	$2.01x10^{+11}$	$2.62x10^{+01}$	$8.20x10^{-07}$	$2.15x10^{-05}$	5.64
Plutonium-239,40*	$8.22x10^{+09}$	1.07	$1.70x10^{-06}$	$1.82x10^{-06}$	0.48
Plutonium-238	$4.11x10^{+09}$	$5.34x10^{-01}$	$1.50x10^{-06}$	$8.01x10^{-07}$	0.21
Ruthenium-103,106*	$1.85x10^{+12}$	$2.40x10^{+02}$	$2.20x10^{-08}$	$5.29x10^{-06}$	1.39
Antimony-124,125*	$2.47x10^{+10}$	3.20	$1.20x10^{-08}$	$3.84x10^{-08}$	0.01
Strontium-89,90*	$6.37x10^{+11}$	$8.28x10^{+01}$	$4.30x10^{-07}$	$3.56x10^{-05}$	9.35
Sulfur-35	$1.80x10^{+12}$	$2.34x10^{+02}$	$1.10x10^{-08}$	$2.57x10^{-06}$	0.68
Technetium-99	$5.45x10^{+10}$	7.07	$6.90x10^{-08}$	$4.88x10^{-07}$	0.13
Thorium-232	$2.06x10^{+08}$	$2.67x10^{-02}$	$8.90x10^{-06}$	$2.38x10^{-07}$	0.06
Uranium*	$4.32x10^{+10}$	5.61	$3.90x10^{-07}$	$2.19x10^{-06}$	0.57
Yttrium-91	$1.23x10^{+11}$	$1.60x10^{+01}$	$8.20x10^{-09}$	$1.31x10^{-07}$	0.03
Zinc-65	$1.54x10^{+11}$	$2.00x10^{+01}$	$1.30x10^{-07}$	$2.60x10^{-06}$	0.68
Zirconium,Niobium-95*	$1.49x10^{+11}$	$1.94x10^{+01}$	$7.40x10^{-08}$	$1.43x10^{-06}$	0.38
Total screening value from radionuclides released to surface water				$3.81x10^{-04}$	100

*Barium,lanthanum-140 was screened as barium-140; cerium-141,144 as cerium-144; plutonium-239,40 as plutonium-239; ruthenium-103,106 as ruthenium-106; antimony-124,125 as antimony-125; strontium-89,90 as strontium-90; uranium as uranium-235 and uranium-238; and zirconium,niobium-95 as zirconium-95.
Source: Phase II Rad-Screening.xls Excel spreadsheet (3).

From Table C-2, iodine-131 and tritium contributed about 51 and 34 percent, respectively, of the total screening value; argon-41 contributed about 7 percent; and iodine-129 and plutonium-239,240 each contributed between 2 and 3 percent of the total screening value. From Table C-3, cesium-137 and strontium-90 contributed about 75 and 9 percent of the total screening value, respectively.

Through this process, the Phase II study identified the following key radionuclides for release to air pathways: americium-241, argon-41, carbon-14, cesium-137, hydrogen-3, iodine-129, iodine-131, plutonium-238, plutonium 239,240, ruthenium 103,106, strontium 89,90 and uranium (3). The key radionuclides for release to water pathways were cesium-137, cobalt-60, hydrogen-3, iodine-129, iodine-131, phosphorus-32, plutonium-238, plutonium-239,240, strontium-89, strontium-90, sulfur-35, technetium-99, uranium, yttrium-91, zinc-65, and zirconium, niobium-95 (3).

C.1.3 Screening Results for Step Two of the Phase II Screening Analysis

In Step Two of the Phase II screening assessment, a smaller list of radionuclides was identified for release to air and water by a process, summarized in Table C-4 and Table C-5 (from Phase II), that determined the relative importance of the above key radionuclides by exposure pathway. The percent contribution of each radionuclide to the total screening value for each exposure pathway was the basis for ranking the radionuclides. The radionuclides that ranked among the top three for at least two of the seven exposure pathways were selected for detailed source term development in the Phase II study. These radionuclides are shown in **bold** in Tables C-4 and C-5.

Table C-4 Results of Phase II Screening Analysis for Air Release Screening Pathways*

Radionuclide†	All Path-ways	Inha-lation	Ingestion			Ground Contami-nation	Plume Immer-sion	No. of Path-ways‡
			Milk	Produce	Meat			
Americium-241								0
Argon-41	**X**						**X**	**2**
Carbon-14								0
Cesium-137						X		1
Hydrogen-3	**X**	**X**	**X**	**X**	**X**			**5**
Iodine -129	**X**		**X**		**X**			**3**
Iodine -131	**X**	**X**	**X**	**X**	**X**	**X**		**6**
Plutonium-239,40	**X**	**X**		**X**				**3**
Plutonium-238		X						1
Ruthenium-103,196						X		1
Strontium-89,90								0
Uranium						**X**		**1§**

*Results of Step Two in the Phase II screening analysis. The radionuclides that ranked among the top three for at least two of the seven exposure pathways were selected for detailed source term development.
†The radionuclides identified in the Step One of the Phase II screening analysis that contributed greater than 0.1 percent of the screening value for all exposure pathways.
‡Number of times that a particular radionuclide ranked high in at least two air exposure pathways.
§Uranium was included in the detailed source development in the Phase II study because of its concentrated use in the M-Area and its potential chemical toxicity.
Source: Phase II (3).

On the other hand, although cesium-134, ruthenium-103,106, and cerium-141,144 were not included in the Phase II list of key radionuclides for surface water pathways, it appears that they should have been included. The screening value for these three radionuclides exceeded the 0.1-percent criterion used for Step One of the Phase II screening assessment.

From this assessment, Table C-6 lists the radionuclides considered for Phase III. Radionuclides cited in Phase II as aggregated quantities were separated into separate isotopes using the assumptions and procedures outlined in Section C.2 of this appendix.

Table C-5 Results of Phase II Screening Analysis for Water Release Screening Pathways*

Radionuclide†	All Pathways	Ingestion					Ground Contamin-ation	Number of Pathways‡
		Water	Fish	Milk	Produce	Meat		
Cesium-137	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**7**
Cobalt-60	**X**						**X**	**2**
Hydrogen-3	**X**	**X**						**2**
Iodine-129								0
Iodine-131	**X**			**X**				**2**
Phosphorus-32	**X**	**X**	**X**					**3**
Plutonium-239,40								0
Plutonium-238								0
Strontium-89,90	**X**	**X**	**X**	**X**	**X**	**X**		**6**
Sulfur-35						X		1
Technecium-99					X			1
Uranium							**X**	**1§**
Yttrium-91								0
Zinc-65	X							1
Zirconium, Niobium-95								0

*Results of Step Two in the Phase II screening analysis. The radionuclides that ranked among the top three for at least two of the seven exposure pathways were selected for detailed source term development.
†The radionuclides identified in the Step One of the Phase II screening analysis that contributed greater than 0.1% of to the screening value for all exposure pathways.
‡Number of times that a particular radionuclide ranked high in at least two surface water exposure pathways.
§Uranium was included in the detailed source development in the Phase II study because of its concentrated use in the M-Area and its potential chemical toxicity.
Source: Phase II (3).

Table C-6 Radionuclides Considered for Phase III

Released to the Air		Released to Surface Water	
Hydrogen-3	Iodine-131	Hydrogen-3	Iodine-129
Carbon-14	Cesium-134,137	Phosphorus-32	Iodine-131
Argon-41	Uranium	Sulfur-35	Cesium-134
Strontium-89,90	Plutonium-238	Coablt-60	Cesium-137
Ruthenium-103,106	Plutonium-239,240	Zinc-65	Chromium-141,144
Iodine-129	Americium-241	Zirconium, Niobium-95	Uranium
		Technecium-99	Plutonium-238
		Ruthenium-103,106	Plutonium-239,240

C.1.4 Phase III Analysis of Phase II Screening Assessment

The Phase II screening assessment was reviewed for Phase III. For the air pathways, although Ru-103,106 was included in the list of key radionuclides, it did not appear to actually meet the 0.1 percent screening value criterion for Step One of the screening assessment. Its screening value was only 0.012 percent of the total (3).

For the surface water pathways, although Y-91 was included in the list of key radionuclides, it did not appear to actually meet the 0.1 percent screening value criterion for Step One of the screening assessment. Its screening value was only 0.03 percent of the total (3). Similarly, I-129 had a screening value of 0.05 percent, which was smaller than the 0.1 percent criterion set forth in Phase II.[3]

C.2 Phase III Assumptions for Partitioning Mixed Isotopic Activity

This appendix section addresses the assumptions and procedures used in Phase III to partition radionuclide activities reported[4] as aggregated quantities into individual isotopes. Partitioning assumptions and procedures are discussed herein for:

- Strontium-89,90.
- Zirconium,Niobium-95.
- Cesium-134,137.
- Uranium.
- Plutonium.
- Americium-241,243.
- Unidentified alpha and unidentified beta-gamma activity.

[3] The bases for the release estimates could not be determined for Phase III. The Phase III source term (0.358 Ci) was significantly smaller than that used in the Phase II report (1.20 Ci). Even assuming the larger source term, iodine-129 did not pass the 0.01 percent screening criterion used in the Phase II report.
[4] Aggregated quantities were reported in the Phase II report (3) and various SRS references.

C.2.1 Strontium-89,90

Strontium-89 and strontium-90 are shown as an aggregated constituent (strontium-89,90) for liquid released from SRL to seepage basins, liquid released from D-Area to streams, liquid released to seepage basins in the Central Shops, and atmospheric releases from the F- and H-Areas (4).

Strontium-89 and strontium-90 are fission products generated from the bombardment of uranium-235, uranium-238, and plutonium-239 with neutrons. The number of curies related to the generation of strontium-89 and stontium-90 in the production reactors was calculated, assuming a typical fuel element composition (5). Table C-2 summarizes the activity associated with each of these strontium isotopes (5).

Table C-7 Accumulated Fission Yields of Strontium Isotopes

		Activity (Curies) Remaining at Various Times After End of Irradiation				
Isotope	**Half-Life or Ratio**	**0 Seconds**	**24 Hours**	**100 Days**	**200 Days**	**2 Years**
Sr-89	53.21 days	$9.080 \times 10^{+7}$	$8.962 \times 10^{+7}$	$2.468 \times 10^{+7}$	$6.707 \times 10^{+6}$	$6.685 \times 10^{+3}$
Sr-90	28.28 years	$2.219 \times 10^{+6}$	$2.219 \times 10^{+6}$	$2.204 \times 10^{+6}$	$2.189 \times 10^{+6}$	$2.113 \times 10^{+6}$
Sr-89/ Sr-90	Ratio	40.92	40.38	11.20	3.06	0.0032
Sr-89/(Sr-89 + Sr-90):		98%	98%	92%	75%	0.3%

Source: Carlton et al, 1994 (5).

The percentages listed in Table C-7 were used to partition strontium-89,90 data into strontium-89 and strontium-90 for the following situations:

- Separations Areas: Fuel and target elements were stored in the reactor basins for a nominal period of 200 days after completion of irradiation before being processed in F- and H-Areas (5). For F- and H-Areas, it was assumed that releases to the atmosphere occurred 200 days after completion of irradiation in the reactors. Strontium-89, 90 atmospheric releases were therefore partitioned to 75 percent strontium-89 and 25 percent strontium-90 for these releases.

- Administration (A) Area: Environmental releases of strontium-89, 90 in A-Area were attributed to releases from SRL to the SRL seepage basins. SRL conducted research using various forms of uranium and plutonium. Strontium isotopes were generated as a result. SRL also worked with californium-252 for several years, and strontium-90 is a daughter product of this isotope. The proportion of strontium-89 to strontium-90 could not be determined for SRL operations; therefore, it was assumed that all of the environmental releases attributed to strontium-89,90 were strontium-90. This assumption was conservative because the ingestion effective dose conversion factors used for this study are larger for strontium-90 than they are for strontium-89 (6). So are the inhalation effective dose conversion factors for all lung absorption classes (6).

- D-Area: D-Area was used to separate light water from the heavy water moderator withdrawn from the reactors (6). This process was assumed to occur within one year after receipt of the moderator from the reactors. The typical delay time between removal of the moderator from the reactor and processing in D-Area was unclear; therefore, it was conservatively assumed that all of the environmental releases attributed to strontium-89,90 were strontium-90. Again, strontium-90 has larger inhalation and ingestion effective dose conversion factors than does strontium-89 (6).

- Central Shops: The Central Shops (CS) were used for repairing equipment from the reactors and separations areas. Before repair, the equipment was cleaned with water that was held for decay before discharge to seepage basins. Discharge of the water to seepage basins was assumed to occur approximately two years after the cleaning water was used and became contaminated with the strontium-89,90. Table C-7 shows that a delay time of two years resulted in decay of strontium-89 by 13.7 half-lives, or a factor of about 13,000. Therefore, the activity (curies) of strontium-89,90 from Central Shops was attributed to strontium-90.

C.2.2 Zirconium-95, Niobium-95

Zirconium-95 and niobium-95 are fission products. Niobium-95 is also the daughter product of zirconium-95. Zirconium-95 has a half-life of 64.02 days, and niobium-95 has a half-life of 34.98 days. Table C-8 shows that these isotopes are initially generated as fission products in equal mass amounts (7).

Table C-8 Accumulated Fission Yields of Zirconium-95 and Niobium-95

Fission with Neutron Energy	Accumulated Yield	
	Zirconium-95	Niobium-95
Uranium-235 with 0.0253 eV	0.06	0.06
Uranium-235 with 1.0 MeV	0.06	0.06
Uranium-238 with 1.0 MeV	0.05	0.05
Plutonium-239 with 0.0253 eV	0.05	0.05
Plutonium-239 with 1.0 MeV	0.05	0.05

Source: KAERI, 2003 (7).

The activity of a radioactive isotope in terms of the number of radioactive transformations per unit time is given as:

$$A = ? N \qquad \text{(Eqn. C.2-1)}$$

Where:

A = Activity (e.g., disintegrations per second).
? = Radioactive decay constant (ln 2/half-life).
N = Number of atoms of a radioactive isotope.

Assuming that equal masses of zirconium-95 and niobium-95 are produced in the reactors and assuming that the reactors operate with the neutron thermal energies shown in Table C-8, the initial activity of each isotope is given by:

$$A_{t=0} = ? N_o \qquad \text{(Eqn. C.2-2)}$$

Where N_o = The number of each isotope produced per fission event.

At any time t greater than 0, equation 2 applies:

$$A(t) = ? N_o e^{-?} \qquad \text{(Egn. C.2-3)}$$

Because the fission yields (the number of atoms emitted) of zirconium-95 and niobium-95 are equal, their contribution to the gross activity of zirconium-95, niobium-95 is calculated to be 35 percent for zirconsium-95 and 65 percent for niobium-95 immediately upon their generation in the reactor (an estimate based on the half-lives of the isotopes).

The half-life of the daughter is not much smaller than the half-life of the parent isotope. The time (t_{max}) at which the maximum activity of niobium-95 will occur (based on its production from the decay of zirconium-95) is 67 days, calculated from the following:

$$t_{max} = \frac{\ln \frac{l_{Nb}}{l_{Zr}}}{l_{Nb} - l_{Zr}} \qquad \text{(Eq. C2-4)}$$

After 67 days, the activity of niobium-95 begins to decline at the same rate as the decline in the activity of zirconium-95 (this is called transient equilibrium). This ratio can be calculated by the following (8):

$$\frac{A_{Nb}}{A_{Zr}} = \frac{l_{Nb}}{l_{Nb} - l_{Zr}} = 2.2 \qquad \text{(Eq. C2-5)}$$

Based on the decay chain and the calculated ratio after the 67-day maximum, the ratio of isotopic activity approaches a constant value where 31 percent of the total activity is due to zirconium-95 and 69 percent of the activity is due to niobium-95. These percentages are appropriate for operations that would occur after the removal of the fuel and targets from the reactors. By SRS process area, then, the following isotopic fractions were used:

Reactor areas:	35 percent zirconium-95	65 percent niobium-95
All other areas:	31 percent zirconium-95	69 percent niobium-95

These assumed values were based on assumptions meant to best reflect actual operating conditions and environmental releases. In determining the potential dose to individuals from these same isotopes, Carlton and Denham used more conservative assumptions that are based on their impact on dose (9).

C.2.3 Cesium-134, 137

Cesium isotopes (cesium-134 and cesium-137) were generated at the SRS as reactor fission products. (Technically, cesium-134 is an activation product because it is produced by neutrons interacting with cesium-133, which is a stable fission product.) At times, cesium-137 was separated from other fission products for further use as an energy source. Combined cesium-134,137 is documented in environmental releases reported from D-Area (4). Cesium-134 has a half-life of 2.06 years while cesium-137 has a half-life of 30.1 years. Table C-9 shows the yields of cesium-134 and cesium-137 resulting from fission of uranium and plutonium by neutrons of different energies (7).

Because the yield of cesium-134 is small compared with that of cesium-137, cesium-137 was expected to contribute nearly all of the activity of cesium-134,137. Therefore, the activity measured for cesium-134,137 was attributed to cesium-137.

Table C-9 Accumulated Fission Yields of Cesium Isotopes

Fissile with Neutron Energy	Accumulated Yield	
	Cesium-134	Cesium-137
Uranium-235 with 0.0253 eV	$1x10^{-07}$	0.06
Uranium-235 with 1.0 MeV	$5x10^{-07}$	0.06
Uranium-238 with 1.0 MeV	$3x10^{-09}$	0.06
Plutonium-239 with 0.0253 eV	$1x10^{-05}$	0.07
Plutonium-239 with 1.0 MeV	$1x10^{-05}$	0.07

Source: KAERI, 2003 (7).

C.2.4 Uranium

The relative abundance of the various uranium isotopes released into air and water was dependent on a number of factors. The primary factor was the enrichment. Enrichment increases the relative abundance of the lower weight isotopes (uranium-234 and uranium-235) and decreases the proportion of the higher weight isotopes (uranium-238). A second factor was whether the uranium had been subjected to neutron irradiation in a reactor. Reactor irradiation would have resulted in the production of uranium-236. While it is fairly certain that the uranium used at SRS facilities (in particular, the reactors and separations facilities) was irradiated in reactors, only limited information exists concerning uranium enrichment levels. Therefore, the analysis of the isotopic composition of uranium found in air and water discharges is largely based on general assumptions.

However, due to two key properties of the various uranium isotopes (half life and dose conversion), changes to the composition would not have a substantive effect on the results of the SRS dose reconstruction. Because all of the uranium isotopes have very long half-lives (240,000 years and longer) in comparison to the period being studied (39 years), radioactive decay could not have had a significant effect on the relative abundance of the isotopes after they were released. In addition, inhalation and ingestion effect dose conversion factors for the four uranium isotopes fall within a ~15 percent range; therefore, the doses received from equal amounts of the different isotopes would be about the same (6).

Until the mid-1990s, alpha-emitting radioisotopes were detected using instrumentation that measured gross alpha activity. This gross alpha count was attributed to a combination of (primarily) uranium and plutonium isotopes. The fraction of the gross alpha assigned to each of these elements varied depending on the facility or process emitting the alpha radioactivity. In M-Area (where reactor fuel was manufactured), alpha radioactivity was solely attributed to uranium. When the SRS conducted dose calculations, assumptions were made about the type of uranium present (natural, enriched, or depleted), with the corresponding isotopic fractions used (10). This approach is used below to estimate the curie fraction of each uranium isotope for the applicable SRS facilities.

In Cummins et al, "U-Nat" (natural uranium) represents "uranium-235, 238" (4). Uranium-235 and uranium-238 represent the majority of the mass of naturally occurring uranium. However, it should not be assumed that all uranium measured in environmental releases at the SRS was natural uranium. Despite this nomenclature, uranium actually occurs in three basic forms in the SRS environment—natural, depleted, and enriched. Natural uranium is processed to remove uranium-238 so that a higher concentration of uranium-235 is achieved, thus creating enriched uranium. The enrichment process creates a byproduct called depleted uranium. Depleted uranium was either disposed of as a waste or reused in target materials for producing plutonium isotopes. Evans et al provides approximate isotopic

compositions for each of these waste forms (11). Note that for enriched uranium, two basic types of fuel were manufactured and used at the SRS—Type M and Type F. Because it is unclear as to how much Type M fuel versus Type F fuel was used, Table C-10 shows an average isotopic composition for enriched fuel assuming the same mass of Type M and Type F fuel. Note that these compositions include uranium-234 and uranium-236. Although the original data sources only reference uranium-235 and uranium-238, it was assumed for Phase III that these other uranium isotopes were also present.

Table C-10 Isotopic Composition of Savannah River Uranium Wastes

Isotopic Composition (Weight %)*	Isotope			
	Uranium-234	Uranium-235	Uranium-236	Uranium-238
Natural	0.0055	0.7200	N/A†	99.2745
Depleted	N/A†	0.2	N/A†	99.8
Enriched‡	1.45	81.55	9.8	7.2
Half-Life (years)§	$2.45 \times 10^{+5}$	$7.03 \times 10^{+8}$	$2.34 \times 10^{+7}$	$4.47 \times 10^{+9}$

*Evans et al. 1992 (11).
†N/A – data not available.
‡Average of Isotopic Composition for Type M and Type F fuels.
§KAERI, 2003 (7).

Using the above weight percentages, the contribution to the activity for each isotope was calculated using Equation C1-1 and presented in Table C-11.

Table C-11 Activity Fraction for Specific Isotopes in Uranium Wastes

Activity Fraction (%)	Isotope			
	Uranium-234	Uranium-235	Uranium-236	Uranium-238
Natural	49.49	2.25	N/A*	48.26
Depleted	N/A*	1.27	N/A*	98.73
Enriched	91.73	1.79	6.45	0.03

*N/A – data not available.

The Phase III radiological assessment takes into account the isotopic distributions listed in Table C-11 as addressed below for each major group of SRS facilities.

- Reactor Areas: Any release of uranium in the reactor areas to streams and seepage basins was assumed to occur after the storage of spent fuel (containing enriched uranium) and target materials (containing depleted uranium) in spent fuel basins and disassembly basins (11). Basin purge water was normally discharged to the plant streams and seepage basins along with the reactor secondary cooling water. Uranium releases from the reactors to the atmosphere occurred due to the venting of "harps" (storage containers located underwater in the reactor basin which contained failed fuel and target elements) to the reactor stack (9). The ratio of enriched to depleted uranium that was used in the production reactors is not known and cannot be calculated. Because more enriched uranium (on a mass basis) than depleted uranium was probably used in the reactors, the activity fractions from Table C-11 for enriched uranium were used for environmental releases from the reactors.

- Separations Areas: Based on Evans et al., the F-Area facilities separated plutonium-239 from uranium targets primarily comprised of depleted uranium (11). Therefore, activity fractions in Table C-11 associated with depleted uranium were used for environmental releases from F-Area. In H-Area,

uranium-235 was recovered from enriched fuel. According to Evans et al., enrichment levels in H-Area fuel ranged from 1.1 percent to 94 percent uranium-235 (11). Therefore, the activity fractions in Table C-11 associated with enriched uranium were used for environmental releases from H-Area.

- M-Area: Reactor fuel and targets were fabricated in M-Area. Atmospheric releases of uranium were very small compared to the releases from F-Area. These releases were in the form of natural and depleted uranium, although it is unclear to what proportion these two forms of uranium were released (11). For the purposes of Phase III, natural uranium activity fractions from Table C-11 were assumed for atmospheric releases because uranium-234 is present in natural uranium in measurable quantities and is known to have been emitted from the SRS. Because depleted uranium has been found in stream sediments (11), the activity fractions for depleted uranium from Table C-11 were used for all liquid releases.

- A-Area (SRL): SRL worked with all forms of uranium. An average of the activity fractions for all three forms of uranium was used, assuming that an equal mass of natural, depleted, and enriched uranium was released. This assumption resulted in the following percentages of uranium isotopic activity: 91.44 percent for uranium-234; 1.8 percent for uranium-235; 6.4 percent for uranium-236; and 0.36 percent for uranium-238.

- CMX-TNX: Some natural uranium was used in fuel and target development at TNX (11). For this reason, activity fractions from Table C-11 for natural uranium were used for releases from CMX-TMX.

- D-Area: The rework of degraded moderator from reactor areas was the most likely source of alpha activity, which is assumed to be uranium (11). The moderator most likely contained a mixture of uranium isotopes representing both depleted and enriched uranium. To be consistent with the assumptions for the reactor areas, activity fractions from Table C-11 for enriched uranium were used for environmental releases from D-Area.

C.2.5 Plutonium

Plutoium-238, plutonium-239, and plutonium-240 were the primary plutonium isotopes of interest in environmental releases at the SRS. Plutonium-239 and plutonium-240 were often reported as plutonium-239 because these two isotopes were indistinguishable in alpha spectroscopy measurements (12). All three of these isotopes were produced by the reactors and were present in F- and H-Area processes. The most common form of plutonium produced at the SRS was weapons-grade plutonium. Weapons-grade plutonium had an isotopic composition similar to that shown in Table C-12.

Table C-12 Isotopic Composition of Weapons-Grade Plutonium

Mass and Activity Fractions	Plutonium Isotopes				
	Pu-238	Pu-239	Pu-240	Pu-241*	Pu-242
Mass Fraction	0.00012	0.938	0.058	0.0035	0.00022
Activity Fraction (using Equation C.2-1)	0.0047	0.1337	0.0302	0.8313	0.0000

* Plutonium-241 plus americium-241.
Source of Mass Fractions: Mark, 1993 (13).

Two issues that were resolved were the partitioning assumptions for activity described as combined plutonium-239,240 and activity described as total plutonium.

Activity described in Phase II as plutonium-239,240 was assumed to be plutonium-239. From Table C-12, the activity fraction of plutonium-240 is about 20 percent of that of plutonium-239. Also, the inhalation and ingestion effective dose conversion factors used in this report are similar for plutonium-240 to those for plutonium-241 (6).

With respect to total plutonium, despite comprising a very small mass fraction of weapons-grade plutonium, plutonium-241 (plus its daughter product americium-241) contributes approximately 83 percent of the activity (Table C-12). Americium-241 is addressed as a separate constituent; therefore, plutonium-241 is indirectly addressed in the dose assessments. Also, the ingestion and inhalation dose coefficients for plutonium-241 are much smaller than those for plutonium-238, plutonium-239, and plutonium-240 (6). Because plutonium-239 was the primary plutonium product at the SRS and has similar ingestion and inhalation effective dose conversion factors as plutonium-238 and plutonium-240 (6), all "Total Plutonium" releases to the environment were assumed to be plutonium-239.

C.2.6 Americium-241,243

Americium-241 is a daughter product of plutonium-241 and has a half-life of 432.2 years. Americium-243 has a half-life of 7,370 years. Americium-241 and americium-243 are reported as "Am-241,243" in environmental reports through 1992 because at that time these two isotopes could not be easily distinguished in laboratory analyses. In recent years, improved laboratory techniques allowed for separate measurement of these two isotopes. Based on these new techniques, it appears that any americium that appeared in SRS environmental samples was americium-241. Americium-243 is used as a tracer in laboratory analyses but does not appear to be attributable to the original environmental samples (14).

Americium-241 is an unwanted byproduct in the production of plutonium; however, on occasion, it was isolated and used for medical applications and well-logging sources. In addition, neptunium-237 could be produced through alpha decay of americium-241 (15). Very small quantities of americium-243 could have been generated as a byproduct of producing medical isotopes; however, as stated above, these quantities appear to be immeasurable.

For Phase III, americium-241,243 was assumed to be 100 percent americium-241.

C.2.7 Unidentified Alpha Emitters/Unidentified Beta-Gamma Emitters

Many of the radioactive releases at the SRS were detected using gross alpha and gross beta?gamma activity measurements. If the isotopes were known due to process knowledge, then the measurements were assigned to the isotopes in the environmental release reports. If the isotopes were not known, then the environmental release reports reflected unidentified alpha and unidentified beta?+ gamma measurements (11). The unknown constituents comprising unidentified alpha and unidentified beta ?+ gamma measurements were most likely a combination of several isotopes.

The SRS could not assign the unidentified alpha and unidentified beta?gamma activity measurements to specific isotopes. For this reason, these unidentified measurements were attributed to single isotopes to allow for conservative estimates of their dose contribution. Unknown alpha activity was assigned to plutonium-239, which has larger dose conversion factors than the uranium isotopes for many of the exposure pathways (6). In addition, plutonium-239 is one of the more prevalent plutonium isotopes at the SRS. Other transuranic isotopes have been produced and used at the SRS (such as neptunium-237, curium-244 and californium-252) that have contributed to the measurement of unidentified alpha, but these isotopes were primarily produced during brief periods and have dose conversion factors 100 to 1,000 times smaller than plutonium-239 (6). Therefore, using plutonium-239 for unidentified alpha values was a conservative assumption.

Many isotopes could contribute to unidentified beta-gamma activity measurements. For conservatism, unidentified beta-gamma activity was attributed to strontium-90, which was commonly found in environmental releases throughout the SRS facilities. With a half-life of 28 years, strontium-90 will also remain in the environment longer than most of the other beta- and gamma-emitting isotopes of concern.

C.3 Adjustment Factors for Surface Water Transport to Savannah River

This section describes the method by which the uncertainties and loss mechanisms associated with transport of radionuclides by surface water from their points of release to the Savannah River were addressed. The Phase II Report describes a model for estimates of release of hydrogen-3, strontium-90, and cesium-137 to the Savannah River based on environmental monitoring data and other parameters and processes that affect the transport of the contaminants in surface water. For Phase III of the SRS dose reconstruction project, the results of the Phase II model for these three radionuclides were extrapolated to all other radionuclides of interest.

Using the approach described herein, radionuclide concentrations in the Savannah River at an appropriate exposure location were determined. These concentrations were determined considering the discharge of radionuclides from all major surface water bodies draining the SRS, including Lower Three Runs Creek. Nonetheless, the approach described herein was not used to determine possible radiation exposures from public access to Lower Three Runs Creek. These exposures were determined by another method as addressed in Chapter 7 of this report.

C.3.1 Introduction

Figure C-1 depicts the major facilities releasing radionuclides to surface water bodies on the SRS site. These facilities include:

- The C-, P-, K-, L-, and R-Reactor areas.
- The H- and F-Separations areas.
- The A-Area.
- The M-Area.
- The D-Area and CMS-TNX.
- The Central Shops (CS) Area.

The reactor areas were the sources of most radionuclides released to surface water. Releases from the reactor and separations areas included radionuclides discharged directly to onsite streams as well as to reactor and separations areas seepage basins. Radionuclides released into seepage basins were delayed in transit through ground water before being released via surface seeps into onsite streams. This delay allowed for radioactive decay. Surface water releases of radionuclides were highest in the early to middle 1960's and decreased into the 1980's.

Also, Figure C-1 shows the five major onsite streams that received radionuclides from SRS facilities. Water from Upper Three Runs Creek, Fourmile Branch, Pen Branch, and Steel Creek passes through the Savannah River Swamp before it discharges into the Savannah River. Water from Lower Three Runs Creek does not pass through the swamp. Finally, Figure C-1 shows Road A which passes through the SRS from the southeast to the northwest. Road A is significant because environmental monitoring stations are located where Road A crosses the above five SRS streams. These Road A monitoring stations are the final points on the SRS site of routine stream monitoring before discharge of the stream water to the Savannah River.

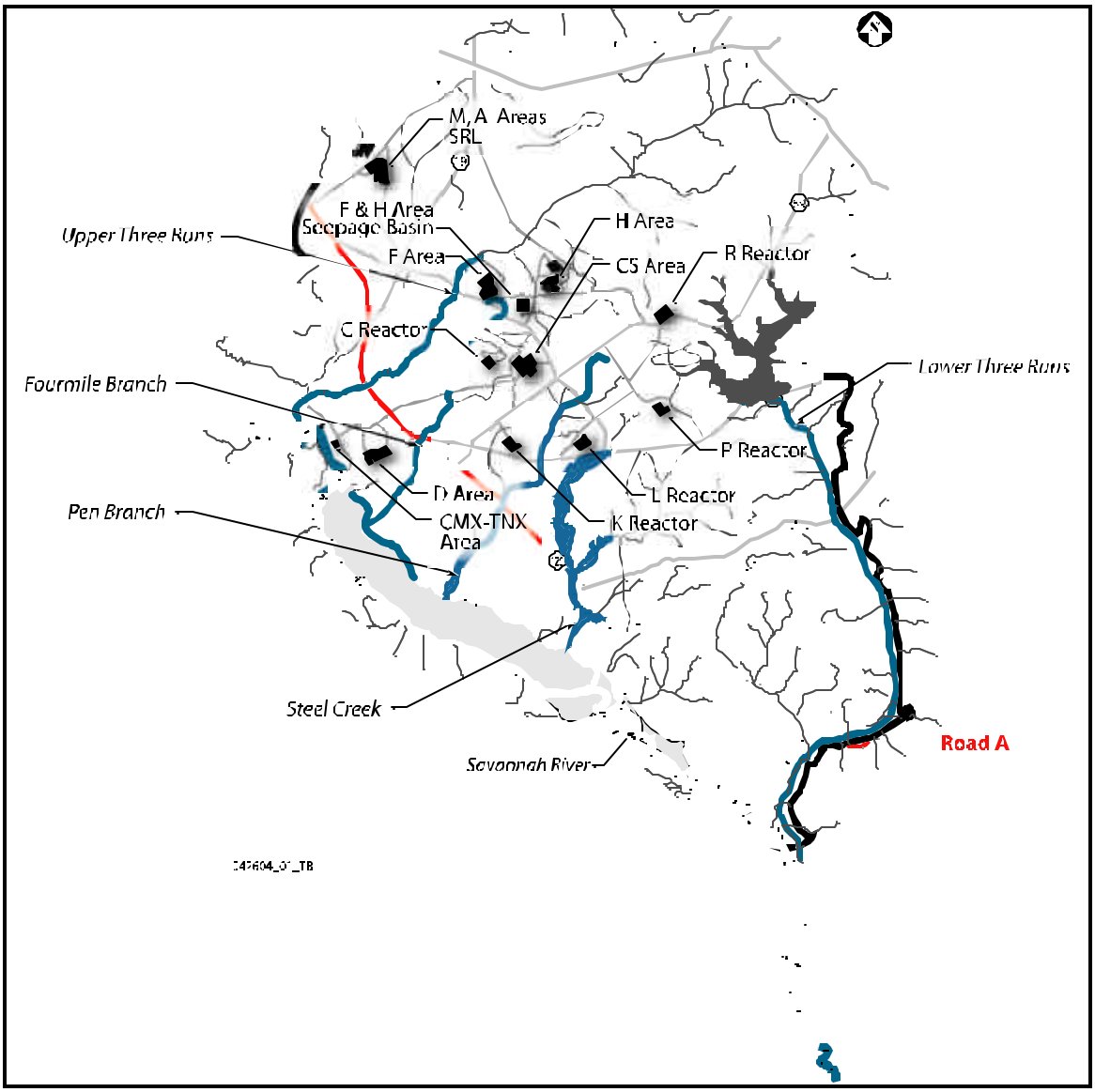

Figure C-1 Major SRS Sources of Release to Surface Water

Figure C-1 serves to point out the following difficulties inherent in deriving a radionuclide source term for surface water:

- Releases to surface water were not dispersed (in the sense that releases to air were dispersed) but eventually drained to one of the streams that flowed into the Savannah River.
- Each stream flowing offsite could have contained the contribution of more than one SRS facility or Area.
- Radionuclides discharged to streams were not immediately transported to locations on the Savannah River where the radionuclides could have been contacted by humans. Streams containing radionuclides had to flow for several miles before being discharged to the Savannah River. On the way, many radionuclides were sorbed into stream and swamp sediments, reducing the inventory eventually released offsite.

- Although radionuclides released to the air could be dispersed to all points of the compass by wind vectors, radionuclides released to surface waters on the SRS were channeled by streams and rivers. This means that radiation exposures could only occur at well-defined geographic locations such as publicly accessible locations below site discharge points into the Savannah River.
- Much liquid effluent was discharged over the years to seepage basins rather than directly to rivers. Transport of radionuclides through the ground water from the seepage basins to site steams was delayed through sorption and the usual slow ground-water flow.
- All but one of the major onsite streams discharging radionuclides to the Savannah River passed through the Savannah River Swamp. Due to sedimentation processes characteristic of wetlands, many radionuclides were deposited into swamp sediments. The swamp, however, historically flooded about 20 percent of the time. Flooding tended to increase releases from the swamp to the Savannah River.

Because of these considerations, a source term was developed for Phase III that estimated radionuclide concentrations at an exposure location downstream of the points of radioactive discharge from all SRS streams. These concentrations reflect the concentrations that exist **after** the radionuclides were transported through surface water from the various points of the SRS site release to the exposure location.[5]

The starting point for this effort was the Phase II estimates of release to surface water (3). This reference identified nearly two dozen key radionuclides that had been released to surface water from SRS facilities during the years of nuclear material production. Phase II also developed a model for discharge into the Savannah River for three of these radionuclides (tritium, cesium-137, and strontium-90).

For the Phase III report, the task was to complete the estimates of release into the Savannah River for all the other key radionuclides that were identified in Phase II for release to surface water. This task included the following projects:

- Reviewing the Phase II information and supplementing its estimates of release to surface water for several radionuclides.
- Partitioning radionuclides reported as aggregated quantities (e.g., combined strontium-89 and strontium-90) into individual isotopes consistent with the approach described in Section C.2 of this appendix.
- Developing a procedure that accounted for the delay experienced by all key radionuclides while being transported from their various points of release to the Savannah River.

This Phase III procedure used a set of annual adjustment factors that extended to other radionuclides the Phase II modeled releases of hydrogen-3, strontium-90, and cesium-137 to the Savannah River. In this way, annual radionuclide concentrations in the Savannah River were determined for the 22 radionuclides listed in Table C-13.

[5] This approach is different from that used for release of radionuclides to air. Annual radionuclide quantities released from four groups of SRS facilities were determined as discussed in Chapter 5. (These annual releases are listed in Appendix B as the source term for radionuclides released to air.) Then, the transport of these radionuclides by wind to exposure locations around the SRS site was estimated using a Gaussian plume model as discussed in Chapter 6. The output of the Gaussian plume model was the concentrations of radionuclides annually existing in air and deposited onto the ground at these exposure locations.

Table C-13 Radionuclides Considered for Savannah River Source Term

Cerium-144	Iodine-131	Strontium-89	Uranium-236
Cesium-134	Niobium-95	Strontium-90	Uranium-238
Cesium-137	Phosphorus-32	Sulfur-35	Zinc-65
Cobalt-60	Plutonium-238	Technicium-99	Zirconium-95
Hydrogen-3	Plutonium-239	Uranium-234	
Iodine-129	Ruthenium-106	Uranium-235	

C.3.2 Phase II Modeled Release to Savannah River of Tritium, Strontium-90, and Cesium-137

Chapter 5 of Phase II discusses in detail how the accounting of releases to the surface water pathway ***at the point of release*** is not an accurate estimate of the actual releases from the SRS site to the Savannah River. In addition to direct releases to onsite streams, waters were released to seepage basins which held the waste for some period of time. These waste waters would seep into the soil and eventually reach the surface at the nearby streams. The southwestern edge of the SRS site along the Savannah River consists of a wetland, which slows the flow of water to the Savannah River as well as acts as a sink for dissolved constituents that are sorbed or taken up by minerals, sediments, plants, and other biota in the swamp. In addition to these physicochemical means of reducing the releases to the Savannah River, radioactive decay affects the concentrations of constituents that would reach the Savannah River.

As described in Chapter 5 of the Phase II report, a relatively simple model was used to project the release to the Savannah River of hydrogen-3, strontium-90, and cesium-137 based on concentrations of these constituents measured at the sampling stations along Road A (the sampling point closest to the river) (3). These three radionuclides were identified in Phase II as important possible contributors to either offsite release or dose, and had been monitored extensively during the years of nuclear material production.

The Phase II model explicitly considers the following factors (3):

- Transport of radionuclides through surface water as dissolved and suspended constituents.
- Release of previously retained radionuclides by periodic flooding of the Savannah River Swamp.
- Measurement uncertainty.

The effects of the various physical and chemical interactions of released radionuclides with the soil, biota, and other features of the SRS generally decreased the modeled radionuclide quantities reaching the Savannah River. On the other hand, when incorporated into the Phase II model, many of the radionuclide measurement uncertainties increased the modeled quantities discharged to the Savannah River (3).

The mathematical procedures used to estimate the transport of radionuclides to the Savannah River considered dissolved radionuclides as well as the transport of radionuclides attached to suspended and bottom sediments of various sizes. The dissolved concentration at any location was found using a mass conservation equation obtained from Till, 1983 (16):[6]

$$C_{x,t} = \frac{Q(x-\Delta x,\ t-\Delta t)C(x-\Delta x,\ t-\Delta t)e^{-\lambda\Delta t}}{Q_{x,t}} \qquad \text{(Eq. C.3-1)}$$

[6] Terminology for this discussion is from Phase II.

Where:

Cx,t	=	dissolved radionuclide concentration at location x and time t,
Qx,t	=	flow rate at location x and time t,
λ	=	radionuclide decay constant
Δx,t	=	travel time in stream (s)
Δx	=	change in location (m)
x	=	distance (m)
t	=	time (s)

The travel time in the stream (Δx,t) was the time it took the radionuclide to move from Road A (its last point of measurement) to the Savannah River. The travel time depended on the flow rate and velocity of the particular stream, and the distance from Road A to the Savannah River.[7] The final activity of the radionuclide entering the Savannah River was reduced by radioactive decay that occurred during this travel time.

The flow rate of the dissolved radionuclide (pCi/s) was determined by multiplying the concentration in water (pCi/m3) by the flow rate of the water (m3/s) (3).

The concentration of radionuclides attached to sediment (Cp) was calculated from the dissolved radionuclide concentration and the distribution coefficient (K_d) by (3):

$$Cpx,t = K_d \; Cx,t. \qquad \text{(Eq. C.3-2)}$$

Where Cp is in units of pCi/g and the distribution coefficient, K_d, is a measure of the amount of radionuclide sorbed on sediment:

$$K_d = \frac{\text{amount of radionuclide sorbed on sediment}}{\text{amount of radionuclide left in solution}} \qquad \text{(Eq. C.3-3)}$$

And the sediment transport rate in water was given as (16):

$$ST = aQb \qquad \text{(Eq. C.3-4)}$$

Where ST is the sediment transport rate (units of g/s), and the parameters (a and b) are constants estimated for each sediment size range. For Phase II, it was assumed that a = 0.0004 and b = 3 based on studies at the SRS (17).

From this, the flow rate of the radionuclide absorbed in transported sediment (Ci/s) was given as the product of the concentration in sediment (pCi/g) and the sediment transport rate (g/s). The total flow rate was the sum of that flow rates for dissolved and suspended radionuclides, and this sum multiplied by the number of seconds in a year gave the yearly activity transported to the Savannah River (3).

In addition to these mathematical relationships, the model used to project the release of these radionuclides to the Savannah River considered periodic flooding of the Savannah River Swamp and sampling and measurement uncertainties (3). The Savannah River Swamp flooded about 20 percent of the time (74 days per year on the average) during the period from 1958 to 1967. It was assumed that additional releases to the Savannah River occurred from the swamp when flooding occurred. This uncertainty was considered a source of bias that increased releases for radionuclides like cesium and

[7] For example, this distance was 12 km for Fourmile Branch.

strontium that were retained in the swamp. Detailed records existed for annual rainfall amounts. For most years, releases were increased for cesium and strontium by 20 percent (with a range of 10 to 30 percent). For years having high rainfall (e.g., 1964 and 1971), a value of 40 percent (with a range of 25 to 60 percent) was assumed. For years having low rainfall, it was assumed that the swamp flooded only 10 percent of the time (with a range of 5 to 15 percent) (3).

Uncertainties associated with the release estimates were considered from analytical errors in the measurement of flow and in sampling and determination of radionuclide concentrations in water. (Because tritium was not impacted heavily by flow through the Savannah River Swamp, sampling and analytical uncertainties were the major sources of uncertainty in the release estimates for tritium.) The effluent volume to the site streams was monitored reasonably well by both the SRS and the USGS (3). Estimates of error for the routine concentration measurements varied with the radionuclide, the sample preparation, and the counting procedure (3).

Table C-14 summarizes the factors that were considered in estimating the releases of tritium, cesium-137, and strontium-90 to site streams and their discharge to the Savannah River. Several time periods were considered due to changes in sampling procedures and analytical methods. In addition, the retention within the swamp varied among the radionuclides as described above (3).

Table C-14 Factors Considered in the Uncertainty Estimates for Surface Water Source Terms for Key Radionuclides

Radio-nuclide	Time Period	Measured Effluent Release	Measured in Stream at Road A	Estimated Measurement Uncertainty	Effect of Swamp	
					K_d Values	Flooding
Tritium	1954-1957	yes	No	50%	none	none
	1958-1959	yes	Yes	40%	none	none
	1960-1973	yes	Yes	25%	none	none
	1974-1992	yes	Yes	15%	none	none
Cesium-137	1954-1958	no	No	60%	10,000*	1.1 to 1.4†
	1959-1973	yes	Yes	50%	10,000*	1.1 to 1.4†
	1974-1992	yes	Yes	25%	10,000*	1.1 to 1.4†
Strontium-90	1954-1960	some	No	60%	100*	1.1 to 1.4†
	1961-1973	yes	Yes	50%	100*	1.1 to 1.4†
	1974-1992	yes	Yes	25%	100*	1.1 to 1.4†

*The median estimate is listed; the range of K_d values is: cesium (50–80,000) and strontium (8–4000).

†Based on rainfall amounts for each year; in general, the swamp flooding occurred about 20 percent of the time each year when the average rainfall was about 47 inches. In 1964, very heavy rainfall (73 in) and extensive flooding occurred; in 1954, it was quite dry (28 in) and little swamp flooding occurred.

Source: Phase II (3).

Measurements specific for cesium-137 and strontium-90 were not made in early years. Before circa 1960, only nonvolatile beta activity was measured. To estimate annual cesium-137 releases for times when specific measurements were not made, a ratio was calculated of cesium-137 to nonvolatile beta activity when both measurements were made at the same time and location. This ratio was used, along with nonvolatile beta activity measurements, to estimate levels of cesium-137 activity in site streams at Road A when cesium-137-specific measurements were not made. A similar procedure was used for strontium-

90. Using this information, a stochastic uncertainty analysis of the model was performed on the three radionuclides, leading to a range of values calculated each year for each radionuclide (3).

C.3.3 Development of Savannah River Source Term for Phase III

C.3.3.1 Challenges

The development of a mathematical model that accounted for the transport of radionuclides through onsite surface water bodies until they were discharged into the Savannah River was considered desirable. However, as discussed in Section C.3.1., this approach contained numerous challenges and would have been difficult to develop and validate. The complex nature of radionuclide transport by surface water at the SRS requires consideration of the loss mechanisms, time delays, and uncertainties that influence radionuclide concentrations reaching the Savannah River. Transport of released radionuclides across the SRS into the Savannah River is neither simple nor direct.

These difficulties were apparent to the preparers of the Phase II report who created a model that estimated releases of tritium, strontium-90, and cesium-137 into the Savannah River. This model started with monitoring data measured at onsite sampling points where Road A crossed onsite streams and projected discharge into the Savannah River considering transport of radioactive constituents in dissolved and particulate forms, the retention of radionuclides in the Savannah River Swamp and their release during heavy floods, and sampling and measurement uncertainties.

The Phase II work led to consideration, for Phase III, of extending the Phase II model to the other key radionuclides identified in the Phase II screening assessment. Unfortunately, direct modeling similar to that performed in the Phase II study was not possible. Because the concentrations of most radionuclides were below detectable limits at the Road A intersections, the basis of the Phase II model for the remaining radionuclides was unavailable.

It was also considered unreasonable to merely assume point-of-release information (as reported by Cummins et al [4] and by annual SRS environmental reports) as a source term for discharge into the Savannah River. This approach would have presented concentrations in the Savannah River that were generally higher than was actually the case. The approach would have been a conservative one, but it would not have represented the storage of radionuclides in the swamp and their release during floods. In addition, this approach would not have represented measurement uncertainty.

C.3.3.2 Summary of Approach

In light of the challenges discussed above, a modification of the Phase II modeling approach was used for Phase III to determine annual release of radionuclides to the Savannah River. This approach was used to determine annual concentrations of radionuclides in the Savannah River from all bodies of surface water releasing radionuclides into the river. The annual concentrations were used to determine the levels of radiation doses and cancer risks that may have been associated with these releases.[8]

For Phase III, the annual concentrations of radionuclides released into the Savannah River were determined by using annual adjustment factors as shown in the following equation:

$$CSri(t) = APORi(t) / VSR(t) \; AFi(t) \qquad \text{(Eqn. C.3-5)}$$

[8] Five exposure pathways were considered in Phase III for release of radionuclides to surface water: consumption of fish taken from contaminated river or creek water, external exposure while occupying the shoreline of the contaminated river or creek, external exposure from swimming in the river, inadvertent ingestion of water while swimming in the river, and external exposure from boating on the river.

Where:

CSri(t) = Annual concentration of radionuclide i in the Savannah River at the designated exposure location.

APORi(t) = Activity of radionuclide i annually released into all SRS streams seepage basins, and containment basins, as determined at the point of release.

VSR(t) = Annual volume of Savannah River water flowing through or past a designated exposure location on the Savannah River.

AFi(t) = Annual adjustment factor for radionuclide i.

Adjustment factors were developed for each year for three classes of radionuclides encompassing different ranges of the soil-to-water distribution coefficient (K_d). The adjustment factors are the ratio of the median of the Phase II modeling results for each year, respectively, for hydrogen-3, strontium-90, and cesium-137, to the activity released from SRS facilities for each year, respectively, for hydrogen-3, strontium-90, and cesium-137, as determined at the points of release. That is, the adjustment factors were calculated as follows:

$$AFi(t) = \frac{\text{Annual median of Phase II modeled discharge to Savannah River of hydrogen-3, strontium-90, or cesium-137 (Ci)}}{\text{Annual hydrogen-3, strontium-90, or cesium-137 release at point of release (Ci)}} \qquad \text{(Eq. C.3-6)}$$

The adjustment factors thus calculated were used for other radionuclides having similar K_ds (i.e., Table C-15):

Table C-15 Application of Adjustment Factors to Radionuclides

Adjustment Factors Determined For:	Were Applied To:
Hydrogen-3	Hydrogen-3, Sulfur-35, Technicium-99, Iodine-129, Iodine-131
Strontium-90	Phosphorus-32, Cobalt-60, Zinc-65, Strontium-89, Strontium-90, Niobium-95, Zirconium-95, Ruthenium-106, Cerium-144, Uranium
Cesium-137	Cesium-134, Cesium-137, Plutonium-238, Plutonium-239

For equation C.3-5, the annual volume of the Savannah River was determined using data from the U.S. Geological Survey (USGS). In equation C.3-5, the annual activity of hydrogen-3 and strontium-137 that was released was the same annual activity for these two radionuclides that was assumed in the denominator of equation C.3-6. Hence, the annual activity released into the Savannah River was the same for these radionuclides as that modeled in Phase II. But for strontium-90, two different point-of-release data files were compiled—one for developing the annual adjustment factors and one for estimating annual discharge of strontium-90 to the Savannah River (see Section C.4.1).

C.3.4 Components of Phase III Approach

This section discusses important components of the Phase III approach to estimate the annual concentrations of radionuclides in the Savannah River resulting from production of nuclear materials at the SRS.

Section C.3.4.1 briefly discusses the environmental studies, reports, and other data used to compile point-of-release activity estimates for the radionuclides identified in Table C-13. As part of this process, the activities for radionuclides identified as mixtures of isotopes were partitioned among specific isotopes.

Section C.3.4.2 provides Phase III estimates of the annual Savannah River flow rate over the period from 1954 to 1992.

Section C.3.4.3 addresses the use of soil-to-water distribution coefficients for grouping radionuclides for application of the adjustment factors.

Section C.3.4.4 calculates and presents the Phase III adjustment factors.

C.3.4.1 Annual Radionuclide Release at Points of Release

The principal reference used to develop the annual radionuclide point-of-release data files was Cummins et al (4). This reference was used for releases during the years 1954 through 1989, while SRS environmental reports were used for the years 1990 through 1992 (18-20). To develop the data files, a guiding decision had to be made about the specific releases to be included.

Liquid releases from the site can be placed into the following three categories (4):

- Category 1 - Direct releases to onsite streams.
- Category 2 - Migration from seepage basins into onsite streams.
- Category 3 - Direct releases to seepage and containment basins.

Although one might think that the total release to site streams should be the sum of Categories 1 and 2, the Phase II report generally used the sum of Categories 1 and 3 to represent the liquid source terms in the screening assessment.[9] There appear to be at least two reasons for this choice: (1) because migration from the seepage basins is distributed in time and space, measurements of concentrations immediately downstream of the seepage basins may under-represent the total flux from the seepage basins to the streams; and (2) the sum of Categories 1 and 3 should be a conservative estimate of liquid releases to site streams.

For these reasons, the annual sums of releases from Categories 1 and 3 were chosen as representative of SRS releases to site streams. This has two implications: (1) the adjustment factors based on modeled releases of hydrogen-3, strontium-90, and cesium-137 used the sums of Categories 1 and 3 as the denominators of the adjustment factors; and (2) these adjustment factors were applied to the sums of Categories 1 and 3 for radionuclides having similar K_d's.

This decision meant that tritium evaporated from seepage and containment basins was excluded from the point-of-release data file created for tritium released to water. Evaporated tritium was included in the Phase III atmospheric releases (Chapter 5).

[9] Exceptions are hydrogen-3 and iodine-131, where only release to streams was considered for the screening assessment.

It also meant that the estimated cesium-137 desorption from the Fourmile Creek bed that was reported by Cummins et al (4) was not included in the data files. The activity reported in this desorption was already included in the Category 1 and 3 releases as described above. Use of desorption estimates would have caused double counting.

Based on these assumptions, point-of release data files were compiled for each of the 22 radionuclides considered for release to the Savannah River. For all radionuclides except strontium-90, a single data file was constructed for each radionuclide. But two data files were constructed for strontium-90: one for developing the annual adjustment factors (Equation C.3-6) and one for estimating annual discharge of strontium-90 to the Savannah River (Equation C.3-5).

There were reasons why two different point-of-release data files were complied for strontium-90. One reason was that the adjustment factor determined for strontium-90 was applied to several other radionuclides as shown in Table C-15. Therefore, it was important to assure that any assumptions pertaining to the annual release of strontium-90 were not overweight projections of other radionuclides that may have similar K_d's but are otherwise dissimilar. Another reason was that much of the release data for strontium-90 were given as an aggregated mix of strontium-89 and strontium-90, or as unidentified beta-gamma activity (see below). However, Phase II modeled releases into the Savannah River based only on environmental monitoring data for strontium-90, and not on mixed strontium-89,90 activity or on unidentified beta-gamma activity (3).

The data sets used to develop the two point-of-release data files for strontium-90 are listed in Table C-16. Each data set consisted of all indicated activity that was annually released into streams, seepage basins, and containment basins.

Table C-16 Data Sets Used for Strontium-90

Strontium-90 Point-of-Release Data Used to Determine Strontium-90 Discharge to Savannah River (Equation C.3-5)	Strontium-90 Point-of-Release Data Used for Adjustment Factors (Equation C.3-6)
Strontium-90 data	Strontium-90 data
Strontium-90 activity partitioned from Strontium-89,90 data	Strontium-90 activity partitioned from Strontium-89,90 data
Unidentified beta-gamma activity	

The Phase III assumptions and procedures for partitioning aggregated radionuclide quantities into individual radionuclides are in Section C.2 of this appendix.

C.3.4.2 Savannah River Flow Rate

Annual flow rates for the Savannah River were obtained from two sources—the United States Geological Survey (USGS) and Hayes and Marter (21,22). For the years 1954 through 1969, and for the years 1983 through 1992, the USGS provided flow rates for the Savannah River as measured at Burtons Ferry Bridge (U.S. Highway 301) near Millhaven, Georgia (21). This monitoring station is located about 500 feet downstream of the bridge on U.S. Highway 301 linking Screven County, Georgia, with Allendale County, South Carolina. Hence, it is downstream of all surface water discharge points into the Savannah River.

No information was available from the USGS for this monitoring station for the years 1970 through 1982. For these years, flow rates were projected from flow rates measured at Augusta, Georgia. The projected

flow rates were obtained from Hayes and Marter (22). These authors determined a correlation coefficient of 0.98 when data for the Burtons Ferry Bridge and Augusta monitoring stations were fitted to the following equation: $y = mx + b$

Where:

y is the projected flow rate at Burtons Ferry Bridge.
x is the measured flow rate at Augusta.
m and b are coefficients obtained from the regression analysis ($m = 1.1486 \pm 0.0330$ and $b = -202 \pm 298$ (22).

The flow rates assumed for this report are listed in Table C-17 in units of cubic feet per second (cfs). Also, the Savannah River volumes used for this report are listed as calculated assuming 365 days per year (except for 366 days per year every leap year), and as converted to liters.

Table C-17 Savannah River Flow Rates and Annual Volumes as Determined for Burtons Ferry Bridge (U.S. Highway 301)

Year	Leap Year	Annual Mean Value* (cfs)	Water Volume (Liter)	Year	Leap Year	Annual Mean Value* (cfs)	Water Volume (Liter)
1954		7,382	$6.60x10^{+12}$	1974		11,101	$9.93x10^{+12}$
1955		5,974	$5.34x10^{+12}$	1975		15,408	$1.38x10^{+13}$
1956	L	6,309	$5.66x10^{+12}$	1976	L	13,914	$1.25x10^{+13}$
1957		8,312	$7.43x10^{+12}$	1977		11,646	$1.04x10^{+13}$
1958		11,038	$9.87x10^{+12}$	1978		10,522	$9.41x10^{+12}$
1959		9,748	$8.72x10^{+12}$	1979		13,252	$1.18x10^{+13}$
1960	L	13,112	$1.18x10^{+13}$	1980	L	13,201	$1.18x10^{+13}$
1961		10,909	$9.75x10^{+12}$	1981		6,599	$5.90x10^{+12}$
1962		10,580	$9.46x10^{+12}$	1982		7,169	$6.41x10^{+12}$
1963		11,138	$9.96x10^{+12}$	1983		12,348	$1.10x10^{+13}$
1964	L	20,497	$1.84x10^{+13}$	1984	L	12,759	$1.14x10^{+13}$
1965		12,785	$1.14x10^{+13}$	1985		7,167	$6.41x10^{+12}$
1966		11,175	$9.99x10^{+12}$	1986		6,175	$5.52x10^{+12}$
1967		10,573	$9.45x10^{+12}$	1987		8,955	$8.01x10^{+12}$
1968	L	9,624	$8.63x10^{+12}$	1988	L	5,364	$4.81x10^{+12}$
1969		10,945	$9.79x10^{+12}$	1989		7,966	$7.12x10^{+12}$
1970		8,208	$7.34x10^{+12}$	1990		11,860	$1.06x10^{+13}$
1971		10,686	$9.55x10^{+12}$	1991		11,670	$1.04x10^{+13}$
1972	L	11,235	$1.01x10_{+13}$	1992	L	11,860	$1.06x10^{+13}$
1973					14,431	$1.29x10^{+13}$	

* Flow rate from USGS Station ID: 02197500.

C.3.4.3 Effect of the Distribution Coefficient, K_d, On Release Estimates

The soil-to-water distribution coefficient, K_d, is a measure of the partitioning between solid and liquid phases that a radionuclide experiences as it passes through environmental media. As radioactive contaminants move through the soils, sediments, and the swamp at the SRS site, they are attracted to various surfaces. This attraction results in a delay (retardation) of the transport of the contaminant through the system, relative to the flow of water. The amount of a particular radionuclide that will reach the Savannah River will be, in part, a reflection of this retardation phenomenon and its radiological half-life.

Even though the K_d values for all of the radionuclides considered in this analysis span many orders of magnitude, the radionuclides have been combined into three groups, based upon their K_d (units of milliliters to grams [mL/g]):

1. $K_d < 10$.
2. $10 < K_d < 1{,}000$.
3. $K_d > 1000$.

These groups correspond to the nominal K_d values used in the Phase II modeling: 0, 100, and 10,000 mL/g, respectively. All radionuclides assigned to a particular group were assigned the same annual adjustment factor calculated for that group. Table C-18 summarizes the grouping.

Table C-18 Grouping of Radionuclides According to K_d Values

Radionuclide	Soil-to-Water Distribution Coefficient, K_d (mL/g)			Adjustment Factor‡
	Phase II Value	Soil Value*	Swamp Value†	
Hydrogen-3	**0**	0		Hydrogen-3
Iodine-129,131		1.55		Hydrogen-3
Technicium-99		2.49		Hydrogent-3
Sulfur-35		7.5		Hydrogen-3
Ruthenium-103,106		55		Strontium-90
Cobalt-60		60		Strontium-90
Strontium-89,90	**100**	3,040	1,676	Strontium-90
Niobium-95		160		Strontium-90
Phosphorus-32		173		Strontium-90
Zinc-65		200		Strontium-90
Cerium-141,144		490	255	Strontium-90
Zirconium-95		600		Strontium-90
Uranium		1,000	170	Strontium-90
Plutonium		4,100		Cesium-137
Cesium-134, 137	**10,000**	59		Cesium-137

*Source: Kaplan, 2003 (23).
†Source: Kaplan and Serkiz, 2000 (24).
‡The annual adjustment factors are listed in Table C-20.

In reviewing the K_d's assumed for Phase II and used to group radionuclides by annual adjustment factor, the K_d assumed for strontium-90 appeared to be low compared to other values cited in the literature, and the K_d assumed for scandium-137 appeared to be high. K_d values used for the Phase II modeling were orders of magnitude different from site-specific values recently reported by the SRS (23). In the Phase II modeling, a range of K_ds having a median value of 10,000 mL/g were used for cesium, whereas the range of values used for strontium had a median value of 100 mL/g. Median K_ds reported by Kaplan et al for agricultural soils are 59 mL/g for cesium and 3,041 mL/g for strontium, respectively (23). However, another report by Kaplan reports K_d values that appear to be more appropriate for the swampy soils at issue in the holdup of radionuclides released from the SRS. For example, a "reasonably conservative" value cited for the strontium K_d in the swamp was 1,676 mL/g (24). But, without further explanation of and examination of the Phase II model, it is difficult to characterize the apparent reversal of cesium and strontium K_d values. Other uncertainties, such as measurement uncertainty and uncertainty in the release from the swamp during flooding, were also considered in the estimation of releases for hydrogen-3, strontium-90, and cesium-137. These uncertainties are not the same from one radionuclide to another.

C.3.4.4 Adjustment Factor Development

Adjustment factors were calculated by dividing the median values of the Phase II release model by the point-of-release inventories discussed in Sections C.3.3.2 and C.4.2. Table C-19 lists these values and inventories. Table C-20 lists the resultant adjustment factors.

Note that the adjustment factor initially calculated for tritium in year 1954 was 20.8814, which is 3 times larger than the next highest tritium adjustment factor and about 20 times larger than the median value of all adjustment factors over 39 years. This large factor was calculated because of the inclusion of estimated releases from D-Area in the Phase II modeling of tritium release to the Savannah River. In 1954, 17,530 curies of tritium from D-Area was assumed to be released to a stream (3). This D-Area release, however, is not documented in Cummins et al (4).

In Phase III, tritium release from D-Area was thought to be the only reason for such a large adjustment factor in 1954. Consequently, the other radionuclides in this group (i.e. iodine-129,131; technicium-99; and sulfur-35) should not be similarly adjusted as this could result in significant overestimation of their true releases. Another reason for not using such a large adjustment factor for the tritium group in 1954 was that the functionality of D-Area was heavy water rework, and site effluent release data (4) did not show that iodine, technetium, and sulfur were released from that facility in 1954. The factor 1.0 was thus used for the tritium group in 1954 to avoid overestimation of other radionuclide releases.

Table C-19 Phase II Median Values and Point of Release Inventories Used for Adjustment Factors

Year	Point of Release Inventories			Phase II Median Values		
	Hydrogen-3	Cesium-137	Strontium-90	Hydrogen-3	Cesium-137	Strontium-90
1954	$3.66x10^{+02}$	$1.80x10^{-01}$	$3.90x10^{-02}$	$7.64x10^{+03}$	$1.41x10^{-01}$	$4.13x10^{-02}$
1955	$5.87x10^{+03}$	1.37	$8.16x10^{-01}$	$1.32x10^{+04}$	$2.65x10^{-01}$	$1.45x10^{-01}$
1956	$9.39x10^{+03}$	3.43	$1.04x10^{+01}$	$1.50x10^{+04}$	1.11	$3.60x10^{-01}$
1957	$2.24x10^{+04}$	$8.40x10^{+02}$	$1.96x10^{+02}$	$2.16x10^{+04}$	1.16	1.54
1958	$2.88x10^{+04}$	$1.04x10^{+02}$	$1.58x10^{+01}$	$2.88x10^{+04}$	9.51	$8.30x10^{-01}$
1959	$5.17x10^{+04}$	$4.14x10^{+01}$	$2.18x10^{+01}$	$6.29x10^{+04}$	3.59	1.80
1960	$6.09x10^{+04}$	$4.36x10^{+01}$	$2.36x10^{+01}$	$6.98x10^{+04}$	7.60	$1.76x10^{+01}$

Year	Point of Release Inventories			Phase II Median Values		
	Hydrogen-3	Cesium-137	Strontium-90	Hydrogen-3	Cesium-137	Strontium-90
1961	$8.11x10^{+04}$	$4.06x10^{+01}$	9.85	$8.28x10^{+04}$	$1.03x10^{+01}$	4.22
1962	$7.23x10^{+04}$	$1.03x10^{+02}$	$1.04x10^{+01}$	$6.47x10^{+04}$	$1.92x10^{+01}$	6.78
1963	$9.66x10^{+04}$	$1.23x10^{+02}$	$2.10x10^{+01}$	$9.69x10^{+04}$	$1.68x10^{+01}$	$1.07x10^{+01}$
1964	$1.17x10^{+05}$	$1.30x10^{+02}$	$1.41x10^{+01}$	$1.21x10^{+05}$	$5.15x10^{+01}$	$1.13x10^{+01}$
1965	$1.28x10^{+05}$	$5.56x10^{+01}$	$1.17x10^{+01}$	$1.06x10^{+05}$	$2.35x10^{+01}$	5.22
1966	$1.33x10^{+05}$	$5.36x10^{+01}$	6.12	$9.56x10^{+04}$	$2.72x10^{+01}$	4.46
1967	$1.04x10^{+05}$	$6.87x10^{+01}$	6.72	$8.75x10^{+04}$	$3.80x10^{+01}$	4.82
1968	$1.07x10^{+05}$	$7.08x10^{+01}$	9.19	$8.39x10^{+04}$	$2.08x10^{+01}$	5.46
1969	$7.88x10^{+04}$	$5.14x10^{+01}$	$1.02x10^{+01}$	$7.64x10^{+04}$	$1.04x10^{+01}$	3.58
1970	$6.61x10^{+04}$	$4.43x10^{+01}$	7.26	$4.25x10^{+04}$	$1.02x10^{+01}$	3.89
1971	$4.47x10^{+04}$	$1.05x10^{+01}$	3.14	$4.44x10^{+04}$	1.69	3.81
1972	$6.09x10^{+04}$	9.14	1.25	$4.68x10^{+04}$	$6.28x10^{-01}$	1.92
1973	$8.69x10^{+04}$	7.48	$9.01x10^{-01}$	$6.10x10^{+04}$	$4.44x10^{-01}$	2.07
1974	$5.61x10^{+04}$	8.09	$4.27x10^{-01}$	$5.41x10^{+04}$	$7.01x10^{-01}$	1.72
1975	$5.15x10^{+04}$	7.75	$9.12x10^{-01}$	$4.93x10^{+04}$	$3.61x10^{-01}$	1.46
1976	$7.32x10^{+04}$	8.94	$4.76x10^{-01}$	$4.64x10^{+04}$	$1.46x10^{-01}$	1.18
1977	$4.59x10^{+04}$	6.58	$5.55x10^{-01}$	$4.03x10^{+04}$	$2.45x10^{-01}$	$9.04x10^{-01}$
1978	$3.76x10^{+04}$	$1.04x10^{+01}$	2.06	$3.55x10^{+04}$	$1.04x10^{-01}$	$6.20x10^{-01}$
1979	$4.52x10^{+04}$	6.27	2.68	$2.84x10^{+04}$	$1.04x10^{-01}$	$6.24x10^{-01}$
1980	$3.54x10^{+04}$	1.83	$1.55x10^{-01}$	$3.00x10^{+04}$	$7.72x10^{-02}$	$5.05x10^{-01}$
1981	$3.94x10^{+04}$	2.81	1.04	$2.51x10^{+04}$	$1.16x10^{-01}$	$4.61x10^{-01}$
1982	$3.15x10^{+04}$	2.85	$6.98x10^{-01}$	$3.08x10^{+04}$	$8.36x10^{-02}$	$3.95x10^{-01}$
1983	$4.06x10^{+04}$	3.43	$2.35x10^{-01}$	$3.24x10^{+04}$	$7.74x10^{-02}$	$3.84x10^{-01}$
1984	$3.58x10^{+04}$	6.13	$9.44x10^{-02}$	$3.23x10^{+04}$	$1.22x10^{-01}$	$4.25x10^{-01}$
1985	$3.40x10^{+04}$	6.23	$1.70x10^{-01}$	$2.21x10^{+04}$	$5.14x10^{-02}$	$2.25x10^{-01}$
1986	$4.52x10^{+04}$	$1.13x10^{+01}$	$1.28x10^{-01}$	$2.21x10^{+04}$	$5.51x10^{-02}$	$3.26x10^{-01}$
1987	$2.75x10^{+04}$	$1.54x10^{+01}$	$5.69x10^{-02}$	$2.04x10^{+04}$	$1.98x10^{-01}$	$3.63x10^{-01}$
1988	$1.44x10^{+04}$	6.39	$4.40x10^{-02}$	$1.82x10^{+04}$	$2.92x10^{-01}$	$2.63x10^{-01}$
1989	$3.97x10^{+03}$	$2.10x10^{-01}$	$1.68x10^{-02}$	$1.76x10^{+04}$	$1.82x10^{-01}$	$2.56x10^{-01}$
1990	$2.62x10^{+03}$	$4.83x10^{-02}$	$4.28x10^{-01}$	$1.53x10^{+04}$	$4.29x10^{-02}$	$5.41x10^{-01}$
1991	$1.06x10^{+04}$	$2.64x10^{-02}$	$8.91x10^{-02}$	$2.64x10^{+04}$	$2.57x10^{-02}$	$1.14x10^{-01}$
1992	$2.00x10^{+03}$	$1.02x10^{-01}$	$7.86x10^{-01}$	$1.30x10^{+04}$	$8.46x10^{-02}$	$8.84x10^{-01}$

Table C-20 Liquid Effluent Adjustment Factors by Radionuclide Group and Year

Year	Group 1 Hydrogen-3	Group 2 Strontium-90	Group 3 Cesium-137	Year	Group 1 Hydrogen-3	Group 2 Strontium-90	Group 3 Cesium-137
1954	1.0000*	1.0582	0.7813	1976	0.6346	2.4755	0.0163
1955	2.2482	0.1773	0.1927	1977	0.8775	1.6271	0.0372
1956	1.6024	0.0345	0.3224	1978	0.9418	0.3006	0.0101
1957	0.9645	0.0079	0.0014	1979	0.6284	0.2326	0.0165
1958	1.0004	0.0527	0.0918	1980	0.8490	3.2573	0.0423
1959	1.2175	0.0824	0.0867	1981	0.6378	0.4416	0.0412
1960	1.1465	0.7467	0.1744	1982	0.9787	0.5655	0.0294
1961	1.0203	0.4284	0.2528	1983	0.7962	1.6370	0.0226
1962	0.8954	0.6499	0.1871	1984	0.9031	4.5042	0.0200
1963	1.0024	0.5079	0.1362	1985	0.6496	1.3263	0.0083
1964	1.0340	0.8037	0.3964	1986	0.4893	2.5464	0.0049
1965	0.8273	0.4443	0.4223	1987	0.7426	6.3833	0.0128
1966	0.7190	0.7290	0.5078	1988	1.2619	5.9846	0.0456
1967	0.8421	0.7171	0.5530	1989	4.4292	15.1968	0.8696
1968	0.7872	0.5945	0.2933	1990	5.8478	1.2652	0.8899
1969	0.9703	0.3495	0.2026	1991	2.5013	1.2751	0.9724
1970	0.6430	0.5361	0.2313	1992	6.4926	1.1252	0.8279
1971	0.9923	1.2122	0.1611				
1972	0.7686	1.5321	0.0687	**Mean**	1.3325	1.7623	0.2339
1973	0.7021	2.3023	0.0593	**Median**	0.9589	0.8037	0.0918
1974	0.9644	4.0233	0.0866	**Max**	6.4926	15.1968	0.9724
1975	0.9589	1.5961	0.0467	**Min**	0.4893	0.0079	0.0014

*Originally this value was calculated as 20.8814.

C.3.5 Analysis of Adjustment Factor Approach

Clearly, the use of these adjustment factors provided only an approximate estimate of the loss of contamination during transport from the point of release to the Savannah River. Because of differences in the chemistry and the half-lives of each radionuclide, the use of a K_d-based adjustment to the releases can result in over-estimation, as well as underestimation, of the releases to the Savannah River. Nonetheless, because the Phase II modeling considers environmental depletion and delay, as well as measurement uncertainty, the ratio of the modeled annual releases from the site to the recorded annual releases from all SRS facilities represents the net effect of the modeled factors. The resultant medians (50th percentile)

from the Phase II model were taken to be a representative means for extrapolating the Phase II model to the radionuclides that were not modeled explicitly in Phase II.

To check the decision to extrapolate releases to the Savannah River using adjustment factors, two large-scale comparisons were made. First, the Phase II modeled release data were compared to SRS point-of-release data for the radionuclides hydrogen-3, strontium-90, and cesium-137. Second, Savannah River concentrations as calculated using the Phase III extrapolated releases were compared against available monitoring information for four radionuclides.

C.3.5.1 Comparison of Phase II Modeled Releases to SRS Point-of-Release Data

For hydrogen-3, strontium-90, and cesium-137, the annual median (50th percentile) of the Phase II Savannah River release model was compared with the annual point-of-release estimates for these radionuclides as compiled from Category 1 and 3 releases documented in Cummins, 1991 (4). Table C-21 summarizes the results of this comparison.

Table C-21 Comparison of Phase II Median Releases to Savannah River with SRS Point-of-Release Data (Categories 1 and 3 of Cummins, 1991 [4])

Radionuclide	Range of Median of Model to Point-of-Release Ratios	Mean, Median of Model to Point-of-Release Ratios
Hydrogen-3	0.379 – 20.881	1.228*
Strontium-90	0.008 – 6.383	1.379
Cesium-137	0.001 – 0.972	0.234

*This ratio does not include 1954 estimates for hydrogen-3.

It was expected that the median values estimated by the Phase II surface water model should be approximately equal to, or smaller than, the total releases reported by the SRS. With a few exceptions, this was the case. An example exception is the 1954 ratio of the estimated median release to the total tritium release. (The ratio is 20.881 as noted in Section C.4.4.) The Phase II report stated that releases were adjusted if it was believed that reported releases were too low (3). This extremely high ratio is probably a reflection of such an adjustment because reporting of releases in the early years of operations was not as accurate as in later years.

Figure C-2 presents the ratios as a function of time. As depicted on Figure C-2, the ratios are dramatically higher during the last years of operations. These later years may reflect that operations in general were reduced, but there were still releases from the site. In addition, Figure C-2 shows that the variations in time are significant. This is due, in part, to the model that increased releases in years having large spring floods to account for the remobilization of radionuclides stored in previous years in the sediments and biota of the swamp. For this reason, annual adjustment factors are preferable to an average adjustment factor covering all years.

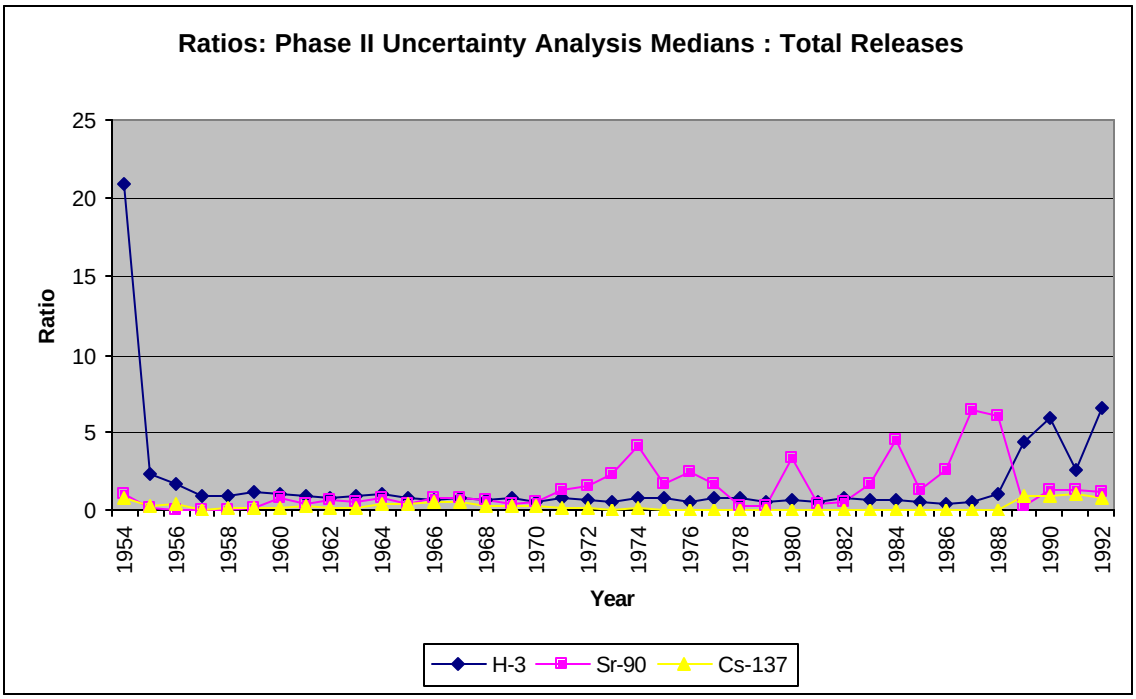

Figure C-2 Annual Ratios of Phase II Median of Savannah River Release Model to SRS Point-of-Release Data

C.3.5.2 Comparison of Modeled to Measured Concentrations

It is instructive to compare the modeled and measured concentrations in the Savannah River. Two sets of modeled radionuclide concentrations were prepared for hydrogen-3, strontium-90, cesium-137, and iodine-131—the four radionuclides for which monitoring data in the Savannah River were generally available. These modeled concentration sets were developed using calculated concentrations based on the following:

- Releases to streams and migration from seepage basins.
- Application of the Phase III model.

These comparisons are not definitive for the following reasons:

- The measured concentrations are highly variable in time and may not be representative of an annual mean value.
- The measured concentrations were frequently made at or near the limits of detection for the instruments used.
- The limits of detection changed in time.
- Only a few radionuclides were measurable for a significant portion of the 39-year study period.
- As described in the Phase II report, the modeled releases are uncertain because the exact behavior of the sediment, swamp, river, streams, and biota has not been precisely modeled and probably cannot be precisely modeled.

Nevertheless, the modeled releases provide information that can be used to judge the efficacy of the Phase III approach for estimating radionuclide release to the Savannah River.

The first concentration set was comprised essentially of Category 1 and Category 2 releases as described in Section C.4.1. These releases were divided by the Savannah River flow (Section C.4.2) as determined at the Burtons Ferry Bridge downstream of the SRS where Highway 301 crosses the Savannah River. This concentration set represents essentially no consideration of holdup in site streams and the Savannah River Swamp before discharge to the Savannah River (no use of adjustment factors). The second concentration set consisted of those concentrations for the four radionuclides that were determined using the Phase III release model described in Section C.3.3.2.

These modeled concentrations were compared against measured concentrations in the Savannah River as obtained at the Highway 301 bridge.[10] These measurements represent annual averages. For the years 1964 through 1992, the concentrations were obtained from SRS environmental reports (25-49). For the years 1960 through 1963, no environmental reports were published. For these years, measured water concentrations were obtained from Health Physics Regional Monitoring Semiannual Reports or Semiannual Progress Reports (50-55).

Figures C-3 and C-4 present the results of this comparison. For tritium (Figure C-3), the two sets of modeled concentrations generally resulted in smaller annual concentrations than those measured at U.S. Highway 301. The difference between the modeled and measured concentrations is especially seen from 1960 through 1975; thereafter, agreement is good. For many of the years between 1960 through 1975, the Phase III set of concentrations is slightly larger than the set comprising release to streams and migration from seepage basins.

For strontium-90 (Figure C-4), except for the years 1961 and 1962, there appears to be reasonable consistency between the modeled and measured sets of concentrations. However, for many years (particularly in the 1960's), the concentrations as used in the Phase III study are larger than those comprising the set representing release to streams and migration from seepage basins.

For cesium-137 (Figure C-5), except for the years 1960 through 1963, and 1978, there appears to be a reasonable level of consistency between the Phase III model and measured concentrations. Note that the modeled concentrations considering release to streams and migration from seepage basins are larger than the Phase III modeled concentrations and measured concentrations for most of the 1960's.

For iodine-131 (Figure C-6), there is little difference between either set of modeled concentrations. Both modeled sets appear to be reasonably consistent with measured concentrations.

As discussed above, these comparisons are not definitive. Nonetheless, these do appear to provide support to the conclusion that the modeling approach used for the Phase III study was a reasonable way to proceed.

[10] SRS environmental reports refer to this monitoring location as the River-10 location. This location is at Savannah River mile 120.

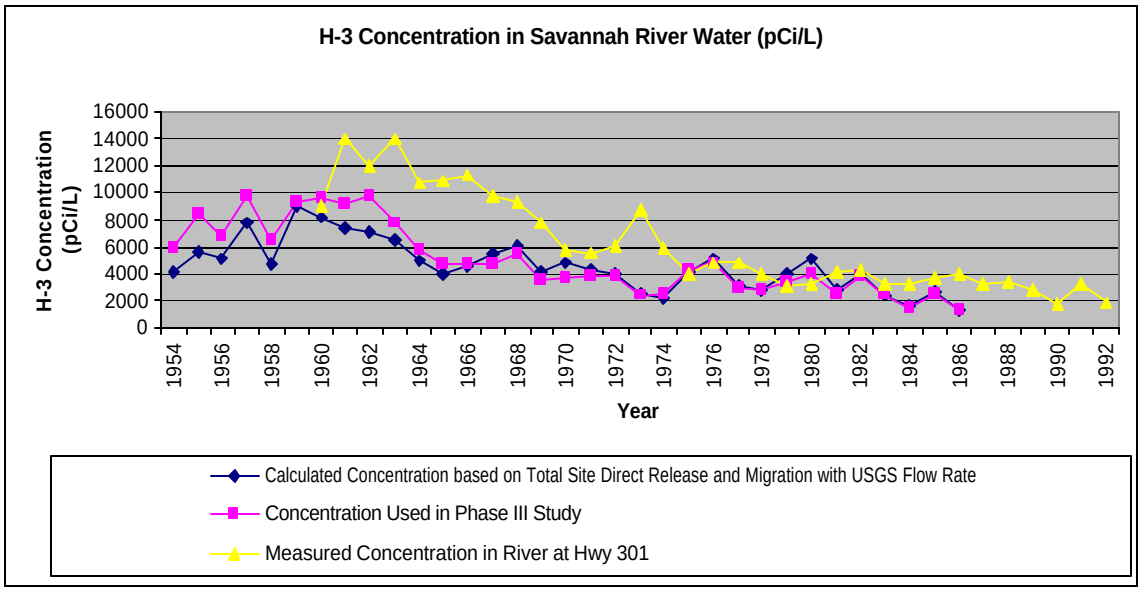

Figure C-3 Tritium Concentrations in Savannah River

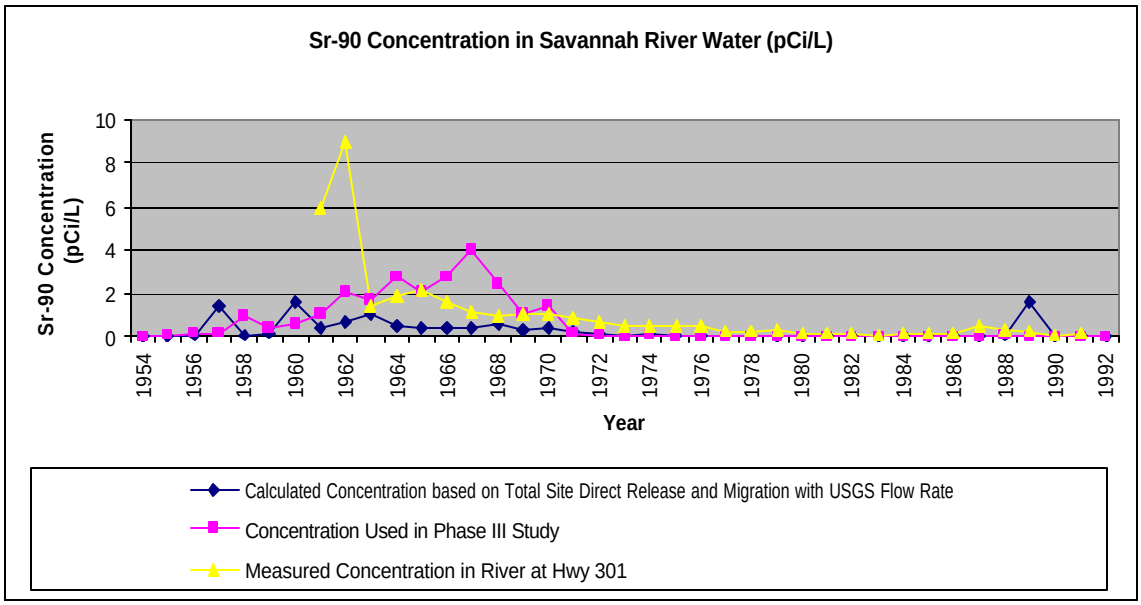

Figure C-4 Strontium-90 Concentrations in Savannah River

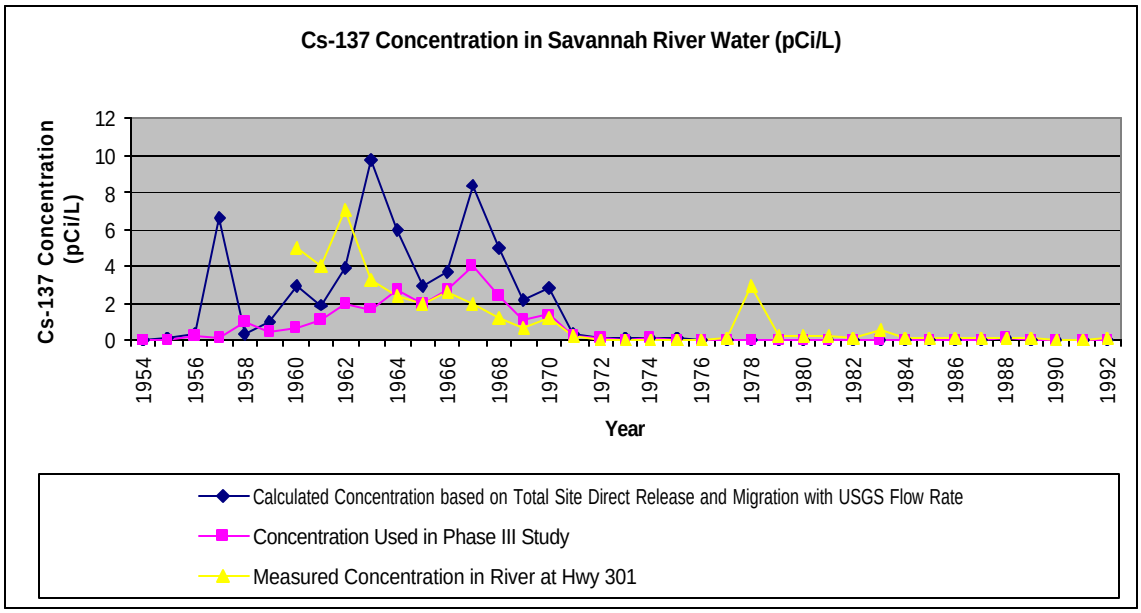

Figure C-5 Cesium-137 Concentrations in Savannah River

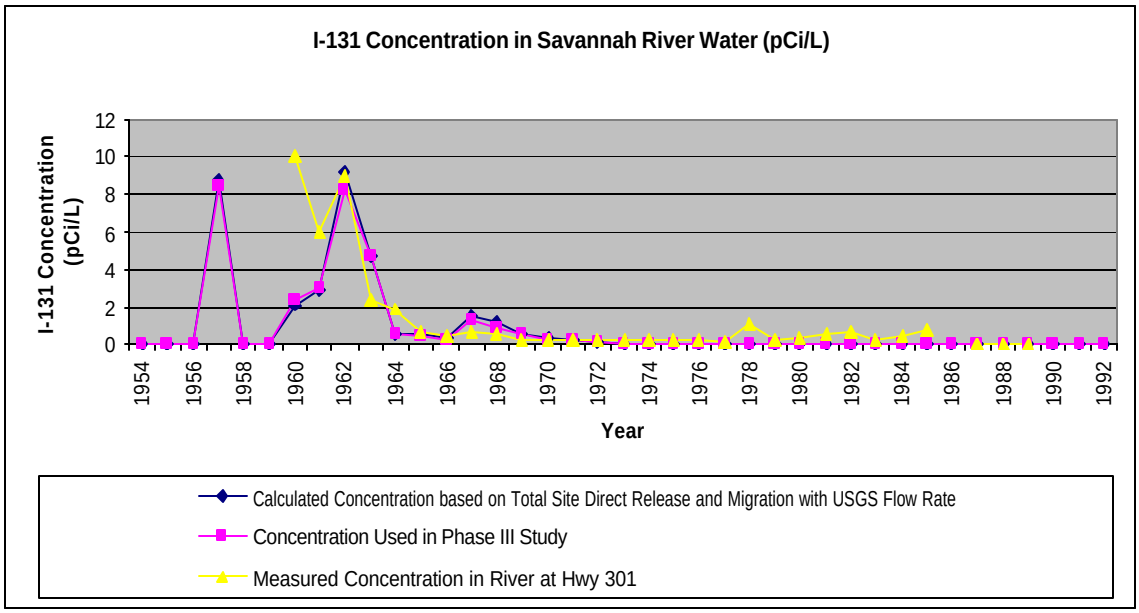

Figure C-6 Iodine-131 Concentrations in Savannah River

C.4 Comparison of Phase II and Phase III Source Terms for Air Release

The purpose of this appendix section is to record the similarities and differences between the Phase II and Phase III estimates of release of radionuclides to the air. Where there are significant differences, the rationale for the differences is stated.

The Phase II report presents data about release to air at several levels of detail. For example, the total releases for a 36-year period of SRS operation are considered for the screening analysis described in Chapter 3, while annual releases to air for particular isotopes and facilities are presented in Chapter 4 (3). In addition, supplementary data are provided in Excel spreadsheets that are linked to the electronic version of the report. Some of these spreadsheets provide releases by facility on a weekly basis.

For Phase III of the SRS Dose Reconstruction Project, annual releases to air are compiled for 16 radionuclides for a 39-year period of SRS operation (see Appendix B). The radionuclides are assumed to be released from four virtual sources as described in Appendix A. For tritium and iodine isotopes, releases are complied according to the assumed chemical form of these isotopes when released.

Data used as input to the Phase III dose and cancer risk assessment were checked in accordance with a Quality Assurance Program. However, to assure an appropriate degree of consistency between the Phase II report and Phase III assumptions, the total releases for all significant radionuclides were compared. This comparison was made more difficult by the large amount of data in the Phase II report and the different ways in which it was employed. For example, the total releases used in Chapter 3 of the Phase II report to screen radionuclides were largely raw releases based on primary sources (e.g., Cummins, 1991[4]). (Section C.1 of this appendix summarizes the Phase II screening assessment.) In Chapter 4, releases were modified for some radionuclides to account for errors in instrumentation and problems with undersampling releases (3). As a result, the total and annual release rates recommended in Phase II are substantially larger than those given in the primary references for some radionuclides (e.g., iodine-131, total plutonium, and uranium) (3).

In the following discussion, the total releases used for the Phase II screening assessment are compared with the total releases used for Phase III of the SRS dose reconstruction project. The Phase II information was obtained from the Rad-screening.xls Excel worksheet which is linked to the electronic version of the Phase II report. After comparing the releases, the reasons for significant differences are discussed.

Table C-22 presents the total releases to air over 39 years (1954-1992) from the four virtual sources considered in Phase III. These total releases have been summed from annual releases from each virtual source using the four Excel spreadsheets that were used as input to the dose and cancer risk assessments performed for Phase III. These spreadsheets are AB5492A.xls, AG5492B.xls, AO5492.xls, and AQre92A.xls.

Table C-23 presents the total release into the air that was used in the Phase II screening assessment as well as the total release used for the Phase III source term. The Phase II totals are over 36 years while the Phase III totals are over 39 years. Also, many of the radionuclides are aggregated groups of radionuclides (e.g., strontium-89,90). The Phase II release estimates were provided in terms of these radionuclide groups. The totals provided in the Phase III column in Table C-23 are the sums of the activities for the individual isotopes listed in Table C-22 (e.g., the strontium-89,90 value [$4.7 \times 10^{+1}$]in the Phase III column in Table C-23 is the sum of the strontium-89 [1.15] and strontium-90 [$4.58 \times 10^{+1}$]) values in Table C-22.

Table C-22 Total 39-Year Release to Air (Ci) for Phase III Assessment by Virtual Source

Radionuclide*	C-, K-, L-Reactors, D-Area, CMX-TNX†	F- and H-Areas†	A- & M-Areas & SRL	P- & R-Reactors†	Total from All Virtual Sources
Americium-241	0	$5.88x10^{-3}$	$2.61x10^{-7}$	0	$5.88x10^{-3}$
Argon-41	$3.91x10^{+6}$	0	0	$2.45x10^{+6}$	$6.36x10^{+6}$
Carbon-14	$1.12x10^{+3}$	$1.24x10^{+3}$	0	$6.12x10^{+2}$	$2.97x10^{+3}$
Cesium-137	$5.15x10^{-5}$	3.51	$2.65x10^{-3}$	$7.03x10^{-6}$	3.51
Hydrogen-3	$5.37x10^{+6}$	$8.47x10^{+6}$	$1.84x10^{+4}$	$1.91x10^{+6}$	$1.58x10^{+7}$
Hydrogen-3EL	0	$9.35x10^{+6}$	0	0	$9.35x10^{+6}$
Iodine-129E	0	1.13	0	0	1.13
Iodine-129O	0	4.54	0	0	4.54
Iodine-131E	$1.78x10^{+2}$	$9.30x10^{+3}$	6.36	$2.02x10^{+2}$	$9.69x10^{+3}$
Iodine-131O	$7.61x10^{+1}$	$3.92x10^{+4}$	0	$8.66x10^{+1}$	$3.94x10^{+4}$
Plutonium-238	0	2.08	0	0	2.08
Plutonium-239	$1.57x10^{-4}$	$1.32x10^{+1}$	$3.40x10^{-3}$	$4.63x10^{-5}$	$1.32x10^{+1}$
Ruthenium-106	$2.03x10^{-5}$	$1.58x10^{+2}$	0	$1.02x10^{-5}$	$1.58x10^{+2}$
Strontium-89	0	1.15	0	0	1.15
Strontium-90	$9.33x10^{-2}$	$4.4x10^{+1}$	1.25	$9.28x10^{-2}$	$4.58x10^{+1}$
Uranium-234	0	1.13	$1.59x10^{-4}$	0	1.13
Uranium-235	0	$5.09x10^{-2}$	$7.23x10^{-6}$	0	$5.10x10^{-2}$
Uranium-236	0	$7.93x10^{-2}$	0	0	$7.93x10^{-2}$
Uranium-238	0	2.25	1.55x10-4	0	2.25

*Hydrogen-3 means tritium released in an oxide form as in evaporated water, while hydrogen-3EL means tritium released in an elemental form. Similarly iodine-129E and iodine-31E mean iodine isotopes released in an elemental form, while iodine-129O and iodine-131O mean iodine released in an organic form.
†Includes evaporated tritium from reactor and separations areas seepage basins—see Appendix A.

In addition, the Phase II totals listed in Table C-23 are those obtained from the Excel spreadsheet supporting the Phase II screening assessment (Rad-screening.xls). The values in this spreadsheet do not in all cases match those provided in Table 3A-2a of the Phase II report (3).

Table C-23 lists the numerical difference between the Phase III values and Phase II values as well as the percent difference (determined as: (Phase III – Phase II) x 100 / Phase III). An X marking the Note column means that further discussion is provided below.

Table C-23 Comparison of 39-Year Phase III Total Releases (Ci) to 36-Year Phase II Releases Used for Phase II Screening Assessment (Ci)

Radionuclide	Phase III Total from All Virtual Sources	Phase II Total Used for Screening Assessment	Difference (Phase III – Phase II)	Percent Difference (Phase III –Phase II) x 100/Phase III	Note
Americium-241	$5.88x10^{-3}$	0	+ $5.88x10^{-3}$	+ 100	X
Argon-41	$6.36x10^{+6}$	$6.40x10^{+6}$	- $4.00x10^{+4}$	- 0.638	
Carbon-14	$2.97x10^{+3}$	$3.00x10^{+3}$	- $3.00x10^{+1}$	- 0.901	
Cesium-137	3.51	3.50	+ $1.00x10^{-2}$	+ 0.316	
Hydrogen-3	$2.51x10^{+7}$	$2.45x10^{+7}$	+ $6.00x10^{+5}$	+ 2.44	
Iodine-129	5.67	5.70	- $3.00x10^{-2}$	- 0.448	X
Iodine-131	$4.91x10^{+4}$	$2.50x10^{+3}$	+ $4.66x10^{+4}$	+ 94.9	X
Plutonium-238	2.08	1.00	+ 1.08	+ 51.8	X
Plutonium-239	$1.32x10^{+1}$	3.5	+ 9.70	73.6	X
Ruthenium-103,106*	1.58x10+2	1.70	+ $1.56x10^{+2}$	98.9	X
Strontium-89,90*	4.70x10+1	1.54	+ $4.55x10^{+1}$	96.7	X
Uranium*	3.51	1.00	+ 2.51	71.5	X

*In the Phase II study, ruthenium-103,106 was screened assuming that all activity was ruthenium-106. Strontium-89,90 activity was screened assuming that all activity was strontium-90, and uranium activity was screened assuming that all activity was uranium-235. For Phase III, activity reported as uranium was partitioned among the uranium isotopes (uranium-234, uranium-235, uranium-236, and uranium-238) as discussed in Section C.2 of this appendix.

Americium-241

The Excel spreadsheet summarizing the Phase II screening assessment (rad_screening.xls) is confusing regarding the analysis of americium-241. This spreadsheet contains several separate tables. In the Level 1 screening table, there is no value placed in the column with the heading "Atmospheric Release Rate from SRS," "Ci/36 y." Table C-23 reflects this entry of zero. However, the next column in the Level 1 screening table with the heading "Ci/y" contains the value $5.60x10^{-03}$, which is converted in the next column to $2.07x10^{+08}$ Bq/y. This value is then combined with a hypothetical flow rate from a stack to calculate a concentration and then a screening value of 5.48 Sv. In the Level 2 screening table, the atmospheric release rate is given as $2.1x10^{+09}$ Bq/y with a corresponding screening value of 5.5 Sv. Thus, even though the Level 2 screening release rate is a factor of 10 larger, the screening value is the same. Because the air screening factor provided in NCRP Report No. 123 (p. 97 of NCRP 1996 [2]) is 1.0 for americium-241 for all air release pathways, the values in the Level 1 screening table are regarded as being consistent although the values in the Level 2 screening table have an anomalous release rate.

It appears to be more than a coincidence that the value ($5.60x10^{-03}$ Ci) listed for Ci/y in the Level 1 screening table is only slightly smaller than the total Phase III value over 39 years ($5.88x10^{-03}$ Ci). (Because the Level 1 screening was for only 36 years, we would expect that value to be slightly smaller.) In any event, the total americium-241 activity assumed in the Phase III source term is consistent with data from various site reports, including Cummins 1991 (4) and Carlton 1997 (9).

It is also interesting to note that if one divides the total Phase III americium-241 release ($5.88x10^{-03}$ Ci) by 39 years, one arrives at an average release rate of approximately $1.51x10^{-04}$ Ci/y. This release rate is smaller by a factor of about 37 than the value stated in the Phase II Level 1 screening table ($5.60x10^{-03}$). Assuming this smaller release rate, the Level 1 screening value would also have been reduced by a factor of 37 (i.e., 0.15 Sv). This screening value would not have exceeded 0.1 percent of the total screening value as summed over all radionuclides. This value of 0.1 percent was the criterion used in Phase II to determine key radionuclides for further analysis.

Iodine-131 and Iodine-129

The Phase III value is about 20 times larger for iodine-131 than the Phase II screening assessment value. The reason for this is that after performing the screening assessment, the Phase II study further investigated releases of iodine-131 from SRS facilities. In Chapter 4-2 of the Phase II report, it is argued that iodine releases were underestimated due to limitations of the sampling and detection equipment (3). A model to account for these uncertainties was constructed and the results were quantified in a supplemental Excel spreadsheet linked to the Phase II report (Revised_I-131_Releases(F,H).xls). Median values (50th percentile) from these increased estimates of iodine-131 releases sum to over 48,000 Ci from the F- and H-Separations areas. These increased releases were then added to the modified iodine-131 releases from the reactors (Phase II supplemental spreadsheet Est_I-131_Releases_(Reactors).xls). For Phase III, annual iodine-131 release rates were used that were consistent with the modified annual release rates developed in Chapter 4-2 of Phase II rather than the annual release rates used in the Phase II screening assessment. This accounts for the almost 20-fold increase in iodine-131 releases used for the Phase III calculations.

It is also interesting to note the following statement from p. 4.2-18 of the Phase II report:

> The revised estimates of iodine-131 releases have been criticized by SRS staff (56) because they found good agreement between environmental concentrations predicted using the originally reported release estimates for 1956 and contemporary environmental measurements. They also cited similar comparisons made in an earlier plant report (57). As was discussed above, in the 1950s, both the effluent and environmental concentrations of iodine-137 were estimated using sampling media that were not highly reliable. Uncertainties in meteorological modeling, even for flat terrain, are on the order of a factor of 3-4 without consideration of plume depletion. In view of the quality of both sets of measurements and the uncertainties involved, the comparisons between predicted and measured concentrations in 1956 are not conclusive. When Reinig made comparisons in 1959, he had no knowledge of the unreliability of the sampling systems.

Furthermore, it is interesting to note that the Phase II report made no similar adjustment to the iodine-129 releases, although it is expected that some of the same instrumentation and sampling issues would have applied to that isotope. Given the limited description of the model used in the Phase II report, it is not clear whether the large difference in decay constant between iodine-131 (half-life is 8.04 d) and iodine-129 (half-life is $1.57x10^{+7}$ y) accounts for the application of the correction only to iodine-131. For Phase III, the total iodine-129 releases are consistent with those recorded by the site and listed in the Phase II screening assessment.

Plutonium-238, Plutonium-239, Uranilum-235,238

Phase III values for plutonium and uranium isotopes are larger than comparable values from the Phase II screening assessment. After the Phase II screening assessment was performed, plutonium and uranium isotopes were adjusted from the screening values used in the Phase II report based on considerations articulated in Chapter 4-4 of Phase II. (The Phase II report accounted for uncertainties such as

transmission line losses, filter efficiencies, and acute accidental releases.) The adjusted Phase II estimates of release of plutonium and uranium from the F- and H-Separations areas are provided in a Phase II supplemental Excel spreadsheet (Estimated_Source_Term.xls). These estimates are listed as 5th, 50th, and 95th percentile values. The 50th percentile of the sum of total plutonium (plutonium-238 and plutonium-239) released from F- and H-Areas over 36 years was 15.2 Ci. The 50th percentile of the sum of total uranium released from F- and H-Areas over 36 years was 3.48 Ci.

The median (50th percentile) values from a Phase II supplemental Excel spreadsheet (Estimated_Source_Term.xls) were used as the bases for Phase III assessments of plutonium and uranium releases from the F- and H-Separation Areas. To this plutonium and uranium activity (which covered 1954 through 1989) was added small quantities of plutonium and uranium reported in SRS environmental reports for the years 1990 through 1992 (18-20). These releases were then partitioned into appropriate plutonium and uranium isotopes according to the isotopic partitioning considerations delineated in Section C.2 of this appendix. In addition, about 0.08 Ci of unidentified alpha activity was assumed to be plutonium-239.

<u>Ruthenium-103,106</u>

The Excel spreadsheet linked to the electronic version of Phase II (Rad-Screening.xls) shows that the total release over 36 years as apparently used for ruthenium-103,106 was different for Steps One and Two of the Phase II screening assessment. For Step One of the assessment (Air Step-1 on the spreadsheet), releases over 36 years were given as 1.7 Ci (about $6.3 \times 10^{+10}$ Bq). But for Step Two of the screening assessment (Air Step-2 on the spreadsheet), the release rate for ruthenium-103,106 is given as $1.6 \times 10^{+11}$ Bq/y. If this value is multiplied by 36 (the number of years used by Phase II for screening) and divided by $3.7 \times 10^{+10}$ to convert to Ci, the value is 155.7 Ci. This value is much larger than the 1.7 Ci listed in the Air Step-1 table on the worksheet. Furthermore, another Phase II Excel spreadsheet linked to Chapter 4-2 of Phase II (Ann_B-G_Part_Releases.xls) lists ruthenium-103,106 releases for F- and H-Canyons. The sum of these F- and H-Canyon releases is 158 Ci, which is consistent with the Air Step-2 table on the Rad-Screening.xls worksheet. Finally, Figure 4.2-15 of the Phase II report shows the time history of ruthenium releases. The values shown in that graph are clearly inconsistent with 1.7 Ci released. Therefore, if the entry from the Air Step-2 table equal to 158 Ci is used to represent the Phase II value, it will match up well with the Phase III release values.

<u>Strontium-89,90</u>

The value compiled for strontium-89 plus strontium-90 for use in the Phase III dose reconstruction is similar to the 1.5 Ci used in the Phase II screening evaluation. However, as discussed in Section C.2 of this appendix, unidentified beta-gamma activity for Phase III was assumed to be strontium-90. This activity was added to reported releases of strontium-90 and to strontium-90 activity determined from partitioning activity reported as strontium-89,90 in SRS reports. The additional strontium-90 activity resulting from adding the unidentified beta-gamma activity was about 45 Ci over the period of consideration.

C.5 Comparison of Phase II and Phase III Source Terms for Water Releases

The purpose of this appendix section is to record the similarities and differences between the Phase II and Phase III estimates of release of radionuclides to surface water. Where there are significant differences, the rationale for the differences is stated.

The Phase II report presents data on releases at several levels of detail. For example, total releases for a 36-year period of operation were considered for the screening analysis described in Chapter 3; annual

values for a particular isotope and facility were presented in Chapter 5 (3). In addition, some of the spreadsheets in the supplementary data provided releases by facility on a weekly or monthly basis (3). Because of the approach adopted for the Phase III dose reconstruction, the liquid releases to two receiving bodies of water are compiled by radionuclide. The two bodies of water represent locations for exposure to water released radionuclides for receptors in various receptor groups (scenarios).

The data used as input to Phase III of the SRS Dose Reconstruction Project was checked as part of a Quality Assurance Program. However, to assure appropriate agreement between the Phase II and Phase III reports, the total releases for all significant radionuclides were compared.

C.5.1 Background

A relatively simple model was used in Phase II to estimate the releases to the Savannah River for hydrogen-3, strontium-90, and cesium-137. Because it was necessary to consider more radionuclides than the three that had been modeled in Phase II, a means to extend those considerations to additional radionuclides was sought. Direct modeling similar to that performed in Phase II was not possible because most of the concentrations of most radionuclides were below detectable limits at the Road A intersections. For this reason, the basis for the Phase II modeling was unavailable. Therefore, for Phase III, the Phase II modeling results for the three radionuclides were extrapolated to the additional radionuclides. Adjustment factors were developed for each year for three classes of radionuclides encompassing different ranges of K_d. These adjustment factors are the ratio of: (1) the median of the Phase II modeling results for each year, respectively, for hydrogen-3, strontium-90, and cesium-137 to (2) the annual activity released from SRS facilities into surface water, respectively, for hydrogen-3, strontium-90, and cesium-137 as determined at the point of release.

Liquid releases from the site were placed into the following three categories (4):

- Category 1 - Direct releases to onsite streams.
- Category 2 - Migration from seepage basins into onsite streams.
- Category 3 - Direct releases to seepage basins.

For Phase III, the annual sum of the Categories 1 and 3 releases were chosen as being representative of SRS releases to site streams. This had two implications: (1) the adjustment factors based on modeled releases of hydrogen-3, strontium-90, and cesium-137 used the sum of Categories 1 and 3 as the denominator of the adjustment factor, and (2) these adjustment factors were applied to the sum of Categories 1 and 3 for radionuclides having similar K_ds. Although these annual liquid releases for Categories 1 and 3 were derived from fundamental data (e.g., Cummins, 1991 [4]), they are consistent with the Phase II report.

C.5.2 Comparison of Phase III Releases with Phase II Screening Assumptions

Because of the approach adopted for Phase III of the SRS Dose Reconstruction Project, the releases to streams, seepage basins, and containment basins were compiled by radionuclide as point-of-release estimates. Two desirable checks place the Phase III analysis in context: (1) comparison of the point-of-release estimates used in Phase III to the screening values used in Phase II, and (2) comparison of the extrapolated releases used in Phase III to the screening assessment values used in Phase II. Table C-24 makes these comparisons.

Table C-24 Comparison of Phase III Releases with Phase II Screening Assumptions

Releases from Phase II Water-Step 1 Screening		Sum of 36-year Releases from Cummins Data - Basis for Phase III Point-of-Release Estimates		Sum of 36-year Phase III Releases to Savannah River		
Radionuclide	**Surface Water Release from SRS (Ci/36 yr)**	**Cat. 1+Cat. 3 Unless Otherwise Noted (Ci/36 yr)**	**Ratio, Screening to Phase III Basis**	**Eval.**	**Phase III Release to River (Ci/36 yr)**	**Ratio, Phase III River Release to Screening**
Cerium-141,144	$7.00x10^{+02}$	$7.08x10^{+02}$	0.99		$4.58x10^{+02}$	$6.54x10^{-01}$
Cesium-134	$1.35x10^{+01}$	$1.35x10^{+01}$	1.00		2.87	$2.13x10^{-01}$
Cesium-137	$1.95x10^{+03}$	$1.95x10^{+03}$	1.00		$2.57x10^{+02}$	$1.32x10^{-01}$
Cobalt-60	$8.40x10^{+01}$	$8.42x10^{+01}$	1.00		$5.40x10^{+01}$	$6.43x10^{-01}$
Hydrogen-3	$1.50x10^{+06}$	$1.53x10^{+06}$	0.98	*	$1.73x10^{+06}$	1.16
Iodine-131	$3.03x10^{+02}$	$3.02x10^{+02}$	1.00	*	$2.88x10^{+02}$	$9.50x10^{-01}$
Iodine-129	1.20	3.00	see note	*	2.71	2.26
Phosphorus-32	$1.96x10^{+02}$	$1.96x10^{+02}$	1.00		$1.29x10^{+02}$	$6.60x10^{-01}$
Plutonium-239,240	8.00	7.9	1.01		2.95	$3.69x10^{-01}$
Plutonium-238	4.00	4.0	0.98		$7.08x10^{-01}$	$1.77x10^{-01}$
Ruthenium-103,106	$1.80x10^{+03}$	$1.80x10^{+03}$	1.00		$1.30x10^{+03}$	$7.25x10^{-01}$
Strontium-89,90	$6.20x10^{+02}$	$7.11x10^{+02}$	0.87	*	$4.60x10^{+02}$	$7.42x10^{-01}$
Sulfur-35	$1.75x10^{+03}$	$1.75x10^{+03}$	1.00		$1.53x10^{+03}$	$8.77x10^{-01}$
Technicium-99	$5.30x10^{+01}$	$5.30x10^{+01}$	1.00		$5.47x10^{+01}$	1.03
Uranium-235,238	$4.20x10^{+01}$	$4.15x10^{+01}$	1.01		$1.19x10^{+01}$	$2.83x10^{-01}$
Zinc-65	$1.50x10^{+02}$	$1.50x10^{+02}$	1.00		$9.64x10^{+01}$	$6.43x10^{-01}$
Zirconium,Niobium-95	$1.45x10^{+02}$	$9.64x10^{+02}$	0.15	*	$8.23x10^{+02}$	5.67
						Average Ratio

Releases from Phase II Water-Step 1 Screening		Sum of 36-year Releases from Cummins Data - Basis for Phase III Point-of-Release Estimates		Sum of 36-year Phase III Releases to Savannah River		
Radionuclide	**Surface Water Release from SRS (Ci/36 yr)**	**Cat. 1+Cat. 3 Unless Otherwise Noted (Ci/36 yr)**	**Ratio, Screening to Phase III Basis**	**Eval.**	**Phase III Release to River (Ci/36 yr)**	**Ratio, Phase III River Release to Screening**
Tritium Group: I-129, I-131, Tc-99, S-35						1.28E+00
Strontium Group: Ru-103,106, Co-60, Sr-89,90, Nb/Zr-95, P-32, Zn-65, Ce-141, 144, Uranium						6.21E-01
Cesium Group: Cs-134, 137, Plutonium						2.23E-01

C.5.2.1 Comparison of the Phase III Point-of-Release Estimates to Phase II Screening Values

The Table C-24 column headed "Eval." compares the unadjusted Phase III values to the Phase II screening values. A star notation indicates that an explanation is warranted.

Hydrogen-3

For tritium, the Phase II study states that both stream and seepage basins were included as the source of releases to the surface water pathway in the screening assessment (3). It appears from the data presented in the Phase II report that seepage basin data for hydrogen-3 (and iodine-131) were not included in the screening assessment. This is indicated by the good agreement between the stream-only source terms. (The Phase III point-of-release estimates releases to streams, seepage basins, and containment basins.)

Iodine-131

The entry from the Phase II screening assessment is Category 1 release only (i.e., release to streams). This appears to be appropriate because of the eight-day half-life of iodine-131. Any substantial holdup duration would have caused the seepage basin inventory to decay away. The Phase III point-of-release data file only includes releases to streams and not to seepage basins for this isotope.

Iodine-129

In the Phase II report, the 1.2 Ci entry for iodine-129 in the table for the screening calculation was obtained by assuming that 3 Ci entered the seepage basin and 40 percent of that inventory was released from the basin to the stream (3 Ci * 0.4 = 1.2 Ci) (3). Because Phase III modifies all of the other radionuclide inventories using an adjustment factor, the 3-Ci assumption was used.

Strontium-89,90

Although the Phase II screening value and the Phase III base value are different by about 15 percent, this appears to be due to an addition error in the Phase II report. The screening spreadsheet value should have been about 720 Ci based on the note in the spreadsheet indicating how the entry was obtained. However, this difference is not important. When strontium-89,90 releases are applied in the dose reconstruction, unidentified beta-gamma releases were added to the strontium-90 inventory in the amount of 218.88 Ci (before multiplication by the adjustment factor for strontium-90), which dwarfs any differences between the Phase III basis and screening values.

Zirconium,Niobium-95

The Phase II report stated that all estimates of reported releases of zirconium-95, niobium-95, and zirconium,niobium-95 were combined to ensure a conservative approach. However, the value used in the Phase II screening seems to match only the total of zirconium-95 and niobium-95.

C.5.2.2 Comparison of Phase III Savannah River Releases to Screening Values

The adjustment factors, applied on the basis of K_d, are reflected in the ratios of the Savannah River releases (Phase III) to the screening assessment releases (Phase II). Table C-24 presents the average ratios for the three groups of radionuclides (hydrogen-3, strontium-90, and cesium-137 groups).

The radionuclides scaled to hydrogen-3 have, on average, increased values compared with the screening assessment inventories (+28 percent). The strontium-scaled nuclides have, on average, 62.1 percent of the screening value. The cesium-scaled nuclides have, on average, about 20 percent of the screening values. This is due to hold-up in the environment based on use of different K_d values. These values compare, in general, with the adjustment factor values for each scaling group averaged over all the years, which are, respectively, 0.749, 0.711, and 0.232. Because the ratio for each nuclide depends on applying the annual adjustment factor for the group to the annual releases for the radionuclide, the sum of the products depends upon the release history of the radionuclide. This accounts for the variability of the ratios within each group.

C.6 References

1. National Council on Radiation Protection and Measurements (NCRP). Screening techniques for determining compliance with environmental standards, releases of radionuclides to the atmosphere. NCRP Commentary No. 3. Bethesda, Maryland. 1989.

2. National Council on Radiation Protection and Measurements (NCRP). Screening models for releases of radionuclides to air, surface water, and ground water. NCRP Report No. 123. Bethesda, Maryland. 1996.

3. Risk Assessment Corporation (RAC). Savannah River Site environmental dose reconstruction project—phase II: source term calculation and ingestion pathway dose retrieval evaluation of materials released from the Savannah River Site. RAC Report No. 1-CDC-SRS-1999-Final. April 30, 2001.

4. Cummins CL, Hetrick CS, and Martin DK. Radioactive releases from the Savannah River Plant 1954-1989, environmental protection department summary. WSRC-RP-91-684. 1991.

5. Carlton WH, Evans AG, Geary LA, Murphy CE, Strom RN. Assessment of strontium in the Savannah River Site environment. WSRC-RP-92-984. May 6, 1994.

6. U.S. Environmental Protection Agency. Federal Guidance Report 13 cancer risk coefficients for environmental exposure to radionuclides: CD supplement. EPA 402-C-99-001, Rev. 1. Oak Ridge National Laboratory and U.S. EPA. April 2002.

7. Korea Atomic Energy Research Institute. Table of nuclides [online]. 2000-2002. [cited 2003 Jan 10]. Available from URL: *http://www2.bnl.gov/ton/.*

8. Hankins O. Selected readings for NE 301. Fall 1988.

9. Carlton WH and Denham M. Assessment of selected fission products in the Savannah River Site environment. WSRC-TR-96-0220. April 1997.

10. Hefner JD. [personal communication] 2003 Jan 21.

11. Evans AG, Bauer LR, Haselow JS, Hayes DW, Martin HL, McDowell WL, et al. Uranium in the Savannah River Site environment. WSRC-RP-92-315, Rev. 0. December 9, 1992.

12. Carlton WH, Evans AG, Geary LA, Murphy CE, Pinder JE, Strom RN. Assessment of plutonium in the Savannah River Site environment. WSRC-RP-92-879, Rev. 1. 1994.

13. Mark JC. Explosive properties of reactor-grade plutonium. Science& Global Security, Vol. 4, pp. 111-128. Gordon and Breach Science Publishers. 1993.

14. Hefner JD. [personal communication] 2003 Feb 12

15. Carlton WH. Assessment of neptunium, americium, and curium in the Savannah River Site environment. WSRC-TR-97-00266. December 1997.

16. Till JE and Meyer HR (eds.). Radiological assessment – a textbook on environmental dose analysis. NUREG/CR-3332. ORNL-5958. U.S. Nuclear Regulatory Commission. Washington, D.C. September 1983.

17. Ruby CH, Reinhart PJ, Reel CL. Sedimentation and erosion trends of the Savannah River plant reactor discharge creeks final report. RPI/R/81-22. Research Planning Institute, Inc. Columbia, South Carolina. 1981.

18. Cummins CL, Martin DK, Todd JL. Savannah River Site environmental report (U). WSRC-IM-91-28. Westinghouse Savannah River Company, Environmental Monitoring Section. Savannah River Site, Aiken, South Carolina. 1991.

19. Arnett MW, Karapatakis LK, Mamatey AR, Todd JL. Savannah River Site environmental report for 1991 (U). WSRC-TR-92-186. Westinghouse Savannah River Company, Environmental Monitoring Section. Savannah River Site, Aiken, South Carolina. 1992.

20. Arnett MW, Karapatakis LK, Mamatey AR. Savannah River Site environmental report for 1992. WSRC-TR-93-075. Westinghouse Savannah River Company, Environmental Monitoring Section. Savannah River Site, Aiken, South Carolina. 1993.

21. United States Geologic Survey. USGS flow rate at highway 301. (date??)

22. Hayes DW and Marter WL. Historical flow rates for dose calculations. SRL-ETS-91057. Westinghouse Savannah River Company, Savannah River Laboratory. June 10, 1991.

23. Kaplan DI. K_d values (mL/g) for SRS soils. [personal communication] 2003 Mar 25.

24. Kaplan DI, Serkiz SM. In-situ K_d values and geochemical behavior for inorganic and organic constituents of concern at TNX Outfall Delta. WSRC-TR-99-00488. Westinghouse Savannah River Company. 2000.

25. Ashley C. Environmental monitoring at the Savannah River Plant, annual report—1964. DPST-65-302. Savannah River Laboratory. E.I. Dupont de Nemours & Co. Aiken, South Carolina. June 15, 1965.

26. Ashley C. Environmental monitoring at the Savannah River Plant, annual report—1965. DPST-66-302. Savannah River Laboratory. E.I. Dupont de Nemours & Co. Aiken, South Carolina. August 1966.

27. Ashley C. Environmental monitoring at the Savannah River Plant, annual report—1966. DPST-67-302. Savannah River Laboratory. E.I. Dupont de Nemours & Co. Aiken, South Carolina. 1967.

28. Ashley C. Environmental monitoring at the Savannah River Plant, annual report—1967. DPST-68-302. Savannah River Laboratory. E.I. Dupont de Nemours & Co. Aiken, South Carolina. 1968.

29. Ashley C. Environmental monitoring at the Savannah River Plant, annual report—1968. DPST-69-302. Savannah River Laboratory. E.I. Dupont de Nemours & Co. Aiken, South Carolina. June 1969.

30. Ashley C. Environmental monitoring at the Savannah River Plant, annual report—1969. DPST-70-302. Savannah River Laboratory. E.I. Dupont de Nemours & Co. Aiken, South Carolina. May 1970.

31. Ashley C. Environmental monitoring at the Savannah River Plant, annual report—1970. DPST-71-302. Savannah River Laboratory. E.I. Dupont de Nemours & Co. Aiken, South Carolina. 1971.

32. Ashley C. Environmental monitoring at the Savannah River Plant, annual report—1971. DPST 72-302. Savannah River Plant. E.I. Dupont de Nemours & Co. Aiken, South Carolina. September 1972.

33. Ashley C, Zeigler CC. Environmental monitoring at the Savannah River Plant, annual report—1972. DPSPU 73-302. Savannah River Plant. E.I. Dupont de Nemours & Co. Aiken, South Carolina. 1973.

34. Ashley C, Zeigler, CC. Environmental monitoring at the Savannah River Plant, annual report—1973. DPSPU 74-302. Savannah River Plant. E.I. Dupont de Nemours & Co. Aiken, South Carolina. 1974.

35. Ashley C, Zeigler CC. Environmental monitoring at the Savannah River Plant, annual report—1974. DPSPU 75-302. Savannah River Plant. E.I. Dupont de Nemours & Co. Aiken, South Carolina. August 1975.

36. Ashley C, Zeigler CC. Environmental monitoring at the Savannah River Plant, annual report—1975. DPSPU 76-302. Savannah River Plant. E.I. Dupont de Nemours & Co. Aiken, South Carolina. 1976.

37. Ashley C, Zeigler CC. Environmental monitoring at the Savannah River Plant, annual report—1976. DPSPU 77-302. Savannah River Plant. E.I. Dupont de Nemours & Co. Aiken, South Carolina. March 1978.

38. Ashley C, Zeigler CC. Environmental monitoring at the Savannah River Plant, annual report—1977. DPSPU 78-302. Savannah River Plant. E.I. Dupont de Nemours & Co. Aiken, South Carolina. December 1978.

39. Ashley C, Zeigler CC. Environmental monitoring at the Savannah River Plant, annual report—1978. DPSPU 79-302. Savannah River Plant. E.I. Dupont de Nemours & Co. Aiken, South Carolina. January 1981.

40. Ashley C, Zeigler CC, Culp PA, Smith DL. Environmental monitoring at the Savannah River Plant, annual report—1979. DPSPU 80-302. Savannah River Plant. E.I. Dupont de Nemours & Co. Aiken, South Carolina. November 1982.

41. Zeigler CC. Environmental monitoring at the Savannah River Plant, annual report—1980. DPSPU 81-302. Savannah River Plant. E.I. Dupont de Nemours & Co. Aiken, South Carolina. 1983.

42. Ashley C, Zeigler CC. Environmental monitoring at the Savannah River Plant, annual report—1981. DPSPU 82-302. Savannah River Plant. E.I. Dupont de Nemours & Co. Aiken, South Carolina. April 1984.

43. Ashley C, Padezanin PC, Zeigler CC. Environmental monitoring at the Savannah River Plant, annual report—1982. DPSPU 83-302. Savannah River Plant. E.I. Dupont de Nemours & Co. Aiken, South Carolina. June 1984.

44. DOE, 1985.

45. Zeigler, 1986.

46. Zeigler, 1987.

47. Zeigler, 1988.

48. Davis HA, Martin DK, Todd JL. Savannah River Site environmental report for 1988 (U). WSRC-RP-89-59-1. Westinghouse Savannah River Company. Aiken, South Carolina. 1989.

49. Cummins CL, Martin DK, Todd JL. Savannah River Site environmental report for 1989 (U). WSRC-IM-90-60. Westinghouse Savannah River Company. Aiken, South Carolina. 1990.

50. E.I. du Pont de Nemours & Company. Health physics regional monitoring, semiannual report, January through June 1960. DPSPU 60-25-26. Savannah River Plant. October 1960.

51. E.I. du Pont de Nemours & Company. Health physics regional monitoring, semiannual report, July through December 1960. DPSPU 61-25-4. Savannah River Plant. 1961.

52. E.I. du Pont de Nemours & Company. Health physics regional monitoring, semiannual report, January through June 1961. DPSPU 62-25-2. Savannah River Plant. February 1962.

53. E.I. du Pont de Nemours & Company. Health physics regional monitoring, semiannual report, July through December 1961. DPSPU 62-25-9. Savannah River Plant. May 1962.

54. E.I. du Pont de Nemours & Company. Health physics environmental monitoring, semiannual report, July through December 1962. DPSP 63-25-10. Savannah River Plant. June 1963.

55. E.I. du Pont de Nemours & Company. Health physics regional monitoring, annual report, 1963. DPSPU 64-11-12. Savannah River Plant. June 1964.

56. Heffner JD. Comments on CDC's final draft report on phase II of the Savannah River Site dose reconstruction project (U). ESH-EMS-99-0461. May 11, 1999.

57. Reinig WC. Technical bases for Savannah River Plant radioactive waste release standards. SRS Phase II Database HAG1994090212. July 1, 1999.

Hall and Coombs, 1956. Hall, R.M.and J.P. Coombs. Note to H.A. McClearen. Subject: Argon-41 Stack Effluent Activity. SRS Phase II Database SVK199506091. December 1956.

Miller and Patterson, 1956. Miller, D.A. and C.M. Patterson. Plant Manager and Superintendent Health Physics. Letter to G.H. Giboney, Atomic Energy Commission. Subject: Crave Project. DPSP-56-842. SRS Phase II Database PGV1994042881. 3 August 1956.

Murphy, 1991. Murphy, C.E., Jr., L.R. Bauer, D.W. Hayes, W.L. Marter, C.C. Zeigler, D.E. Stephenson, D.D. Hoel, and D.N. Hamby. *Tritium in the Savannah River Site Environment (U).* WSRC-RP-90-424-1, Revision 1. Westinghouse. SRS Phase II Database MJC1994051310. May 1991.

APPENDIX D TRANSPORT, PATHWAY, AND DOSE ASSESSMENT

The primary purpose of this appendix is to summarize the mathematical relationships used in Version 2 of GENII to model the transport of radionuclides through the air from a release point to an exposure location, the exposure of humans to radionuclides existing at that exposure location, and the annual radiation dose and cancer risk resulting from that exposure. Exposure of humans to radionuclides is assessed through 18 exposure pathways – 13 pathways associated with radionuclides released to the air, and 5 pathways associated with radionuclides released to surface water. Each pathway may cause radiation exposure either through external exposure to radiation, through ingestion of radionuclides, or through inhalation of radionuclides.

ATL assessed the movement of radionuclides by air to an exposure location in a different manner than the movement of radionuclides by surface water to an exposure location. For air transport, ATL used the Gaussian plume model contained in the GENII code. This Gaussian plume model is described in Section D.2. Radionuclide concentrations in air at an exposure location, as calculated using this Gaussian plume model, were used along with GENII-calculated radionuclide deposition rates as source terms for the subsequent GENII assessments of the 13 exposure pathways considered for radionuclides released to the air.

For water transport, ATL used a procedure independent of the GENII code. ATL considered radionuclide holdup in surface water sediments, as well as dilution by surface water bodies, as part of a procedure discussed in Appendix C and Chapter 7. ATL used this procedure to develop radionuclide concentrations that were used as source terms for the subsequent GENII assessments of the 5 exposure pathways considered for radionuclides released to surface water.

The mathematical relationships presented in this appendix have been obtained from the [GENII SDD]. ATL included these mathematical relationships to enable the reader to relate the results of the analyses to their mathematical bases. ATL was concerned that the lack of this information would have detracted from the report's discussion of important variables that influenced the calculated doses and risks, and believed that many readers would not possess a copy of the [GENII SDD]. To enable easier referencing by the reader, ATL generally used the same terminology and notation as those used in the GENII SDD. This enabled easier referencing by the reader.

In addition, the mathematical relations described in Sections D.2 through D.4 are each composed of a set of parameters, each requiring a numerical value. To avoid a voluminous and complicated appendix, we generally defer a discussion of the assumed values for parameters that are used in the base-case GENII calculations to other appendices.

D.1 Overview of Transport, Pathway Exposure, and Dose and Risk Assessment

This section consists of two principal subsections. Subsection D.1.1 addresses some considerations that guided ATL decisions about the transport and exposure pathways to be addressed for this phase of the SRS Dose Reconstruction Project. Subsection D.1.2 describes how ATL envisioned the assessment as a linked set of calculation modules, and points the reader toward those parts of the report that address each calculational module.

D.1.1 Selection of Transport and Exposure Pathways

D.1.1.1 Background

This report provides a plausible, yet bounding, assessment of the radiological impacts that may have resulted from release of radioactive material to the environment from 39 years of SRS operation. The report was prepared for the Center of Disease Control and Prevention (CDC), and builds on the work performed by the Risk Assessment Company (RAC) to characterize the principal sources of radionuclide release to the environment. In [Phase II], RAC provided estimates of radionuclides and chemicals discharged over 39 years into the air and into onsite surface waters.

As charged by CDC, ATL performed the analysis in terms of exposure scenarios representing hypothetical families performing plausible activities. The goal of reconstructing possible doses and risks from past SRS operations dictated somewhat different considerations in selecting pathways for analysis than would be the case if the goal was to perform preoperational evaluation for comparison to a regulatory requirement. Analyses performed for comparison against regulatory limits are typically performed in a very conservative manner to assure that doses or risks would not be underestimated even under unusual circumstances. But this level of conservatism would have been unwarranted for the SRS Dose Reconstruction Project. Rather, it was preferable to conduct an assessment that more closely examined plausible rather than extreme activities and pathways. Such an assessment would be more reflective of the mass of the persons in the vicinity of SRS and potentially exposed from site operations.

In addition, by the same logic that guided use of a screening process to identify those radionuclides that contributed the great majority of the possible health effects from site operations, it was desirable to focus on the exposure pathways leading to the largest doses and risks. In practice, the relative significance of different pathways was not initially clear, which prompted a bias for completeness in the initial stages of the analysis.

D.1.1.2 Pathways Considered

The Phase II report identified two principal sources of release of radionuclides into the environment from SRS: release into the air, and release into surface water [Phase II]. The Phase II report identified and quantified the principal radionuclides that were released.[1] To assess the environmental consequences of these releases, ATL used an existing state-of-the-art computer code, Version 2[2] of the GENII family of codes.[3] ATL's process for selecting this code over other computer codes and options is summarized in Appendix H.

Of the exposure pathways addressed in GENII, those considered appropriate for this report are shown in Table D-1. Exposure pathways consist of those associated with release of radionuclides into the air (*air pathways)*, and those associated with release of radionuclides into surface water (*water pathways*). Doses and risks experienced by the receptors may have resulted from three exposure routes: external exposure, ingestion, and inhalation. Exposures from each exposure route represent the sum of exposures from all applicable exposure pathways.

[1] ATL reviewed the estimates of release from the Phase II report, and, using site-specific data, adjusted the Phase II estimates as needed to perform the analyses for this report (see Chapter 5 and Appendix B).
[2] In the rest of this appendix, references to GENII mean Version 2 of GENII.
[3] The original version of GENII was developed in the late 1980s for use at DOE's Hanford Reservation, although the codes were designed with the flexibility to accommodate input parameters for a wide variety of sites. GENII Version 2 incorporates improved transport models, exposure options, dose and risk estimates, and user interfaces.

An overview of the air and water exposure pathways considered for this report is provided in Section D.1.1.2.1. Section D.1.1.2.2 addresses ATL's approach for addressing radiological impacts from ingestion of meat from game animals. Both the CDC and the SRS Health Effects Subcommittee identified the need to consider radiological impacts from ingestion of meat from game animals (see Appendix E).

Table D-1 Exposure Routes and Pathways for Air and Water Pathways

Exposure Route & Pathway	Air Pathways	Water Pathways	All Pathways
External Radiation:			
• Immersion in a Plume of Air	X		X
• Exposure to Contaminated Soil	X		X
• Exposure to a Contaminated Shoreline		X	X
• Exposure to Contaminated Water While Swimming		X	X
• Exposure to Contaminated Water While Boating		X	X
Ingestion:			
• Leafy Vegetable Consumption	X		X
• Root Vegetable Consumption	X		X
• Fruit Consumption	X		X
• Grain Consumption	X		X
• Beef Consumption	X		X
• Poultry Consumption	X		X
• Milk Consumption	X		X
• Egg Consumption	X		X
• Inadvertent Soil Consumption	X		X
• Fish Consumption		X	X
• Inadvertent Ingestion of Water While Swimming		X	X
Inhalation:			
• Inhalation of Contamination in the Air	X		X
• Inhalation of Contamination Resuspended from Soil	X		X

D.1.1.2.1 Pathways Associated with Release of Radionuclides into the Air and Water

Radionuclides discharged from SRS release points were transported to various receptor locations, leading to receptor exposures from external radiation and inhalation pathways. Radionuclides were also deposited on the ground at receptor locations. Contaminated soil exposed receptors to radiation through several pathways. Exposure pathways considered in this report resulting from deposition of contamination on the ground were:

- External radiation exposure to the contaminated soil.
- Inhalation of resuspended soil.
- Inadvertent ingestion of soil from working or playing in soil.
- Consumption of food crops, where the crops were contaminated through root uptake of radionuclides in soil, direct deposition of radionuclides on plant surfaces, or deposition on plant surfaces from radionuclides resuspended from contaminated soil.

Consumption of food products from animals that had consumed forage crops grown in contaminated soil. Forage crops ingested by animals were contaminated through root uptake of radionuclides in soil, direct deposition of radionuclides on plant surfaces, and deposition on plant surfaces from radionuclides resuspended from contaminated soil.

Surface water exposure pathways considered in this study were:

- Ingestion of aquatic animals (e.g., fish) obtained from Savannah River and Lower Three Runs Creek access locations.
- External radiation exposure to radionuclides building up in sediment alongside Savannah River and Lower Three Runs Creek.
- Exposures from swimming in contaminated water, including external exposure to water and accidental ingestion of water.
- External exposures from boating on contaminated water.

Exposures from possible ingestion or inhalation of resuspended sediment were not analyzed. Considering that sediment is normally saturated, resuspension of sediment would have been less likely than resuspension of dryer soil, particularly soil used for growing food and crops that were abraded and dispersed by farm implements. Therefore, ATL concluded that this pathway was likely much smaller than other possible pathways from contaminated surface water. It is also not considered in GENII.

ATL also did not assess radiation exposures caused by use of contaminated river or creek water for irrigation, drinking or cooking, or showering.

Two studies have considered the potential use of the Savannah River for irrigation. The first study, published in 1991, was performed by the Westinghouse Savannah River Company (WSRC), the primary contractor at SRS. It summarized land and water use characteristics around SRS that could be incorporated as site-specific information in dose models [Hamby 1991]. The author contacted the Georgia Department of Natural Resources and the Clemson University Extension Cooperative. These organizations "provided information regarding irrigation practices along the Savannah River from Clark's Hill reservoir to the Atlantic Ocean." They found that "the only known use of Savannah River water for irrigation is by a dairy farmer in Edgefield [County], upstream of the SRS" [Hamby 1991]. This statement implied that the Savannah River was not used as a source of irrigation water downstream of SRS, at least as of the late 1980s and early 1990s. The author recommended that irrigation not be considered as a pathway for ingestion of radionuclides in dose models used for SRS [Hamby 1991].

The second study, issued in 2002 by the South Carolina Department of Health and Environmental Control (SCDHEC), was a critical pathway assessment of SRS to be used to help assess the environmental monitoring program at SRS [Moore 2002]. The author surveyed state employees. This report states: "The state county extension offices report no knowledge of any irrigation system originating from the Savannah River downstream of the SRS. Pine plantations bordering the Savannah River in Allendale and Jasper counties are used by deer hunters." In Georgia, "due to the high elevation of the Georgia river bank, irrigation from the Savannah River is not practical. Irrigation water, therefore, comes from other sources such as groundwater or ponds" [Moore 2002].

ATL contacted an extension engineer in Georgia who verified that, to his knowledge, the Savannah River was not used for irrigation and that irrigation water in Georgia was primarily from ponds and groundwater [Harrison 2003]. ATL also contacted the SCDHEC author of the second assessment, who stated that the extension agents he contacted based their information on their 20 to 30 years of experience [Moore 2003]. ATL concluded that the Savannah River most likely had not been used for irrigation since at least the early 1970s.

In any event, this study considered two farming-family scenarios. The closest to the SRS lived near Girard, Georgia. It would have been unreasonable to assume that this family used the Savannah River as a source of irrigation water. The family farm was about three miles from the river, an unfeasible distance for piping Savannah River water to a farm. Groundwater levels are normally less than 100 feet below the surface in this part of South Carolina and Georgia, making groundwater more easily available and cost effective to use for irrigation. Using ponds that are commonly found on farms in the southeast U.S. is also more cost-effective than pumping water from a river.

With respect to drinking and showering water, the only scenario involving a dwelling located reasonably near a source of contaminated surface water was the Family Near the River. ATL assumed that the family in this scenario lived in or near Martin, SC, which is near Lower Three Runs Creek. ATL has no evidence that persons living in or near Martin used Lower Three Runs Creek as a source of drinking water.

Considering this, ATL concluded that incorporating use of water from Lower Three Runs Creek into the scenario would have been unreasonable.

D.1.1.2.2 Game Animals

Background. Humans could have become exposed to radionuclides by ingesting meat from game animals that had taken up radionuclides. ATL determined that these game animals could be represented by deer and wild fowl.

[ERDA-1537] documents that the deer herd before SRS was officially closed to the public in December 1952 constituted about 20 animals. The population as of the mid 1970s had grown to 5,000 to 8,000. The greatest population densities occurred on the southern and northeastern portions of SRS. Controlled public hunts began in 1965. From that time to the mid 1970s, about 10,000 deer were taken in public hunts, and about 500 were killed for research programs [ERDA-1537]. In addition, several domestic hogs, abandoned in 1952, had reverted to the semi-wild state. SRS began a control program for hog removal, and since 1969, about 125 wild hogs had been killed as of the mid 1970s [ERDA-1537].

Therefore, ATL selected deer to represent all wild mammals assumed to be taken for consumption. Deer was routinely taken by hunters between 1954 and 1992. Although wild hogs were also taken, the numbers killed by hunters were apparently small in comparison to deer. From the mid 1960s to the mid 1970s, the number of wild hogs taken by hunters was only about 1% the number of deer.

With respect to wild fowl, ATL had no evidence that the consumption of wild fowl constituted a major source of human intake of radionuclides during the SRS operational period. Nonetheless, ATL recognized that waterfowl were present on the SRS, mainly during winter migrations. In addition, other game birds such as quail and dove were abundant. [ERDA-1537] observed that the population of quail and dove in the SRS vicinity did not initially decrease when the SRS land was removed from agriculture, but probably reached a record high in the early 1960s. Wild turkeys are also on the site, resulting from use of SRS as a breeding ground.

Hence, ATL felt it plausible that hunters either onsite or in the vicinity of SRS would have taken wild fowl during the period of SRS operations, and that wild fowl represented a possible source of ingestion exposures to some receptors.

Analyzing exposures from contaminated game. Development of exposure pathways for game animals was difficult. For example:

- It was not clear that such pathways were reasonable for game taken on the SRS. Persons would have done so voluntarily with knowledge that the game may have contained radionuclide contamination. This would arguably not have been the case for deer or other game animals taken off the SRS site.
- Unlike animals used for food products such as beef or pork, game animals are generally not confined to a definable location. Game animals may have wandered from one widely separated location to another, consuming grass or other plant products as well as water from SRS streams.
- There was a lack of basic information such as transfer coefficients for deer except for a few isotopes, as well as other computational difficulties (see below).
- It was unclear whether exposures that may result from taking deer on or near SRS were significantly different from exposures elsewhere (see below).

ATL considered options for modeling doses from consumption of contaminated wild game as discussed in [ATL white paper on venison]. ATL determined that with respect to deer, transfer factors for most isotopes of concern were not available. (A transfer coefficient value for ^{137}Cs to deer was available from [IAEA 1994].) ATL also determined that for most years, data about the concentrations of radionuclides in venison were available for one or a few nuclides (^{137}Cs and ^{90}Sr) from SRS annual environmental reports. As discussed in Chapter 11 of the Phase II report, there was a substantial body of information about the concentrations of cesium in meat from deer killed on the SRS and elsewhere in the region. "In general, ^{137}Cs is the radionuclide of greatest concern because of its relatively long half-life (30 years) and its tendency to accumulate in edible (muscle) tissues" [Phase II]. Nonetheless, concentration data for other radionuclides and for missing years would have had to be derived or estimated by ATL.

Perhaps more significantly, the Phase II report notes, "Concentrations measured in deer collected from offsite locations give no indication that mean ^{137}Cs burdens in SRS deer are elevated above the expected background concentrations." The Phase II authors described comparisons between SRS deer and deer taken from other locations in South Carolina and Georgia, and discussed potassium levels in soils as the most likely reason that the mean ^{137}Cs concentrations in the SRS deer were consistently lower. They discussed a study designed to use the fact that the ^{134}Cs/^{137}Cs ratio from SRS releases differed from that in fallout: the cesium ratios in deer in that study "were consistent with global fallout and were comparable to those calculated for offsite deer" [Phase II].

In a 1999 report available on the web site of the University of Georgia's Savannah River Ecology Laboratory, Dr. Michael Smith of the University of Georgia and Peter Fledderman of Westinghouse Savannah River Company provided additional information comparing levels of ^{137}Cs found in deer at SRS with those at Fort Jackson, SC, Fort Stewart, Georgia, Cedar Knoll Plantation, SC and Webb Wildlife Center, SC. These authors provided data showing higher average concentrations of ^{137}Cs in deer at the two military bases than at SRS. They described the soils at the military bases as similar to those at SRS. Deer from the other two locations had much lower concentrations of ^{137}Cs, but the authors maintained that fertilizers with potassium were used at these locations and that this probably reduced the ^{137}Cs levels in the deer [Smith & Fledderman].

The Phase II authors suggested how the deer pathway might be further explored in "future phases of the SRS Dose Reconstruction Project." However, there was a lack of usable data that would have enabled ATL to confidently quantify human exposures via deer consumption from radionuclides released by the SRS. As noted, information was lacking about transfer coefficients for elements other than cesium. A more difficult issue was the lack of data that showed that radionuclide concentrations in venison from SRS were "above background"— i.e, larger than the concentrations in other deer. It was not possible to discern a significant difference in the isotopic ratios between the cesium in the SRS deer and the cesium

from atmospheric fallout.[4] Furthermore, "radioiodine concentrations measured in deer thyroids have consistently corresponded to periods of weapons testing" [Phase II].

Therefore, ATL modeled wild game consumption pathway as a form of beef and poultry consumption .

D.1.2 Dose and Risk Assessment

D.1.2.1 Assessment Modules

Although the calculational procedure for determining dose and risk from long-term operation of SRS is complex, the overall governing relationship between the stages of the calculational procedure is straightforward. For each year that SRS operated between 1954 and 1992, the dose and risk to an individual can be mathematically envisioned for each radionuclide as a set of separate calculational modules. The outputs of each calculational module are multiplied in turn by the next module. For each year and radionuclide, therefore, the annual dose to an individual is:

$$D_i = RE_i \; TR_i \; PA_i \; DF_i$$

And the annual risk to an individual is:

$$R_i = RE_i \; TR_i \; PA_i \; RF_i$$

Where D_i = Annual dose in Sieverts (Sv) for radionuclide i.

R_i = Annual risk for radionuclide i.

RE_i = *Release Module*. Quantity of radionuclide i released to the air (as from a stack) or to a surface water body (Bq)

TR_i = *Air and Surface Water Transport Module*. Mathematical relationships that model the transport of a radionuclide through air or surface water to an exposure location – i.e., a location occupied by a receptor or a location where a receptor obtains foods such as vegetables, beef, or fish. The calculational result of this module is the concentration of the air or water containing that radionuclide at that exposure location -- i.e., m^{-3} of air or L^{-1} of surface water. Note that RE_i x TR_i = Bq/m^3 or Bq/L.

PA_i = *Pathway Assessment Module*. Mathematical relationships (pathway assessments) that model the movement of a radionuclide through each of the exposure pathways listed in Table D-1. The calculational result of this module is the concentration or quantity of a radionuclide that the receptor is exposed to, inhales, or ingests. The units associated with this module depend on the pathway being considered (see below).

DF_i = *Dose and Risk Module*. Dose conversion factor, a relationship that gives the dose to a receptor for radionuclide i for the particular exposure pathway of interest (e.g., Sv per annual exposure to a concentration of 1 Bq per m^3 of air, Sv per Bq ingested from food, water, or other sources of contamination).

RF = *Dose and Risk Module*. Risk conversion factor, a relationship that gives risk of cancer to a receptor for radionuclide i for the particular exposure pathway of interest (e.g., risk per annual exposure to a concentration of 1 Bq per m^3 of air, risk per Bq ingested from food, water, or other sources of contamination), given as an annual probability of cancer incidence or fatality.

[4] If either the concentrations of ^{137}Cs in SRS venison were notably larger than venison from other areas, or the cesium isotopic ratios in SRS venison were notably different that that from venison in other areas, it could have been possible to calculated doses from venison consumed in different scenarios. But such differences cannot be discerned, based on available literature.

Each of these modules is briefly addressed below.

Release Module. The release of radionuclides into the air and surface water is addressed in Appendices A and B. Appendix A addresses the determination of airborne release points for the assessment. Appendix B lists the quantities of radionuclides annually released into the air and water from each source considered in this study, as well as the ATLs bases for these listed quantities. From the information in these appendices, ATL created a series of data files that list the quantities of radionuclides released into the air as a function of major SRS facility and year, and the quantities of radionuclides released into surface water as a function of year. The files were input to GENII using the pre-processor, a program created by ATL to facilitate entry of data into GENII.

Air and Surface Water Transport Module. ATL used different mathematical procedures to model movement of radionuclides to exposure locations, depending on whether the radionuclide release was to air or to water. For release of radionuclides to air, ATL used a sector-averaged Gaussian model contained in the GENII code as described in Section D.2. For release of radionuclides to surface water, ATL considered simple dilution models that differed depending on whether the exposure location being considered was Lower Three Runs Creek or was the Savannah River (Appendix C). For Lower Three Runs Creek, ATL considered radionuclide concentration data as measured in this creek are reported in SRS documents such as annual environmental reports. For the Savannah River, ATL considered a simple dilution model. ATL first estimated the annual quantities of radionuclides that were discharged into the Savannah River from all major surface water systems (including Lower Three Runs Creek), and then diluted this annual discharge by a volume of water equal to the annual river flow rate. The outcome of this module was a set of files containing radionuclide concentrations in water. These files were input into GENII for the pathway assessment.

Pathway Assessment Module. This portion of the assessment was performed using the GENII code. For radionuclides released through the air pathway, the starting point of the pathway assessment was the concentration of radionuclides in air at an exposure location. Radioactive exposures were then assessed for each of the 13 air pathways listed in Table D-1, in accordance with the mathematical procedures summarized in Section D.3. While the radionuclides were in the air, they caused exposures to humans by the following pathways:

1. Inhalation exposures from immersion in air containing radionuclides (Section D.3.3.1).
2. External exposures from immersion in air containing radionuclides (Section D.3.2).

Radionuclides also fell to earth through depositional processes. This deposition resulted in a concentration of radionculides in the top part of the soil. Radionuclides in this top part of the soil then caused radionuclides through additional pathways. Three pathways caused by ground contamination at an exposure location are:

1. External exposures from proximity to contaminated soil (Section D.3.3.2).
2. Inhalation exposures from breathing radionuclides that had been resuspended from contaminated soil (Section D.3.3.3).
3. Ingestion exposures from inadvertently ingesting contaminated soil (Section D.3.3.4).

In addition, radionuclides may be transported through the food chain to humans. This transport mechanism has historically been a very important mechanism for human exposure to radionuclides released to the environment. In GENII, radionclide transport through food chain pathways are considered in two ways. First, GENII considers foods that take up radionuclides from soil (or have radionuclides deposited on food surfaces) and are directly eaten by humans. The four pathways considered in this manner are:

1. Ingestion exposures from eating leafy vegetables (Section D.3.4.1).
2. Ingestion exposures from eating root vegetables (Section D.3.4.1).
3. Ingestion exposures from eating fruit (Section D.3.4.1).
4. Ingestion exposures from eating grain (Section D.3.4.1).

Second, GENII considers animal products that are eaten by humans and have previously consumed contaminated grass or forage. The four pathways considered in this manner are:

1. Ingestion exposures from eating beef (Section D.3.4.2).
2. Ingestion exposures from eating poultry (Section D.3.4.2).
3. Ingestion exposures from drinking milk (Section D.3.4.2).
4. Ingestion exposures from eating eggs (Section D.3.4.2).

For radionuclides released into surface water, the starting point of the pathway assessment was the concentration of radionuclides in water at an exposure location. Radioactive exposures were then assessed for each of the 5 water pathways listed in Table D-1, in accordance with the mathematical procedures summarized in Section D.3. While the radionuclides were in contained within the water, they could they caused exposures to humans by the following pathways:

5. Ingestion exposures from eating fish (Section D.3.4.3).
6. External exposures from swimming in water (Section D.3.6.1).
7. Ingestion exposures from inadvertently drinking water while swimming (Section D.3.6.2).
8. External exposures from boating in water (Section D.3.6.3).

Note that eating fish is another very important mechanism for food-chain transport of radionuclides to humans.

Finally, radionuclides may be deposited from the water onto river or creek sediment. Persons standing or performing other activities along a shoreline may receive external exposures from the radionuclides in these sediments – i.e.:

1. External exposures from a contaminated shoreline (Section D.3.5).

Dose and Risk Module. This portion of the assessment was basically calculated using the GENII code, although certain dose and risk calculations were also performed using the post-processor, a program created by ATL. This module calculated equivalent dose for 23 organs, effective dose, and cancer risk as a function of radionuclide and year for each receptor. Almost all dose and risk conversion factors used for this report were those obtained from EPA's April 2002 update to its Federal Guidance Report No. 13 [FGR-13U]. Section D.4 contains a discussion of radiation dose and risk concepts, and summaries the basic equations used by GENII to calculate dose and risk from exposure to radioactive material.

D.1.2.2 Approach for Presenting Mathematical Relationships used in GENII

The remaining three sections of this appendix present the mathematical relationships used in the GENII code to:

- Model transport of radionuclides through air to an exposure location (Section D.2).
- Perform pathway assessments, include food-chain transport assessments, of radionclides through air and surface water pathways (Section D.3).
- Assess human radiation doses and cancer risks from external exposure to radionuclides, inhalation of radionuclides, and ingestion of radionuclides (Section D.4).

ATL recognized that a rigorous description of the mathematical relationships set forth in GENII would be lengthy and would largely repeat the information in the GENII SDD. Yet ATL also recognized that if the mathematical relationships were not presented in some detail, most readers would be unable to easily relate the results of the analyses to their mathematical bases. (ATL believed that many readers would not have access to a copy of the GENII SDD.) This would have detracted from the report's discussion of important variables that influenced the calculated doses and risks. Hence, ATL herein briefly summarizes the mathematical relationships used in GENII, hoping that this summary would be sufficient for most persons interested in the technical details of the analysis.

ATL used the same terminology and notation as those used in the GENII SDD. This enabled easier referencing by the reader. Also where appropriate, ATL related the equations cited in this section to their application in GENII using the FRAMES software system. In some cases the terminology for particular parameters is somewhat different in the GENII SDD than in the FRAMES interface.[5]

In addition, the mathematical relations described in Sections D.2 through D.4 are each composed of a set of parameters, each requiring a numerical value. To avoid a voluminous and complicated appendix, we generally defer a discussion of the assumed values for parameters that are used in the base-case GENII calculations to other appendices. Some parameters pertain to site-specific considerations such as the density of soil (see Appendix F). Others pertain to human activities that influence the uptake or exposure to radionuclides (e.g., time spent in an exposure location) and are determined in Appendix E. .

D.2 Transport Through Air

D.2.1 Fundamentals of Air Dispersion

Radioactive materials in the form of gases and particulates may be released into the atmosphere and may result in radiation exposure to humans from both external and internal pathways. External exposures may result from immersion in contaminated air or from proximity to radionuclides deposited on the ground, while internal exposures may result from inhalation and ingestion of radionuclides. The magnitude of exposure depends on the concentrations of radionuclides in contaminated media contacted by, or in proximity to, a human receptor. In turn, radionuclide concentrations in contaminated media depend on atmospheric diffusion and deposition processes that affect the transport of radionuclides from the point of release to the location of the receptor.

Figure D-1 and Figure D-2 depict many of the atmospheric processes that affect airborne release and transport [from Till & Meyer, IAEA SS-19]. These include plume rise, dispersion, wind speed and direction, depletion, release height, building effects, and topography and geographic features.

[5] Documentation for use of FRAMES is available on the Internet at the FRAMES Version 1.3 website (http://mepas.pnl.gov/FRAMESV1/index.html) [FRAMES 1.3].

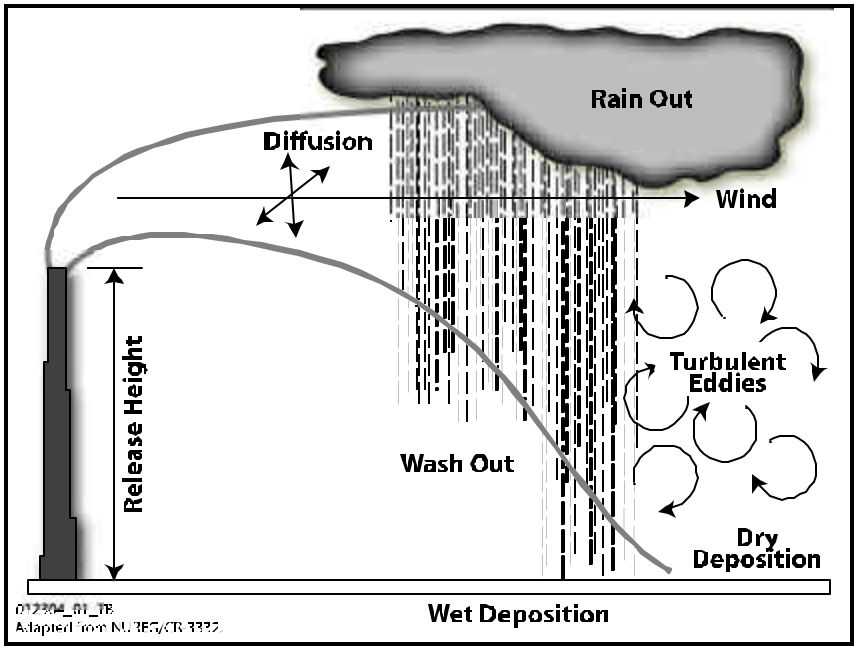

Figure D-1 Atmospheric Dispersion and Removal Processes
Adapted from [IAEA SS-19].

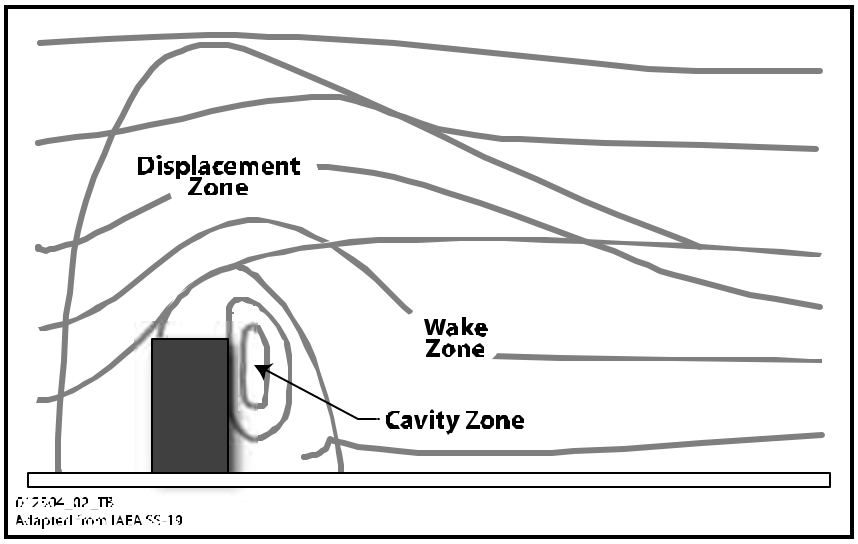

Figure D-2 Air Flow Around a Building
Adapted from [IAEA SS-19].

D.2.1.1 Plume Rise

As a plume of air containing gaseous and particulate materials (effluent) is released from a source such as a tall stack, the effluent may initially rise. Some of the factors influencing plume rise include the temperature of the effluent and the ambient air, the velocity of the effluent leaving the stack, the inside radius of the stack, the wind speed at the release height, and the atmospheric stability (see below). Plume rise affects the "effective stack height" of the release point. Plume rise may significant increase the

effective stack height, which in turn may significantly reduce near-field ground-level concentrations [Till & Meyer].

D.2.1.2 Dispersion

As the effluent plume is transported from the source by wind, turbulent eddies in the atmosphere diffuse the effluent. Consistent with Fick's Law, a concentration gradient exists in the effluent, so that the effluent concentrations in the center of the plume are larger than those toward the plume edges. The combined influences of diffusion and transport are called dispersion.

As the plume moves with the wind, diffusion continues in the vertical direction until certain "boundaries" are reached. Of course, vertical diffusion from the depicted stack (Figure D-1) cannot continue below the surface of the earth. In the other direction, the plume continues to diffuse up to the mixing height, which generally ranges from about 200 m to about 2,000 m above the surface of the earth.[6] Within this atmospheric "mixing layer", friction caused by ground surface roughness and heating combine to generate turbulence that efficiently mixes the effluent. But the top of the mixing layer is marked by a decrease in turbulence brought about by stable atmospheric conditions above. Above this "boundary," further diffusion in the vertical direction is significantly reduced, and the vertical concentration distribution becomes more uniform. The thickness of the mixing layer changes with atmospheric conditions. The mixing layer is generally thickest during the day and during periods having high wind speeds, and it is thinnest at night during periods having low wind speeds. It also tends to be thickest on summer afternoons and thinnest on autumn mornings. Thicknesses also very considerably by geographic location. In either case, the mixing layer depth tends to increase with surface roughness [Till & Meyer].

The stability of the atmosphere within the mixing layer largely determines the intensity of turbulence within the mixing layer and therefore the diffusion of effluent within it. Essentially, conditions within the mixing layer are said to be stable, neutral, or unstable depending on variations of temperature and air density. These variations affect the movement of air particles from one location to another. If the variations tend to retard movement of particles, then the atmospheric conditions are said to be stable; if the variations have no effect on the movement of the particles, then atmospheric conditions are said to be neutral; and if the atmospheric conditions tend to promote the movement of the particles, then atmospheric conditions are said to be unstable. Clearly, unstable conditions promote dispersion of particles within air, while stable conditions retard it.

A common method for describing stability conditions is to differentiate meteorological conditions into stability classes. One of the original classification systems was developed in 1962 by Pasquill, who distinguished six stability classes ranging from Class A (highly unstable) to Class F (highly stable). Pasquill's original classification is reproduced here as Table D-2, and it considers the relationship of wind speed, amount of incoming solar radiation, and cloudiness. Since this classification system was developed, it has been modified by various researchers and regulatory agencies, and other, similar, classification systems have been developed [Till & Meyer]. The choice of a particular classification system, which affects the analyses performed to numerically describe effluent diffusion in air, is somewhat subjective.

[6] Another name for the mixing layer is the planetary boundary layer [Till & Meyer].

Table D-2 Pasquill Stability Categories

A. Extremely Unstable Conditions	*D. Neutral Conditions**
B. Moderately Unstable Conditions	*E. Slightly Stable Conditions*
C. Slightly Unstable Conditions	*F. Moderately Stable Conditions*

Surface Wind Speed at 10 m (m/s)	Daytime Insolation			Nightime Conditions	
	Strong	Moderate	Slight	Thin Overcast or > 3/8 Cloudiness†	= 3/8 Cloudiness
<2	A	A-B	B		
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

*Applicable to heavy overcast day or night.
†The degree of cloudiness is the fraction of the sky above the local apparent horizon that is covered by clouds.

D.2.1.3 Wind Speed and Direction

Clearly, wind speed affects the airborne dispersion of effluent. Higher wind speeds promote dispersion, while lower wind speeds retard it. Wind speeds frequently fluctuate both temporally and with height, as does wind direction.

D.2.1.4 Depletion

Removal mechanisms reduce effluent concentrations within the plume, and include wet and dry deposition, radioactive decay, and chemical change.

Wet deposition processes include rainout and washout. Rainout refers to the interaction of gaseous and particulate effluents with precipitation formation processes within clouds. Effluents are subsequently removed by the precipitation. Washout refers to the removal of gaseous or particulate matter below the cloud layer from contact by falling precipitation. Dry deposition processes include removal of effluent through gravitational settling, or through contact with the ground, vegetation, or other ground cover such as buildings. Although dry deposition is continuous, compared to wet deposition that only occurs during periods of precipitation, dry removal of effluent from air is a less efficient process than wet removal.

Radioactive isotopes decay during transport. The significance of this removal process for exposure to a downwind receptor depends on the radionuclide half-life and the transport time. Chemicals may degrade or otherwise change during transport.

D.2.1.5 Release Height

Generally speaking, the higher the effluent release point, the farther the effluent travels from the release point before significant effluent concentrations reach ground level. NRC notes that for a facility such as a nuclear power plant, gaseous effluents released from tall stacks generally produce peak ground-level air concentrations near the site boundary, while near-ground-level releases usually produce concentrations that monotonically decrease from the release point to all locations downwind [RG 1.111]. Till and Meyer [Till & Meyer] suggest that a common approach is to assume an elevated release when the release point is 2.5 times the height of nearby structures, and to assume a ground-level release when the release point is below the height of the structures (see below).

D.2.1.6 Building Effects

The flow of air and effluent from a release point can be disturbed by surrounding structures. Figure D-2 [from IAEA SS-19] illustrates idealized flow around a single building. The three main zones of airflow around this building are [ISEA SS-19]:

1. The upwind displacement zone, where the approaching air is deflected around the building.
2. The relatively isolated cavity zone immediately on the leeward side of the building.
3. The highly disturbed wake zone further downwind from the building. The exact distance of the downwind wake zone depends on the source configuration and meteorological conditions.

The prevailing dispersion pattern will depend on both the release height and the building geometry. If the release height is greater than about 2.5 times the building height, then building effects on dispersion are relatively small. Dispersion characteristics are similar to those in the displacement zone. If the release height is less than about 2.5 times the building height, the transition between the downwind cavity zone and the wake zone occurs downwind of the release point at a distance of about 2.5 times the square root of the surface area of the largest wall of the building. Variations in dispersion patterns caused by buildings can be considered through modifications of basic atmospheric dispersion models such as the Gaussian plume model.

D.2.1.7 Topographic and Geographic Features

Geographic features such as hills, valleys, and large bodies of water influence dispersion and airflow patterns. For example, effluent released in a well-defined river valley will likely follow the confines of the valley rather than remain in a straight-line trajectory. Surface roughness, including vegetative cover, affects the degree of turbulent mixing. Sites having similar topographical and climatological features can have similar dispersion and airflow patterns. Detailed dispersion patterns, however, are usually unique for each site [GR 1.111, Till & Meyer].

D.2.2 Gaussian Plume Model

One of the most widely used models for numerically describing the movement and dispersion of effluent from a release point is the Gaussian plume model. In theory, notes the IAEA, the Gaussian plume model is limited to rather simple dispersion situations [IAEA SS-19]:

- Dispersion over flat, non-complex terrain.
- Short range transport (about 100 m to 20 km downwind).
- Steady state meteorological conditions.
- No elevated temperature inversions.
- Quasi-continuous releases.
- Transport and mixing in the lee of isolated point sources.
- Non-depositing materials, such as noble gases.

But in practice, the Gaussian plume model has been successfully applied to a wide variety of dispersion problems. This is possible because the model is firmly supported by extensive experimental data, as well as being one of the most widely validated of the general dispersion models [IAEA SS-19].

D.2.2.1 Basic Model

The basic model used for chronic release of effluent from a source is provided below [from GENII SDD]. It describes dispersion of effluent from a single point source assuming that wind always flows in a single,

straight-line direction. Modifications to this model to address the release from multiple sources, and the flow of wind from multiple directions, are described in the next section.

A point source model was used for this report, rather than an area source model, because a point source model best described the release of most of the radioactive material into the air at SRS.[7] Furthermore, no attempt is made to consider plume rise or building effects. Regarding plume rise, offgas from SRS stacks was not particularly elevated in temperature. Therefore, plume rise from SRS stacks should have been comparatively small. In any event, neglecting plume rise was conservative because the assumption of no plume rise deposited more radionuclides on the ground closer to the release point. Regarding building effects, most release of radioactive material occurred from stacks that were considerably taller than nearby buildings. In addition, most receptor locations were several miles from release points, minimizing the local effects of buildings. Finally, ATL determined that the calculational complications associated with consideration of building effects was unwarranted considering the limited availability of long-term meterological data for SRS (see below).

Therefore, the complete straight-line Gaussian plume model used in this study is, from [GENII SDD]:

$$\frac{c\left(x,y,z,H,h_{eff}\right)}{Q'(x)} = \frac{1}{2pU\left(h_s\right)s_y s_z}\exp\left(-\frac{y^2}{2s_y^2}\right)G(z)$$

?(x,y,z,H,h_{eff})	=	the concentration at distance x, crosswind position y, and height z, in a plume with axis at height h_{eff} (Ci/m^3)[8]
Q'(x)	=	the release rate, corrected for deposition and decay as appropriate (Ci/s)
U(h_s)	=	the wind speed at release height, h_s (m/s)
s_y	=	the horizontal diffusion coefficient (m)
s_z	=	the vertical diffusion coefficient (m)
G(z)	=	the vertical dispersion factor.

The vertical dispersion factor includes plume reflection off the ground and off the top of the mixing layer. It is given by [GENII SDD]:

$$G(z) = \sum_{n=-\infty}^{\infty}\exp\left[-\frac{\left(2nH+\left(h_{eff}-z\right)\right)^2}{2s_z^2}\right]+\exp\left[-\frac{\left(2nH-\left(h_{eff}+z\right)\right)^2}{2s_z^2}\right]$$

Where h_{eff}	=	the effective release height (h_s + plume rise) (m)
H	=	the mixing layer thickness (m).

[7] The great majority of airborne releases were from tall stacks from the reactor and separations areas. Relatively small quantities of radionuclides were released into the air (primarily tritium as evaporated water vapor) from seepage basins and other area sources.

[8] In the GENII SDD, radionuclide activity is described in units of curies (Ci) as well as Becquerals (Bq), where 1 Ci = 3.7E+10 Bq.

In GENII, the limits of summation in the second equation are truncated between (-2 < n < 2), a simplification that should not significantly affect the accuracy of the equations. The receptor height (z) is assumed to be one meter.

If the distance from the source is sufficiently large, the value of the vertical diffusion coefficient (in meters) approaches the thickness of the mixing layer (H). Under this condition, the effluent is uniformly mixed in the vertical direction, and the straight-line Gaussian plume model is simplified to [GENII SDD]:

$$\frac{c(x,y,z)}{Q'(x)} = \frac{1}{\sqrt{2p}\,U(h_s)H_u s_y}\exp\left[-\frac{1}{2}\left(\frac{y}{s_y}\right)^2\right]$$

Where H_u = the height of the mixing layer, or the effective release height, whichever is higher.

In GENII, the effluent is considered to be uniformly mixed in the vertical direction when the vertical diffusion coefficient is at least 1.2 times the uniform depth (as defined above) [GENII SDD].

Horizontal and vertical diffusion coefficients in the above equations (i.e., s_y and s_z) may be calculated using a variety of methods that incorporate consideration of stability classes. Horizontal and vertical diffusion coefficients are automatically calculated in GENII when meteorological data is entered using the joint frequency distribution approach. The joint frequency distribution approach is used for this report.

D.2.2.2 Sector Average Model

Wind normally does not blow from the same direction for prolonged periods. So for chronic or long-duration releases, the basic Gaussian plume model is modified using a sector-average approximation. One first draws an imaginary circle around the release point, and divides the circle into a series of arcs. Historically, the circumference around the release point has been divided into 16 sectors corresponding to the 16-major compass directions: N, NE, NNE, E, and so forth. Each sector is a pie-shaped wedge describing a 22.5° arc (360° /16 sectors). (Since 1965, however, directions have been recorded in 10-degree sectors, leading to 36 sectors.) One then estimates the dispersion of effluent in each horizontal direction around the release point. One considers the concentrations produced by each wind direction, wind speed, and stability class, weighted by the frequency with which these conditions occur (the joint frequency distribution), and obtains an average effluent concentration within each sector as a function of distance from the release point.

Although the straight-line Gaussian plume model discussed above is given in Cartesian coordinates, the model when adjusted for sector averaging is normally converted to cylindrical coordinates. The sector average model as used in GENII is [GENII SDD]:

$$\frac{c(q,r,z)}{Q'(r)} = \frac{1}{\sqrt{2p}\,U s_z q_w}G(z)$$

?(?$_i$,r,z) = the concentration at distance r, in sector ?$_i$, at height z (Ci/m^3)

Q'(r) = the total mass of material released, corrected for deposition and decay

?$_w$ = the sector width, which is the larger of the arc length in a 22.5° sector, or 4 times s_y

U = wind speed (m/s)

s_z = vertical diffusion coefficient for distance r (or time t = x/U)

G(z) = vertical factor given by the above equation.

At long distances, the model further simplifies, because of uniform mixing in the vertical direction, to [GENII SDD]:

$$\frac{c(q,r,z)}{Q'(r)} = \frac{1}{U H_u q_w}$$

In GENII, it is again assumed that the plume is uniformly mixed in the vertical direction when the vertical diffusion program is 1.2 times the uniform depth.

D.2.2.3 Joint Frequency Distribution (JFD)

The joint frequency distribution, P_{pjk}, is a function of wind direction sector, p, stability category, j, and wind speed class, k. The joint frequency distribution is computed by compiling meteorological data, usually determined and recorded for each hour, over an appropriate time interval and computing the frequency of occurrence of each joint frequency category. Each joint frequency category represents a band of wind speeds, directions, and stability conditions.

D.2.2.4 Multiple Sources and Receptor Locations

The above discussions regarding the Gaussian plume model, and modifications to account for sector averaging, are for a single source emitting radionuclides into the air. But there are multiple SRS sources as well as multiple receptors. A single receptor may receive radiation exposures from all sources. Even if the release rate from each source was the same, the exposure received by a receptor would differ for each source because of distance and sector-averaging considerations.

The GENII code determines the total exposure received by each receptor as summed over the contribution from all sources. (See Section 5.1.5 of the GENII SDD.) It establishes the location of each receptor and source on a polar grid, and then for each receptor determining the distance and bearing from each source. For each radionuclide, the contribution from each source is summed, leading to a total concentration in air at the receptor's location. This average concentration is then used for further exposure and pathway analyses as addressed in Section D.3.

D.2.2.5 Depletion Processes

As radionuclides transit from a source to a receptor, several processes deplete the quantities of radionuclides in air. These processes include dry and wet deposition and radioactive decay.

D.2.2.5.1 Dry Deposition

Dry deposition is modeled in accordance with an assumption that the flux of material reaching the ground in is proportional to the concentration of the material in the air near the ground [GENII SDD]:

$?_{1ij}(t) = v_{dd} \; X_{ij}(t)$

Where $?_{1ij}(t)$ = the dry deposition rate at position i,j at time t (g/(s m^2)

v_{dd} = the dry deposition velocity (m/s), which is a function of the height at which the concentration is measured or calculated (assumed to be one meter for GENII).

$X_{ij}(t)$ = the concentration at a height of one meter above the ground at position i,j at time t.

Dry deposition velocities may be estimated using an analogy to electrical resistance, in that particles resist falling to the ground surface depending on their physical and chemical characteristics and atmospheric conditions. (Because noble gases are inert, the deposition velocity for noble gases is assumed to be zero.) For *small* particles, the dry deposition velocity is given by:

v_{dd} = $(r_a + r_s + r_t)^{-1}$

Where r_a = aerodynamic resistance (s/m)

r_s = surface resistance (s/m)

r_t = transfer resistance (s/m).

Aerodynamic resistance is a parameter characteristic of the turbulence in the lowest layer of the atmosphere, and can be calculated from the wind speed as:

r_a = $U(z) / u^2$

Where z = the height at which the concentration is estimated

u = the characteristic turbulence velocity, called the friction velocity

U(z) = the wind speed at height z.

The surface resistance is a function of the friction velocity, where:

r_s = $2.6 / (0.4\ u) = 6.5/u$

where 2.6 is a dimensionless empirical constant and 0.4 is von Karman's constant.

The transfer resistance is a mathematical device to establish an upper limit on the deposition velocity. As a default, the transfer resistance is assumed to be 10 s/m for iodine and 100 s/m for particles.

For *large* particles, the gravitational settling velocity of the particles must be considered, and the deposition velocity becomes:

$$V_{dd} = \left(r_a + r_s + r_t + r_a r_s v_s\right)^{-1} + v_s$$

Where v_s is the gravitational settling velocity, a function of particle size and density. GENII uses the same settling velocity as that used in the EPA ISC3 model, or [GENII SDD]:

$$v_s = \frac{\left(r - r_{AIR}\right) g d_p^2 c_2 S_{CF}}{18m}$$

Where ? = the particle density (g/cm^3)

$?_{AIR}$ = the air density (assumed to be 1.2E-3 g/cm^3)

d_p = the particle diameter (µm)

µ = the absolute viscosity of air (assumed to be 1.81E-4 g/cm/s)

c_2 = air units conversion constant (assumed to be 1E-8 $cm^2/\mu m^2$)

S_{CF} = the slip correction factor, which is computed as [GENII SDD]:

$$S_{CF} = 1 + \frac{2x_2\left(a_1 + a_2 \exp\left(-\frac{a_3 d_p}{x_2}\right)\right)}{10^{-4} d_p}$$

Where x_2, a_1, a_2, and a_3 are constants with values of 6.5E-6, 1.257, 0.4, and 0.55E-4, respectively.

D.2.2.5.2 Wet Deposition

Wet deposition of gases is modeled under an assumption that the exchange of gas between air and precipitation is sufficient to maintain equilibrium between the concentrations in the air and in the precipitation. The flux of gas to the ground surface is therefore proportional to the concentration of gas in air at ground level, the precipitation rate, and a solubility constant related to the Henry's Law constant for the gas. The wet deposition rate is given by [GENII SDD]:

$?_{2ij}(t)$ = v_{dw} $X_{ij}(t)$.

Where $?_{2ij}(t)$ = the wet deposition rate for gas at position i,j at time t ($g/(s\ m^2)$).

v_{dw} = the wet deposition velocity (m/s).

$X_{ij}(t)$ = the concentration at a one-meter height above ground surface at position i,j at time t.

And v_{dw} = c S P_r

Where S = the solubility coefficient (dimensionless).

P_r = the precipitation rate in mm/hr.

c = a conversion factor to convert P_r to m/s.

For gases, it is assumed for GENII that the gases are dissolved rapidly by precipitation. The wet deposition model for snow is assumed to be zero if the temperature is less than –3°C. (If temperature data are not available, the wet deposition velocity is zero for all forms of frozen precipitation.) This assumption is made because unless the precipitation is liquid, or has a liquid exterior, the rate of exchange of gases between air and ice is negligible.

For particulates, wet deposition is given by the following model, assuming that the particles are irreversibly collected by impaction as the precipitation falls through the plume [GENII SDD]:

$$w\,3_{ij}(t) = \Lambda \int_o^\infty c_{ij}(z,t)\,dz$$

Where ? is the washout coefficient, a function of the type of precipitation (liquid or frozen), the precipitation rate, and the precipitation collection efficiency.

This integral can be approximated as follows for sector-averaged point sources [GENII SDD]:

$$w_3 = \frac{\Lambda Q'}{U q_w}$$

Where Q' is the release rate corrected for depletion and decay.

For rain and drizzle, GENII uses the following expression to calculate the washout coefficient [GENII SDD]:

$$\Lambda_r = \frac{CE\,P_r}{0.35\,P_n^{1/4}}$$

Where ? $_r$ = the washout coefficient for rain ($hr^{-1)}$

C = empirical constant with a value of 0.5

E = the average collection efficiency, assumed to be unity

P_r = precipitation rate in mm/hr

P_n = normalized precipitation rate (P_r/1 mm/hr)

During periods of hail, snow, and other frozen precipitation, GENII calculates the washout coefficient as [GENII SDD]:

$$\Lambda_r = 0.2\,P_r$$

Where ? $_s$ = the washout coefficient for snow (hr^{-1})

0.2 = empirical constant with units of mm^{-1}

P_s = precipitation rate in mm/hr, liquid water equivalent

D.2.2.5.3 Total Deposition

Given the above formulas for wet and dry deposition, the surface contamination that accumulated at any point during any short period is given as [GENII SDD]:

$$D(x,y,T) = \sum_{o}^{T} \left[w1_{ij}(t) + w2_{ij}(t) + w3_{ij}(t) \right] \Delta t$$

Where D(x,y,T) is the total surface contamination (Ci/m^2) at position (x,y) and for time period T. ? $_{1ij}$, ? $_{2ij}$, and ? $_{3ij}$ are the deposition rates for dry deposition, rain deposition, and snow deposition, respectively. The total deposition rate, which is calculated for the GENII chronic models, is [GENII SDD]:

$$D'(x,y,T) = \frac{1}{T} D(x,y,T)$$

D.2.2.5.4 Radioactive Decay

Radionuclide decay is considered as radionuclides transit between the source and the receptor. For most radionuclides of interest, the decay is negligible, as is the buildup of daughter products. The algorithm for describing radionuclide decay during plume transit is given in Section 5.3.6 and Appendix C of the GENII SDD. The general procedure described in Appendix C for calculating decay chains includes branching as addressed in [Kennedy and Strenge], and in [Strenge 1997]. Appendix C of the GENII SDD also references Lederer and Shirley (1978) and the International Commission on Radiation Protection in

ICRP Publication 38 [ICRP-38] for data on radionuclide half-lives, decay chains, and fractional branching within chains. Half-lives for the radionuclides considered in this report (including daughter products) are listed, in units of days, in Table D-3. They were obtained from Appendix E of [Kennedy and Strenge]. Half-lives are given as the relationship, $\log_e(2)/?_i$, where $?_i$ is the radionuclide decay constant in units (in this case) of days^{-1}.

Table D-3 Half-Lives (days) for Radionuclides Considered in This Report

Isotope	Half-Life	Isotope	Half-Life	Isotope	Half-Life
^{3}H	4.51E+3	^{95}Nb	3.52E+1	^{231}Th	1.06E+0
^{14}C	2.09E+6	^{95}mNb	3.61E+0	^{234}Th	2.41E+1
^{32}P	1.43E+1	^{99}Tc	7.78E+7	^{234}U	8.93E+7
^{35}S	8.74E+1	^{103}Ru	3.93E+1	^{235}U	2.57E+11
^{41}Ar	7.63E-2*	^{106}Ru	3.68E+2	^{236}U	8.55E+9
^{60}Co	1.93E+3	^{129}I	5.73E+9	^{238}U	1.63E+12
^{65}Zn	2.44E+2	^{131}I	8.04E+0	^{238}Pu	3.20E+4
^{89}Sr	5.05E+1	^{134}Cs	7.53E+2	^{239}Pu	8.79E+6
^{90}Sr	1.06E+4	^{137}Cs	1.10E+4	^{240}Pu	2.39E+6
^{90}Y	2.67E+0	^{141}Ce	3.25E+1	^{241}Am	1.58E+5
^{95}Zr	6.40E+1	^{144}Ce	2.84E+2		

*From [FGR-13].

D.2.2.5.5 Correction of Release Rate

To determine the concentrations of radionuclides at the point of interest, one must subtract those radionuclides that are lost through deposition and decay before reaching the point of interest. This is done for the basic Gaussian plume model by correcting the radionuclide release rate. For a given distance, x, from the source, one calculates an effective release rate, Q'(t), in units of Ci/s or Bq/s, which is equal to the actual release rate from which one subtracts the loss up to point x from deposition and decay. This assessment is done in GENII through consideration of conservation of mass. For plume models, the depletion of the source term per unit distance is given as [GENII SDD]:

$$\frac{dQ'}{dx} = -\int_{-\infty}^{\infty} w\left(x, y\right) dy = -\int_{-\infty}^{\infty} d_v\, c^{\,dy}$$

This integral can be solved to give a second integral which is approximated in GENII using a trapezoidal rule. Because the calculational procedure breaks down very close to the source, no depletion is assumed to occur within 100 meters of the source. (See Chapter 5 of [GENII SDD].)

D.2.2.6 Calms

The straight line Gaussian plume model cannot be derived for zero wind speeds. In GENII, a minimum wind speed (1 m/s) is assumed for calm conditions, and a randomly-selected direction. Unless the user of GENII supplies a distribution of low wind speed directions, all wind directions are assumed for GENII to be equally likely [GENII SDD].

D.2.3 Application of Air Transport Models to SRS

ATL identified 15 major sources of radionuclide release to air. ATL then collapsed these 15 sources to four virtual sources of which three are represented by a release point of 61 meters above ground level (AGL) and one of 10 meters AGL (Appendix A).

To estimate transport from these virtual sources to exposure locations, ATL had to develop a set of meterological data that reflected the meterological conditions that existed between 1954 and 1992. The principal need for the meterological data was to establish the joint frequency distributions for input to the GENII computer code.

It would have been desirable to use SRS-specific meterological data that spanned the entire 39-year period of operations. Unfortunately, the SRS meterological program was only established in the early 1970's, leaving a gap of about 20 years in SRS-specific meterological data.

Data from nearby weather stations. To approximate meterological data for the entire 39 years of operation, ATL considered using data from nearby locations. Yet this approach would have contained pitfalls as illustrated in [Weber 2001].

[Weber 2001] documented the results of a study performed by Westinghouse Savannah River Company and Oregon State University to create a meterological database for SRS for the years 1955 through 1961. The authors of this study projected 1992-1996 data from reasonably close National Weather Service (NWS) stations to the 1955-1961 time period at SRS.

The two sets of NWS data used for the study were obtained from NWS sites near the Columbia, South Carolina, airport (CAE) and Bush Field near Augusta, Georgia (AGS). Figure D-3 [from Weber 2001] and Table D-4 [from Weber 2001] respectively illustrate the locations of these two airports relative to SRS and summarizes the differences in measurement parameters relative to SRS.

Columbia, South Carolina, and Augusta, Georgia, lie about 90 km apart from one another in the South Carolina Piedmont, a primarily agricultural area broken by forests, streams, and small communities. The Augusta NWS station is about 30 km west-northwest of the SRS meterological station, while the Columbia NWS station is about 80 km northeast of the SRS meterological station. The terrain surrounding the Columbia NWS station more closely resembles SRS than that surrounding the Augusta NWS station, which is located near swampy terrain in the Savannah River drainage basin. Fog and calm wind conditions occur much more frequently at Augusta than at Columbia or SRS. Also, the wind direction at the Augusta NWS is influenced by "channeling" caused by the presence of the Savannah River.

Unlike the meterological data for SRS, which are obtained from a 61-meter tower (the same height as the stacks at SRS that are primarily responsible for airborne radionuclide release), the data at the Augusta and Columbia NWS stations were obtained from a 10-meter tower. The instrumentation at Augusta and Columbia was less sensitive than that at SRS, so that low wind speeds at Augusta and Columbia were more likely to be recorded as "zeros" (calms) than as actual measurements of speed and direction. In addition, the meterological data at the Augusta and Columbia NWSs were 2-minute averages at the top of each hour (or 1/30 of the weather conditions over each hour). The SRS data, however, are averaged continuously over one-hour intervals.

To illustrate the variability in meterological conditions that can occur between locations that are nominally close, wind roses for the years 1992 to 1996 are provided in Figure D-4 [from Weber 2001] for Augusta, Columbia, and SRS. These wind rose plots depict the frequency of the direction from which the

wind is blowing along with the wind speeds. As shown, the Columbia wind rose shows more frequently northerly winds than does that for SRS, although in both cases winds seem to predominately blow from either the north-through-east sectors or the south-through-west sectors. SRS winds blow more frequently from the southeast than do Columbia winds. The Augusta wind rose is more nearly symmetrical than that for either SRS or Columbia.

The authors [Weber 2001] also compared long-term average data for Augusta and Columbia NWSs. They determined that the 1948-1995 wind rose for Columbia was similar to the 1992-1996 SRS wind rose, and that the 1948-1995 wind rose for Columbia was more similar to a 1955-1961 Columbia wind rose than to the 1992-1996 Columbia wind rose. "In spite of the fact that the 1992-96 time period (as evidenced by the CAE wind rose) is not representative of the longer-term trends, it was nevertheless used to provide the basis for representing the wind direction at SRS" [Weber 2001].

Hence, the authors projected SRS meterological conditions at a 61-meter level for the years 1955 through 1961using recorded data at a 10-meter level for the 1992-1996 time period from the Columbia NWS station. They used three different statistical techniques: (1) a linear regression method, (2) a similarity theory approach, and (3) a statistical differences method. They judged the last method to give the "best" [quotes in original] statistical distribution because of its superior distribution function and lack of appreciable bias [Weber 2001].

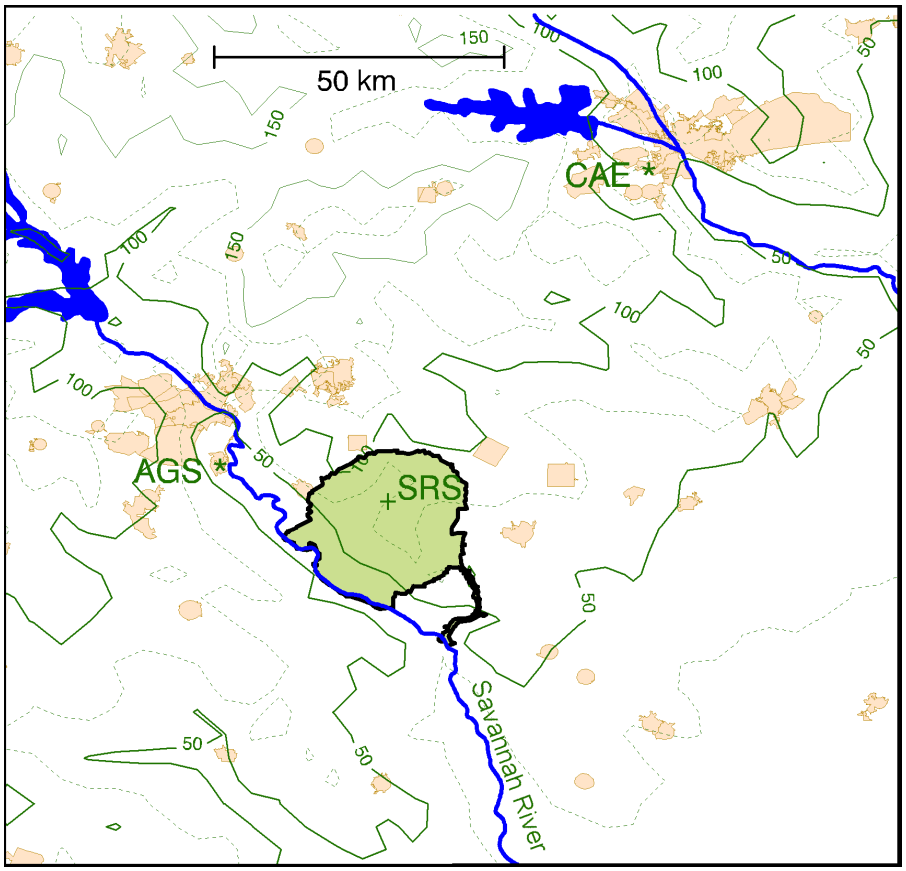

Figure D-3 Map of SRS Showing the Locations of Augusta and Columbia National Weather Service Stations[9]

[9]Adapted from [Weber 2001]. Topographic contours are 25-meter intervals above sea level, with highlighted 50- and 100-meter intervals. Lightly-shaded filled areas denote locations of cities and towns.

Table D-4 Differences Between Measurement Parameters for Augusta and Columbia National Weather Stations and for SRS

Difference	Savannah River Site	Columbia, SC NWS (CAE)	Augusta, GA NWS (AGS)
Height of Sensors	61 meters.	10 meters.	10 meters.
Instrument Sensitivity	High sensitivity.	Robust instrumentation but low sensitivity.	Robust instrumentation but low sensitivity.
Averaging Time	One hour (continuous).	Two minute "snapshots".	Two minute "snapshots".
Topographical Influences	Pine tree forest. Mostly flat within 2 km of the tower. Modest terrain changes beyond.	Airport location. Lies near partially developed suburban landscape.	Airport location. Lies at the edge of the Savannah River drainage basin.

Source: [Weber 2001].

Decision to use twenty-year averages. ATL might have used the projected metrological conditions determined in [Weber 2001] for this report. ATL did not do so, however, because it only covered the years 1955 through 1961, leaving a meterological data gap about a decade long. The scope of this study did not include preparation of this projected data. In addition, it was not apparent that use of the information from [Weber 2001] would have added add appreciably, if at all, to the accuracy of the doses calculated for this study.

Therefore, ATL decided to use SRS-specific data from the SRS meterological station to represent the entire 39 years of operation. Because joint frequency distribution data from the SRS meterological station was available only as five-year averages, ATL averaged four five-year averages to arrive at a twenty-year average.

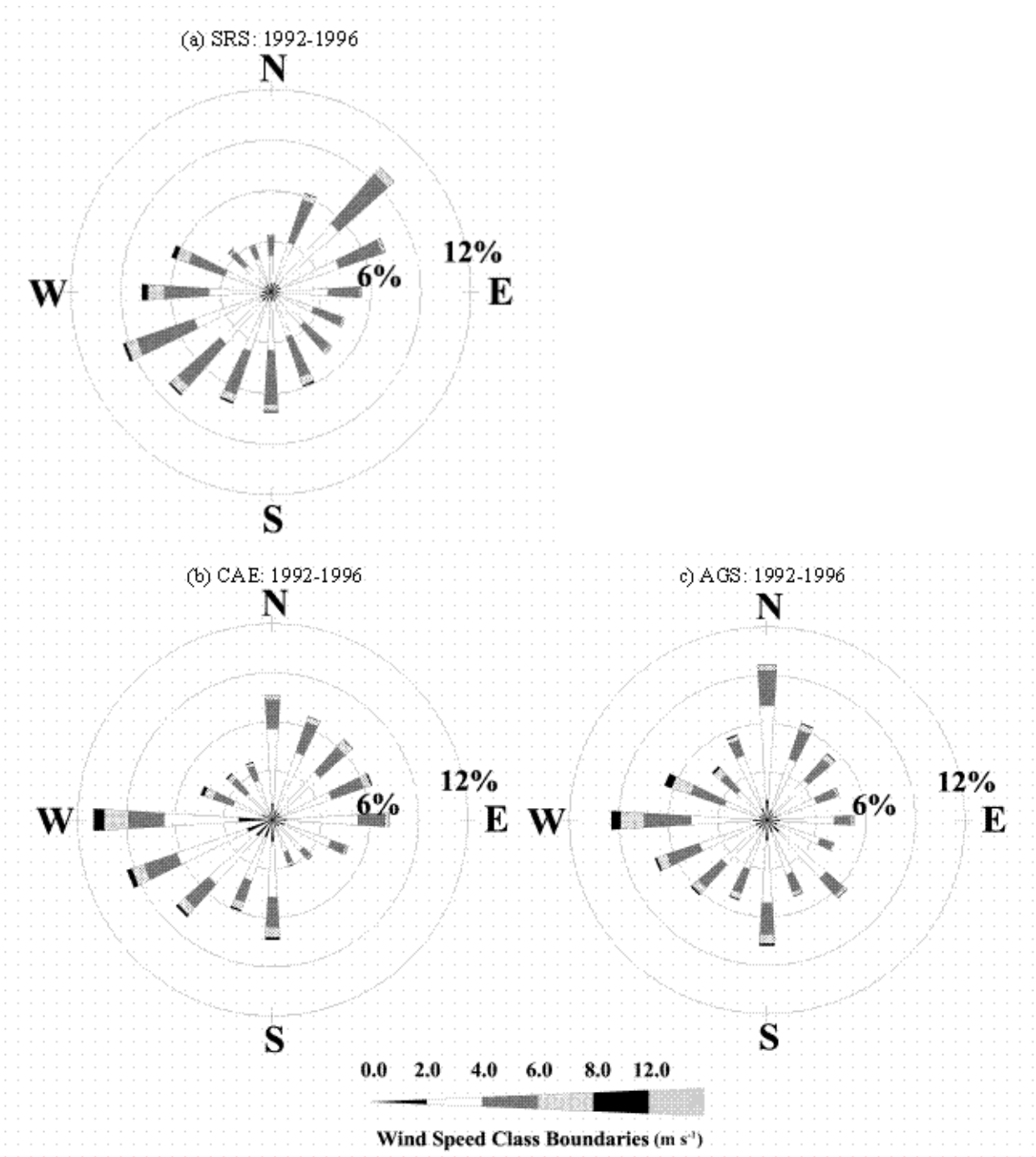

Figure D-4 1992-1996 Wind Rose Plots for SRS and the Columbia and Augusta National Weather Service Stations[10]

[10]Adapted from [Weber 2001].

D.3 Transfer and Exposure Pathways

This section presents the mathematical relationships used in GENII to model the transfer of radionuclides through air and water exposure pathways. The mathematical relationships are from Chapters 9 and 10 of the GENII SDD. This section summarizes the equations used for most radionuclides as well as those used for the behavior of tritium and ^{14}C in environmental pathways.

The general form of the equations in this section can be depicted as Figure D.5.

Given a concentration of a radionuclide in air (Ci/m^3 or Bq/m^3) or water (Ci/L or Bq/L) at an exposure location, the mathematical relationships model the movement of radionuclides through each pathway. Each relationship is composed of a set of parameters, each requiring a numerical value. To avoid a voluminous and complicated appendix, we generally defer a discussion of the assumed values for parameters that are used in the base-case GENII calculations to other appendices. Some parameters pertain to site-specific considerations such as the density of soil (see Appendix F). Others, called Usage Factors in Figure D.5, pertain to human activities that influence the uptake or exposure to radionuclides (e.g., time spent in an exposure location) and are determined in Appendix E in accordance with the exposure scenarios discussed in Appendix E.

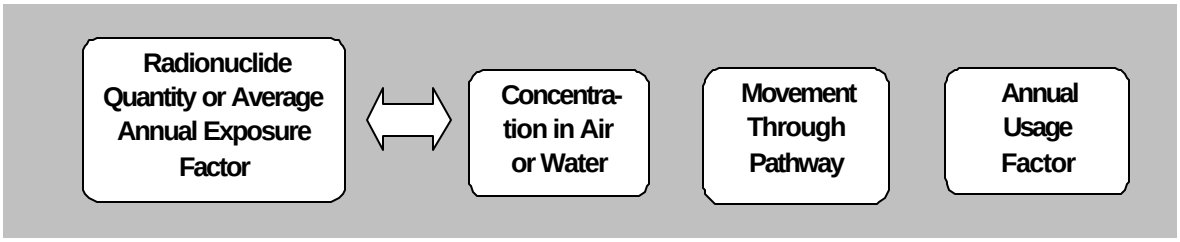

Figure D-5 Illustration of General Form of Equations in Section D.3

The GENII mathematical relationships first determine the following information:

- Annual radionuclide activity ingested (Bq in a year) for ingestion exposure pathways
- Annual radionuclide activity inhaled (Bq in a year) for inhalation exposure pathways
- Annual average exposure factor for external radiation exposure pathways. Units depend on whether exposure results from immersion in air (Bq/m^3) or water (Bq/L), or from proximity to soil or sediment (Bq/kg) or water (Bq/L).

GENII then multiplies this information by dose and risk relationships that are described in [GENII SDD] and summarized in Section D.4.

Not all exposure pathways that are considered in this report may be appropriate for a specific receptor. This situation is illustrated in Table D-5. Although all of the scenario families were exposed to radioactive material through all airborne pathways, only some of the scenario families were exposed to radioactive material through the surface water pathways. Also, the exposure of individual members of each scenario family was different depending on the member. For example, the adult female member of the Urban Family spent her entire time in Augusta, GA. The adult male member of the Urban Family spent 2000 hours a year on the SRS site and the remaining hours in Augusta.

D.3.1 Inhalation of Contaminated Air

Section D.2.1 addresses models describing the movement of radionuclides through the air pathway. The output of the model is the radionuclide concentration (Bq/m^3) at the receptor location, assuming a receptor height of 1 meter, as a function of time (e.g., average concentration over a year).

Exposure as a function of location and time is modeled as an average concentration of radionuclides in air that is inhaled over the time period of concern. The amount that is inhaled is a function of the average breathing rate, which depends on the age of the receptor.

The total amount of radioactive material that is inhaled is given as [GENII SDD]:

$$I_{aaig}(T) = C_{aag}\ U_{aag}\ T_{aag}\ ED_{aag}$$

Where $I_{aaig}(T)$ = total intake of radionuclide i from air inhalation over the period T at air usage location a for individuals in age group g (Bq)

C_{aag} = average air concentration for radionuclide i at air usage location a over time period T (Bq/m^3)

U_{aag} = inhalation rate at air usage location a for individuals in age group g (m^3/d)

T_{aag} = annual intake factor giving days per year that air inhalation occurs at air usage location a for individuals in age group g (d/y)

ED_{aag} = exposure duration for the air inhalation pathway at air usage location a for individuals in age group g (y).

Assumed parameter values for exposure times per individual, and average breathing rates as a function of age group, are provided in Appendix E.

Table D-5 Transport, Transfer, and Exposure Matrix

Transport Mechanism	Transfer Pathway or Activity	Exposure Route	Section	Rural Family One	Rural Family Two	Urban Family	Delivery Person Family	Outdoors Person Family	Family Living Near River	Migrant Family
Air (Sections D.3.1 & 3.3.2)	Plume Inhalation	Inhalation	D.3.3.1	X	X	X	X	X	X	X
	Plume Immersion	External	D.3.2	X	X	X	X	X	X	X
	Ground Contamination	External Exposure	D.3.3.2	X	X	X	X	X	X	X
		Inhalation	D.3.3.3	X	X	X	X	X	X	X
		Ingestion Soil	D.3.3.4							
	Plant and Food Concentration	Ingestion: Vegetables Fruit Grains	D.3.4.1	X	X	X	X	X	X	X
	Animal Product Concentration	Ingestion: Beef Poultry Milk Eggs	D.3.4.2	X	X	X	X	X	X	X
Surface Water (Section D.2.3)	Aquatic Accumulation	Ingestion	D.3.4.3				X	X	X	
	Concentration in Sediment	External Exposure	D.3.5				X	X	X	
	Recreational Swimming	External Exposure	D.3.6.1				X		X	
		Ingestion	D.3.6.2				X		X	
	Recreational Boating	External Exposure	D.3.6.3				X		X	

D.3.2 Immersion in Plume of Contaminated Air

External exposures from immersion in a plume of contaminated air is given as [GENII SDD]:

$I_{eaig}(T) = C_{eai}(T)\ U_{eag}\ TC_p$

$I_{eaig}(T)$ = average exposure factor over the period T for external plume immersion exposure for radionuclide i for an individual in age group g (Bq/m^3)

$C_{eai}(T)$ = average air concentration over the period T at the location of the exposed individual for radionuclide i (Bq/m^3)

U_{eag} = daily exposure factor (daily plume immersion exposure time) giving hours of plume immersion exposure per day for individuals in age group g (h/d)

TC_p = time correction set to T_{eag}/(8760 h/y) for chronic releases

T_{eag} = annual exposure factor (yearly plume exposure time) giving the number of days in a year of external plume immersion for individuals in age group g (d in a y).

Parameter values for calculating external doses from immersion in contaminated air are provided in Appendix F. Important considerations are the age of the receptor, and the duration of exposure.

D.3.3 Ground Contamination Pathways

Exposures and resulting doses arising from ground contamination pathways are addressed here and include external radiation exposures from contaminated soil, inhalation of resuspended soil, and ingestion of contaminated soil.

D.3.3.1 Contamination Buildup and Loss in Soil

To assess doses resulting from ground contamination pathways, one must first consider processes for buildup and loss of radionuclides in soil. Radionuclides accumulate in soil by wet and dry deposition from the air, and from deposition via irrigation. (However, irrigation was not considered a reasonable pathway for the scenarios defined for this report.) Radionuclides are lost by leaching from the surface soil zone, by harvesting vegetation that has taken up radionuclides from the soil, and by radioactive decay. The general model for expressing the buildup and loss of radionuclides from soil is a differential equation of the form [GENII SDD]:

$dA_i(t)/dt = (R_{bi} + R_{ai}) - (?_{Li} + ?_i)\ A_i$

Where A_i = amount of radionuclide i in the surface soil zone at time t (atoms)[11]

R_{ai} = rate of input from atmospheric depletion (wet and dry deposition) (atoms/y)

R_{bi} = rate of input from irrigation water (atoms/y)

$?_i$ = radioactive decay constant for radionuclide i (y^{-1})

$?_{Li}$ = rate constant for leaching radionuclide from the surface soil zone (y^{-1}).

This model is solved in GENII by an integrator that considers radionuclide decay chains. For chronic releases, the initial activity of radionuclide in the soil is assumed to be zero.

[11] As indicated, the basic equation as presented in the GENII SDD is given in units of atoms. The quantity of a radionuclide in soil can be converted from radioactive atoms to activity (Bq) by multiplying by the decay constant, $?_i$.

Losses from harvest are handled outside this differential equation because they occur as isolated events during the year rather than as a continuous process. Losses from harvest are subtracted from the calculated radionuclide amount via a step function at the time of harvest.

Below we discuss the deposition of radionuclides from the air, leaching from the soil zone, and loss by harvest.

D.3.3.1.1 Deposition from the Air

Accumulation from deposition from the air is determined using the calculational relationships for airborne deposition as presented in Chapter 5 of the GENII SDD and summarized in Section D.2.1.6 of this report. For chronic and essentially uniform release of radionuclides over the course of multiple years (see next paragraph), initial radionuclide concentrations in the upper surface of the soil zone are set equal to zero. In each subsequent year the soil concentrations at the end of the year are evaluated based on the concentrations present at the beginning of the year as modified by activity deposited during the year, and by activity lost considering decay and other processes. The average concentration from past years' contributions is represented by the term $C_{si}(T_{yr})$, with units of Bq/m^2. Decay evaluations are made using the GENII decay processor, which considers branching and ingrowth of radioactive chains as needed.

As implied by the above paragraph, the system used in GENII to calculate buildup over the course of several years was designed under the assumption that releases to air (and surface water), and deposition over time, are essentially constant per year. This assumption would be consistent with use of the GENII code for preoperational evaluation of a nuclear facility. In addition, the system for calculating doses and risks using GENII was designed under the assumption that the same dose and risk conversion factors would be used for each year (i.e., one assumes a constant receptor age over the time period of concern).

But GENII is being used for this project for reconstructing past doses and risks rather than evaluating the doses and risks that may result from operation of a new or existing nuclear facility. ATL considers different radionuclide release rates for each of the 39 years of operation, and also considers doses and risks to receptors as they grow up in the area, meaning that over 39 years several sets of age-specific dose and risk conversion factors may be used for each receptor as that receptor grows from an infant to an adult. To address these calculational needs, ATL linked GENII to a custom-designed pre- and post-processor. Doses and risks are calculated for each receptor according to the receptor's age group, and summed over all operational years.

To do this, ATL had to make separate GENII computations for each year of operation. Each time ATL did so, the radionuclide concentrations in the upper surface of the soil zone were set equal to zero as discussed in the first paragraph of this section. Hence, although buildup in soil, and loss through leaching from the surface soil zone, are considered over the course of a year, buildup and loss that may have taken place over all 39 years of SRS operation are not considered directly in GENII. The implications of this calculational limitation on the results of the study are addressed elsewhere.

D.3.3.1.2 Leaching from the Surface Soil Zone

Removal from surface soils through leaching into deeper soils may be addressed in GENII in three optional ways:

1. Calculate leaching using GENII default leach rates.
2. Calculate leaching using a soil removal formula.
3. Calculate leaching using user-provided leach rate constants.

For this report, leaching from the surface soil zone was calculated using the second option: a soil removal rate constant, $?_{si}$. This constant is calculated in GENII according to a general formula developed by Baes and Sharp [B&S 1981]:

$$l_{si} = \frac{10^{-2}(P + 1 - E)}{d_s q_s \left[1 + \frac{10^3 10^{-6} r_s}{q_s} Kd_{si} \right]}$$

Where $?_{si}$	=	removal rate constant for activity of radionuclide i in the surface soil layer (y^{-1})
P	=	total annual precipitation (cm/y)
I	=	total irrigation rate (cm/y)
E	=	total evapotranspiration rate (cm/y)
d_s	=	surface soil thickness (cm)
$?_s$	=	surface soil bulk density (kg/m^3)
T_s	=	surface soil volumetric water content (mL/cm^3)[12]
Kd_{si}	=	surface soil distribution coefficient for radionuclide i (mL/g)
10^{-2}	=	units correction factor (m/cm)
10^3	=	units correction factor (g/kg)
10^{-6}	=	units correction factor (m^3/ml).

In the above equation, the surface soil thickness is the average thickness of the surface soil. If the surface soil is agricultural land, the thickness should be set to represent the plow layer. And where, for this report,

The total infiltration rate is evaluated in GENII as the sum of the total annual precipitation plus the irrigation rate minus the evapotranspiration rate. It represents the quantity, (P + I – E), in the numerator of the above equation. Note that for this report, the total irrigation rate, I, is assumed to equal zero based on the scenarios defined for this report.

D.3.3.1.3 Loss by Harvest

Loss of radionuclides from the surface soil zone is modeled in GENII as a step function applied at the end of each year. The model accounts for plant concentrations at harvest, the annual plant yield, and the soil concentrations at harvest [GENII SDD]:

$C_{si}(t_+)$	=	$C_{si}(t_-)\ [\ (C_{si} - C_{ci}(Th_c)\ Y_c) / C_{si}\ ]$
Where $C_{si}(t_+)$	=	surface soil concentration at soil location s for radionuclide i after correction for harvest removal at time t (Bq/m^2)
C_{si}	=	average (over the year) value of surface soil concentration at soil location s for radionuclide i (Bq/m^2)
$C_{si}(t_-)$	=	surface soil concentration at soil location s for radionuclide i before correction for harvest removal at time t (Bq/m^2)

[12] This unit sited in the [GENII SDD] is functionally dimensionless.

$C_{ci}(Th_c)$ = Concentration of radionuclide i in crop c at time of harvest (Bq/kg)

Y_c = annual harvested yield of crop c (kg/m^2).

In the above equation, the term on the right, within the square brackets, represents the average (over a year) ratio of the contaminant in soil to that in crops. This term is used rather than a simple subtraction of amount harvested because, for short-lived radionuclides, the amount harvested over the year might be larger than the amount remaining in the soil at the end of the year.

In addition, the radionuclide concentration in each food crop considered in GENII ($C_{ci}(Th_c)$) is calculated using the relationships described in Section D.3.4.1 for ingestion of radionuclides through food crops. However, for purposes of the ground contamination pathways, the radionuclides that are ingrown into harvested food crops would be removed from the analysis. (Radionuclides ingrown into food crops are, of course, considered in the food crop ingestion analysis considered in Section D.3.4.1.) Note that GENII allows the user to consider, for purposes of harvesting, a different set of food crop growth parameters (e.g., interception fractions, standing biomass) from those considered for food crop ingestion (see Section F.4.2.1). In any event, for this study, loss through harvesting is conservatively not considered. This conservatism maximizes the concentrations of radionuclides assumed to be concentrated in the top surface of the soil.

D.3.3.2 External Radiation Exposures from Contaminated Soil

To determine exposures one must first calculate, over the year of exposure considered, average soil concentration in units of Bq/m^2. This value is then divided by the soil areal density (units of kg/m^2) to obtain an average concentration in units of Bq/kg. The general form of the equation to calculate average soil concentrations is [GENII SDD]:

$$C_{esi}\left(T_{yr}\right) = \left[C_{si}\left(T_{yr}\right) + \left[R_{ait} + R_{wit}\right] \frac{1}{l_i T_{yr}} \left[T_{yr} - \frac{1 - e^{-l_i T_{yr}}}{l_i} \right] \right] / \left(d_s r_s\right)$$

Where $C_{esi}(T_{yr})$ = average surface soil concentration (including deposition) at soil location s for radionuclide i including deposition during the year (Bq/kg)

$C_{si}(T_{yr})$ = average surface soil concentration at soil location s for radionuclide i at the start of the current year (Bq/m^2)

R_{ait} = constant deposition rate of radionuclide i from air for year t (Bq/(m^{2}y))

R_{wit} = constant deposition rate of radionuclide i from irrigation water for year t (Bq/(m^{2}y))

d_s = thickness of soil containing radionuclide contamination (m)[13]

?$_s$ = density of soil (kg/m^3)

T_{yr} = one year integration period (y).

The term on the right side of the equation, following the [R_{ait} + R_{wit}] term, represents the evaluation of the time-integral from deposition onto soil at a constant rate. Accumulation occurs over a one-year period. Division by the one-year period provides the average soil concentration during the year.

[13] For purposes of modeling for these and other exposure pathways considering deposition of radionuclides onto soil or sediment, one assumes that the radionuclides are uniformly concentrated throughout a narrow band of soil near the earth's surface (e.g., a thickness of about 15 cm (6 in), which is about the depth that a plow would penetrate soil).

The deposition rate for atmospheric (wet and dry) deposition is described in Section D.2.1.6. Deposition from irrigation is not considered (R_{wit} = 0.)

Once average soil concentrations (Bq/kg) are determined, the average exposure factor for exposure to surface-contaminated ground is calculated as [GENII SDD]:

$$I_{esig}(T) = C_{esi}(T)\, U_{esg} \left[SH_h\, FT_{hg} + SH_o\, FT_{og} \right] T_{esg}$$

Where $I_{esig}(T)$ = average exposure factor over time period T for external exposure to contaminated ground for radionuclide i for individuals in age group g (Bq/kg)

$C_{esi}(T)$ = average soil concentration at the location of individual exposure for radionuclide i for time period T (Bq/kg)

U_{esg} = daily exposure factor (daily external ground exposure time) giving hours of exposure to contaminated ground per day for individuals in age group g (h/d)

SH_h = shield factor (indoor shielding factor) for exposure to soil while inside a home (dimensionless)

FT_{hg} = fraction of time spent inside a home (indoors) for individuals in age group g (dimensionless)

SH_o = shield factor (outdoor shielding factor) for exposure to soil while outside (dimensionless)

FT_{og} = fraction of time spent outside (outdoors) for individuals in age group g (dimensionless)

T_{esg} = annual exposure factor (yearly external ground exposure time) giving external ground exposure for individuals in age group g (d).

Assumed values for U_{esg}, SH_h, FT_{hg}, SH_o, FT_{og}, and T_{esg} are provided as a function of receptor in Appendix E.

D.3.3.3 Inhalation of Resuspended Soil

GENII uses a model for inhalation exposure from resuspended radionuclides that incorporates a parameter called the resuspension factor, a factor relating the soil concentration (per unit area) to the air concentration (per unit volume), and is in units of m^{-1}. The mathematical equation for the model is [GENII SDD]:

$$C_{esi}\left(T_{yr}\right) = RF_a \left[C_{si}\left(T_{yr}\right) + \frac{R_{ait} + R_{wit}}{l_i\, T_{yr}} \left[T_{yr} - \frac{1 - e^{-l_i T_{yr}}}{l_i} \right] \right]$$

Where $C_{sai}(T_{yr})$ = air concentration of radionuclide i at soil resuspension exposure location a for a one-year period (Bq/m^3)

RF_a = resuspension factor for soil exposure location s (m^{-1})

$C_{si}(T_{yr})$ = average surface soil concentration over the current year at the soil exposure location s from material deposited in earlier years (Bq/m^2).

Other terms are as defined previously.

The resuspension factor may be estimated in more than one way. GENII offers three optional methods for doing so [GENII SDD]. The method used for this report was to input an assumed resuspension factor in units of m^{-1}.

The resuspension factor had a different value depending on the location where soil resuspension occurs. As addressed in Section F.3.1, a larger resuspension factor was assumed for locations where there was likely to be farming.

Once air concentrations are calculated, the total intake of contamination over the period of concern is given as [GENII SDD]:

$I_{saig}(T)$ = $C_{sai}(T)\ U_{sag}\ F_{sag}\ T_{sag}\ ED_{sag}$

Where $I_{saig}(T)$ = total intake of radionuclide i from resuspension inhalation over the time period T at soil usage location a for individuals in age group g (Bq)

$C_{sai}(T)$ = average concentration of radionuclide i in soil over time period T at soil usage location s (Bq/m^2)

U_{sag} = inhalation rate of air for the resuspension pathway at soil location s for individuals in age group g (m^3/d)

F_{sag} = fraction of a day that resuspension inhalation exposure occurs at soil usage location s for individuals in age group g (dimensionless)

T_{sag} = annual intake factor (resuspended soil inhalation period) giving days per year that resuspension inhalation occurs at soil usage location s for individuals in age group g (d/y)

ED_{sag} = exposure duration for the resuspension inhalation at soil usage location s for individuals in age group g (y).

The exposure duration (ED_{sag}) accounts for possible multiple years of exposure from deposition of radionuclides onto the ground during these years at a constant rate. As addressed in Section D.3.3.1, this period is set at one year because deposition is not constant from year to year, and because multiple age-specific sets of risk and dose conversion factors must be considered. Otherwise, assumed values for U_{sag}, F_{sag}, and T_{sag} are provided in Appendix E.

D.3.3.4 Inadvertent Ingestion of Soil

Inadvertent ingestion of soil is evaluated in the following manner [GENII SDD]:

$$C_{dsi}(T_{yr}) = \frac{10^3}{10^4\, r_s\, d_s}\left[C_{si}(T_{yr}) + \frac{R_{ait} + R_{wit}}{l_i T_{yr}}\left(T_{yr} - \frac{1 - e^{-l_i T_{yr}}}{l}\right)\right]$$

Where $C_{dsi}(T_{yr})$ = average concentration at soil location s for radionuclide i in soil consumed during the current year (Bq/kg)

$C_{si}(T_{yr})$ = average surface soil concentration at soil location s for radionuclide i during the current year (Bq/m^2)

?$_s$ = density of surface soil (g/cm^3)

d_s = thickness of contaminated surface soil layer (cm)

10^4 = units conversion factor (cm^2/m^2)

10^3 = units conversion factor (g/kg).

Other terms are as previously defined.

The total intake is then calculated from the average soil concentration ($C_{dsi}(T_{yr})$) as follows [GENII SDD]:

$$I_{dsig}(T) = 10^{-6}\ C_{dsi}(T)\ U_{dsg}\ T_{dsg}\ ED_{ds}$$

Where $I_{dsig}(T)$ = total intake of radionuclide i from inadvertent soil ingestion over time period T at soil usage location s for individuals in age group g (Bq)

$C_{dsi}(T)$ = average soil concentration for radionuclide i at soil usage location s for time period T (Bq/m^2)

U_{dsg} = ingestion rate for soil location s for individuals in age group g (mg/d)

T_{dsg} = annual intake factor (soil contact days) giving days per year that ingestion occurs at soil usage location s for individuals in age group g (d/y)

ED_{ds} = exposure duration for the soil ingestion pathway at soil usage location s for individuals in age group g (y)

10^{-6} = units conversion factor (mg/kg).

As above, the exposure duration (ED_{ds}) accounts for possible multiple years of exposure from deposition of radionuclides onto the ground during these years at a constant rate. As addressed in Section D.3.3.1, this period is set at one year because deposition is not constant from year to year, and because multiple age-specific sets of risk and dose conversion factors must be considered. Otherwise, assumed values for U_{dsg}, and T_{dsg} are provided in Appendix E.

D.3.4 Food-Chain Transport and Exposure

This section covers the following exposure pathways:

Section	Section Description
D.3.4.1	Ingestion of food crops contaminated with radionuclides, including deposition (surface) contamination as well as root uptake.
D.3.4.2	Ingestion of animals (e.g., livestock) and animal products (e.g., eggs) that have taken up radionuclides through consumption of contaminated forage (from deposition) or consumption of contaminated surface water.
D.3.4.3	Ingestion of contaminated aquatic foods (fish, shellfish, etc.)

These three exposure pathways model transfer of radionuclides through food pathways. The calculations are normally performed using variables generally called transfer factors that describe the ratio (at equilibrium) between contamination levels in two types of media (or environmental compartments). Some variables are partition coefficients — for example, the ratio of contamination levels in soil and in a plant that grows in soil. Other variables describe the steady state ratio between contamination levels in plant matter and contamination levels in animal products (meat, eggs, or milk) that is produced from an animal that consumes the plant matter at a unit intake rate. Still other variables characterize bioaccumulation processes, such as those for fish and shellfish..

Although a substantial body of literature exists for various transfer values, there is considerable uncertainty in any single value assigned to a transfer factor. For this reason, we discuss the selection of values for transfer factor parameters in detail, mainly in Appendix F.

D.3.4.1 Ingestion of Food Crops

This section addresses direct ingestion of crops and plants grown in contaminated soil or dusted with deposited and resuspended soil. These crops and plants include leafy vegetables, other vegetables, cereal grains, and fruit. Special models for calculation of uptake of tritium and ^{14}C in food products are also described. Similar models are used to calculate uptake by animals that are then used as food products by humans. Human ingestion of animal products, including cow's milk, beef and meat, poultry, and eggs from poultry, is considered in Section D.3.4.2

D.3.4.1.1 Radionuclide Concentration in Soil

Deposition considered for the terrestrial food pathways is the deposition that is modeled to exist at the location where the farm product is produced. This deposition is considered as an average value obtained from the output of the atmospheric transport model addressed in Section D.2. The annual average deposition is evaluated as the time integral of the deposited activity for deposition at a constant rate.

Deposition, accumulation, and loss is modeled as a differential equation of the following form [GENII SDD]:

$$\frac{d\,C_{ai}(t)}{d\,t} = R_{ait} - l_i C_{ai}(t)$$

Where $C_{ai}(t)$ = areal concentration from deposition from air to soil or plants at location a for radionuclide i as a function of time (Bq/m^2).

R_{ait} = constant deposition rate of radionuclide i from air at location a (Bq/m^2 y).

?$_i$ = radiological decay constant for radionuclide i (y^{-1}).

The atmospheric deposition rate is the sum of the dry and wet deposition rates.

The soil concentration is used when estimating root uptake to plants, as well as the resuspension and re-deposition of activity onto plant surfaces. The concentration during the year is calculated as the sum of the surface soil concentration from the soil model, $C_{si}(T_{yr})$, discussed previously. The soil concentration is addressed as follows, where the amount deposited is calculated as the time-integral of deposition over the particular annual period considered [GENII SDD]:

$$C_{ci}(T_{yr}) = C_{si}(T_{yr}) + \frac{R_{ait} + R_{wit}}{l_i\,T_{yr}}\left[T_{yr} - \frac{1-e^{-l_i T_{yr}}}{l_i}\right]$$

Where$C_{ci}(T_{yr})$ = average concentration of radionuclide i in farmland soil for crop type c during the year considered (Bq/m^2).

$C_{si}(T_{yr})$ = the average concentration during the current year of radionuclide i in surface soil in location s (where crop c is grown) for deposition from earlier years (Bq/m^2).

Other terms are as previously defined.

D.3.4.1.2 Radionuclide Concentration in Food Crops

The concentration in plants at the time of harvest is calculated as the sum of contributions from deposition onto plant surfaces, plus uptake through roots. Deposition onto plant surfaces includes deposition directly onto plant surfaces, as well as deposition from material resuspended from soil. The general form of the model is given as [GENII SDD]:

$$C_{dci}\left(T_{yr}\right)=\left[R_{aitd}\,r_{dc}+R_{aitw}r_{we}+3.15E7C_{ci}\left(T_{yr}\right)RF_{c}\,Vd_{i}\,r_{dc}+R_{wit}\,\frac{12r_{ic}}{M_{c}}\right]$$
$$\frac{T_{Vc}}{B_{c}}\left[\frac{1-e^{-l_{wi}Tg_{c}\,2.74E-3}}{l_{ei}}\right]$$

Where $C_{dci}(T_{yr})$ = concentration of radionuclide i on plant type c at harvest from deposition processes for a one-year period (Bq/kg wet weight)

T_{yr} = one-year exposure period (y)

r_{dc} = interception fraction from airborne dry deposition for plant type c (dimensionless)

r_{wc} = interception fraction for airborne wet deposition to plant type c (dimensionless)

$C_{ci}(T_{yr})$ = average concentration of radionuclide i in farmland soil for crop type c for the current one-year period (Bq/m^2)

RF_c = resuspension factor for crop soil (m^{-1})

Vd_i = deposition velocity of radionuclide i (m/s)[14]

12 = months per year

r_{ic} = interception fraction for irrigation deposition to plant type c (dimensionless), and assumed to be generally equivalent to r_{wc}

M_c = irrigation period for plant type c (month)

T_{Vc} = translocation factor for plant type c (dimensionless)

B_c = total standing biomass for plant type c (kg wet weight/m^2)

$?_e$ = $?_{wi}$ + $?_i$

$?_{wi}$ = weathering rate constant for crops for radionuclide i (y^{-1})[15]

Tg_c = crop growing period for plant type c (d)

3.15E+7 = units conversion factor (sec/y)

2.74E-3 = units conversion factor (y/d).

And where irrigation is assumed not to occur for scenarios defined for this report.

The plant concentration at harvest from root uptake is given as [GENII SDD]:

[14] In fact, however, the deposition velocity as actually used in the GENII coding is not radionuclide-specific. A value for deposition velocity must be assumed that is the same for all radionuclides.

[15] Note that the value actually input when using GENII is the weathering half-life, in days, as calculated from the relation ln2/ $?_{wi.}$ The GENII coding performs the needed conversion to $?_{wi}$ and corrects from d^{-1} to y^{-1}. In addition, the weathering rate as used in GENII is actually constant for all radionuclides.

$$C_{rci}(T_{yr}) = \frac{C_{ci}(T_{yr}) RP_{sc} Bv_{ci} f_c}{P_3}$$

Where $C_{rci}(T_{yr})$ = concentration of radionuclide i in crop type c from root uptake pathways for a one-year period (Bq/kg wet weight)

Bv_{ci} = concentration ratio for root uptake of radionuclide i in crop type c (Bq/kg dry plant per Bq/kg dry soil)

f_c = dry-to-wet ratio for plant type c (kg dry plant/kg wet plant)

P_3 = areal soil density of farmland soil (kg/m^2)

RP_3 = fraction of plant type c having roots in surface soil zone (dimensionless).

The total concentration in the plant at the time of harvest is the sum of the contribution from the deposition and root uptake pathways, or:

$$C_{hci}(T_{yr}) = C_{dci}(T_{yr}) + C_{rci}(T_{yr})$$

Where $C_{hci}(T_{yr})$ is the concentration in plant type c at harvest for a one-year period (Bq/kg wet weight). Other variables have already been defined.

D.3.4.1.3 Radioactive Decay

GENII has the capability of evaluating radionuclide decay between harvest of food crops and consumption of the crops by humans. The decay calculation is performed in GENII, considering decay chains and branching, using the decay processor described in Section D.2.1.6 of this report. For most radionuclides (those for which decay chains and branching is not a factor), the decay calculation is calculated as follows [GENII SDD]:

$C_{csi}(T_{yr})$ = $C_{hei}(T_{yr})\, e^{-\ ?i\ Thc\ 2.74E-3}$

Where $C_{csi}(T_{yr})$ = concentration of radionuclide i in crop type c at location s at the time of consumption over a one-year period (Bq/kg wet weight)

Th_c = holdup delay time between harvest and consumption for crop type c (d)

$?_i$ = radiological decay constant for radionuclide i(y-1)

2.74E-3 = Conversion factor, years per day (1 year /365 days).

D.3.4.1.4 Interception Factor and Dry-to-Wet Ratio

This factor (also called interception fraction, or retention fraction) accounts for the fact that not all material deposited from the air lands on plant surfaces. A fraction deposited from the air lands on plant surfaces, while the remaining fraction misses plant surfaces and lands on soil. GENII provides two optional methods for performing calculations using the interception fraction [GENII SDD]. ATL performed calculations using user-defined values for wet and dry interception (dimensionless). ATL's assumptions for the wet and dry interception factors, and for dry-to-wet ratios, are presented in Section F.4.2.1.

D.3.4.1.5 Resuspension Factor

The resuspension factor for crop soil (RFc) in the above equation is essentially the same resuspension factor as that described in Section D.3.3.3. RFc is in units of m^{-1} and is the ratio of the radionuclide concentration in air (Bq/m^3) to the areal concentration of radionuclides in the top soil layer (Bq/m^2). For this report, a larger resuspension factor is assumed for locations where farming is assumed to occur than for residential areas.

D.3.4.1.6 Translocation Factor and Weathering

Material deposited on plant surfaces may be absorbed into the plant or may be removed from the plant because of wind, rain, or other weathering processes. The translocation factor (T_{Vc}) is the fraction of the total deposition on plant surfaces that is incorporated into the edible parts of the plant. As a GENII default, a value of 0.1 is assumed for all vegetation except for leafy vegetables and forage crops, for which a value of unity is assumed. (The GENII user may input different assumed parameter values, however.)

Weathering is accounted for by a rate constant, $?_{wi}$, in units of $days^{-1}$, and the GENII default value for this parameter is 14 d^{-1}.

D.3.4.1.7 Tritium and ^{14}C Calculations

Concentrations of tritium and ^{14}C in soil and plants are assumed to be related to the specific activity of these radionuclides in the air or water media. *Need better words*. The fractional content of hydrogen or carbon in a plant or animal product is used to calculate the concentration of tritium or ^{14}C in the product.

Tritium. The hydrogen content in the aqueous (HTO) and dryer portions of the food products is considered when calculating tritium concentration. Also addressed is the creation of organically-bound tritium (OBT) in plant (and animal) products.

Models for tritium are different depending on whether the tritium exists as tritiated water (HTO) or as elemental hydrogen gas (HT).

The general equation for calculating concentrations of tritium as HTO in plant products (Bq per kg of fresh matter) is [GENII SDD]:

$$C_{pp_HTO} = RF_{pp}\ C_{am}\ F_{fw_pp}$$

Where C_{pp_HTO} = the concentration of HTO in the "wet" (fresh matter (fm)) portion of plant products (Bq/kg fm).

RF_{pp} = a reduction factor that accounts for low soil concentrations relative to concentrations in air moisture (varies by vegetable type) (see below)

C_{am} = the concentration of tritium as HTO in air moisture (Bq/L), which is determined by dividing the tritium concentration in air (Bq/m^3) by the absolute humidity in units of (kg or L per m^3)

F_{fw_pp} = the fresh weight fraction (the fraction of the plant having a high aqueous content), which is dimensionless and varies by plant type.

For GENII, it is assumed that the concentration of HTO in plant water equals $0.9C_{am}$ for leafy vegetables and pasture and $0.8C_{am}$ for fruit, root crops and other vegetables, and grain. (That is, RF_{pp} = 0.9 for leafy

vegetables and pasture, and RF_{pp} = 0.8 for fruit, root crops and other vegetables, and grain.) These reduction factors account for dilution from soil water, which has a lower tritium concentration than does air moisture and which affects fruit and root crops more than leaves.

The general equation for calculating concentrations of tritium as OBT in plant products (Bq per kg of fresh matter) is [GENII SDD]:

$$C_{pp_OBT} = RF_1 \; ID_{pp} \; C_{am} \; F_{dm_pp} \; W_{eq_pp}$$

Where C_{pp_OBT} = Tritium concentration existing as OBT in plant products (Bq/kg fw)

RF_1 = Reduction factor for plant leaves (0.9)

ID_{pp} = isotopic discrimination factor for plant products (0.9)

F_{dm_pp} = the dry weight fraction (the fraction of the plant have a very low aqueous content), which is dimensionless and varies by plant type.

W_{eq_pp} = water equivalent factor (dimensionless), which varies by plant type.

OBT concentrations are estimated assuming a plant water concentration of $0.9C_{am}$ for all types of plants (i.e., RF_1 = 0.9.) OBT is assumed to form exclusively in the leaves and be translocated to other parts of the plant. Isotopic discrimination occurring in the formation of OBT is conservatively assumed to result in an OBT concentration that is 0.9 times the concentration in plant water (ID_{pp} = 0.9.)

Parameter values for calculating HTO and OBT concentrations in plant products (RF_{pp}, RF_1, ID_{pp}, F_{fw_pp}, F_{dm_pp}, W_{eq_pp}) are "hard-wired" in GENII and are listed in Table D-6.

Table D-6 Parameter Values for Calculating HTO and OBT Concentrations in Plant Products

Parameter Values	Leafy Vegetables	Fruit	Root & Other Vegetables	Grain	Pasture
Reduction Factor (RF_{pp})	0.9	0.8	0.8	0.8	0.9
Reduction Factor for Leaves (RF_1)	0.9	0.9	0.9	0.9	0.9
Isotopic Discrimination Factor (ID_{pp})	0.9	0.9	0.9	0.9	0.9
Fresh Matter Fraction (F_{fw_pp})	0.906	0.853	0.824	0.117	0.8
Dry Matter Fraction (F_{dm_pp})	0.094	0.147	0.176	0.883	0.2
Water Equivalent Factor (W_{eq_pp})	0.6	0.59	0.58	0.577	0.616

Source: [GENII SDD].

Calculation of tritium as elemental gas (HT) is performed in GENII as an empirical relationship. Although elemental hydrogen is not readily taken up into vegetation, HT is slowly oxidized into tritiated water by microbes in soil. The GENII SDD references work by Peterson and Davis who determined, after numerous observations, that the ratio of HTO in air moisture to HT in air was about 8 (Bq/L)/(Bq/m^3). This led to a modification for GENII of the above model for uptake of HTO in plants, where most terms remain the same but C_{caH} is approximated as $8C_{caHT}$ H, where H in this case is the absolute humidity. Peterson and Davis also recommend that, for HT releases, the isotopic discrimination factor ID_{pp} be set to 1.0, and the reduction factor for HTO, RF_{pp}, be replaced with a supplemental factor numerically equal to 1.5 [P&D 2001]. This results in the following equation for uptake of tritium as HT in plants:

C_{pp_HT} = 1.5 (8C_{caHT}) F_{fw_pp}

= 12 C_{caHT} F_{fw_pp}

And the uptake of tritium as HT in plants as OBT is given as:

C_{pp_OBT} = RF_1 (8C_{caHT}) F_{dm_pp} W_{eq_pp}

= 8 RF_1 C_{caHT} F_{dm_pp} W_{eq_pp}

Where: $C_{pp_OBT,HT}$ = Tritium concentration existing as OBT in plant products from HT (Bq/kg fw)

RF_1 = Reduction factor for plant leaves (0.9)

F_{dm_pp} = the dry weight fraction (the fraction of the plant have a very low aqueous content), which is dimensionless and varies by plant type.

W_{eq_pp} = water equivalent factor, which is dimensionless and varies by plant type.

Carbon-14. It is assumed that plants obtain all carbon from airborne CO_2 and that animals obtain all carbon from ingestion of plants. Because plants acquire most of their carbon from the air, transfer through the root pathway is negligible. Models for ^{14}C are similar to those for tritium. The concentration of ^{14}C in crops from atmospheric contamination is [GENII SDD]:

$$C_{hcaC}(T_{yr}) = \frac{C_{aaC}(T_{yr})F_{Cc}}{P_C}$$

Where $C_{hcaC}(T_{yr})$ = concentration of ^{14}C in crop type c at harvest from atmospheric deposition at year t (Bq/kg wet weight)

$C_{aaC}(T_{yr})$ = annual average air concentration of ^{14}C at usage location a (Bq/m^3)

F_{Cc} = fraction of carbon in crop type c (dimensionless)

P_C = concentration of carbon in the air (kg/m^3).

The concentration of ^{14}C in crops from contamination in the surface soil from initial or previous depositions is calculated from the average annual soil concentration for ^{14}C, or $C_{cC}(T_{yr})$ [GENII SDD]:

$$C_{hcsC}(T_{yr}) = \frac{0.1F_{Cc}C_{sC}(T_{yr})}{0.01\,P_3}$$

Where $C_{hcsC}(T_{yr})$ = concentration of ^{14}C in crop type c at harvest from soil root uptake for one year (Bq/kg wet weight)

$C_{sC}(T_{yr})$ = average surface soil concentration at soil location s for ^{14}C during the current year from material present at the start of the year (Bq/m^2)

F_{Cc} = fraction of carbon in crop type c (kg carbon/kg plant)

P_3 = areal soil density of farmland soil (kg/m^2)

0.1 = assumed uptake of 10% of plant carbon from soil (dimensionless)

0.01 = average fraction of soil that is carbon (kg carbon/kg soil).

The total concentration in food crops is evaluated as the sum of the contributions from air, water, and soil, or:

$C_{hcC}(T_{yr}) = C_{hcaC}(T_{yr}) + C_{hewC}(T_{yr}) + C_{hcsC}(T_{yr})$

Where $C_{hcC}(T_{yr})$ = concentration of ^{14}C in crop type c at harvest for one year (Bq/kg wet weight).

$C_{hewC}(T_{yr})$ = concentration of ^{14}C in crop type c at harvest from irrigation for one year (Bq/kg/wet weight) (assumed to be zero).

Other terms are defined above. No decay is considered between harvest and consumption of crops containing ^{14}C because the radiological half-life of ^{14}C is long.

D.3.4.1.8 Ingestion of Radioactive Material

Ingestion of radioactive material is considered in GENII for leafy vegetables, other vegetables, cereal grains, and fruit. Given an average radionuclide concentration ($C_{csi}(T)$) in food products, the quantity of a given radionuclide ingested over a given time period is calculated as [GENII SDD]:

$I_{csig}(T) = C_{csi}(T)\ U_{csg}\ T_{csg}\ ED_{csg}$

Where $I_{csig}(T)$ = total intake of radionuclide i in food crop c over the period T from ingestion at agricultural location s for individuals in age group g (Bq)

$C_{csi}(T)$ = average concentration in food crop c at agricultural location s for radionuclide i (Bq/kg)

U_{csg} = ingestion rate (food crop consumption rate) of food crop c at agricultural location s by an individual in age group g (kg/d)

T_{csg} = annual intake factor (food crop consumption period) giving the days per year that food crop c is eaten (at the average rate) at agricultural location s by individuals in age group g (d/y)

ED_{csg} = exposure duration for consumption of food crop c at agricultural location s for individuals in age group g (y).

The exposure duration (ED_{csg}) is the number of years that exposure occurs, which for this study is assumed to be one year.[16] Assumed parameter values for the ingestion rate and annual intake factor are provided in Appendix E.

D.3.4.2 Ingestion of Animals and Animal Products

Pathways describing the transfer of radionuclides to humans from animals and animal products generally start with calculations such as those described in Section D.3.4.1, except that transfer factors for forage crops are used, as well as consumption rates and other parameters that are appropriate for the animal. Then, animal-to-human transfer is considered assuming animal products that are characteristic of the area as well as typical rates of consumption.

D.3.4.2.1 Radionuclide Concentration in Animals and Animal Products

Basic equation. The basic radionuclide concentration in a given animal product as determined at the time of harvest (slaughter, milking, egg collection) is [GENII SDD]:

[16] Because the annual quantity of each radionuclide ingested may be different from year to year, ATL recalculates radionuclide ingestion for each year for each receptor rather than assuming ingestion of a uniform radionuclide quantity over several years.

$$C_{hai}(T_{yr}) = Fa_i \left[C_{wi}(T_{yr}) d_{aw} U_{ae} + C_{ai}(T_{yr}) d_{as} U_{as} + \sum_{f-1}^{N_{af}} C_{cfi}(T_{yr}) d_{af} U_{af} \right]$$

$C_{hai}(T_{yr})$	=	concentration of radionuclide i in animal product a at harvest of the animal product for a one-year period (Bq/kg)
T_{yr}	=	one-year exposure period (y)
Fa_i	=	transfer coefficient that relates daily intake rate by an animal to the concentration in an edible animal product a (Bq/L milk per Bq/d for milk, and Bq/kg meat per Bq/d for meat)
$C_{wi}(T_{yr})$	=	average concentration of radionuclide i in water consumed by animals for a year (Bq/L)
$C_{ai}(T_{yr})$	=	average concentration of radionuclide i in soil consumed by animals for a year (Bq/kg dry soil)
$C_{cfi}(Tyr)$	=	concentration of radionuclide i in animal feed type f at the time of consumption for a one-year period (Bq/kg wet weight)
d_{aw}	=	fraction of animal type a water intake that is contaminated (dimensionless)
U_{aw}	=	daily water intake rate for animal type a (L/d)
d_{as}	=	fraction of animal type a soil intake that is contaminated (dimensionless)
U_{as}	=	daily soil intake rate for animal type a (kg/d)[17]
N_{af}	=	number of feed types, f, fed to animal type a
d_{af}	=	fraction of animal type a feed type f intake that is contaminated (dimensionless)
U_{af}	=	daily feed intake rate for animal type a of feed type f (kg/d).

Where animal uptake of contaminated water is not considered for the scenarios defined for this report. Other terms have been already defined.

D.3.4.2.2 Radioactive Decay

GENII has the capability of considering two periods of radioactive decay for human ingestion of animals and animal products: (1) radioactive decay between harvesting and animal consumption of animal feed and forage, and (2) radioactive decay between animal or animal product harvest (e.g., animal slaughter, collection of eggs) and consumption of the animal or animal product by humans.

The first period of radioactive decay is addressed in GENII as explained in Section D.3.4.1.3, except that the calculation is performed for animal feed and forage rather than food crops. Note that different holdup (delay) times may be appropriate for animal feed and forage than would be the case for food crops.

The second period of radioactive decay is again addressed in GENII using the GENII decay processor. For most radionuclides (those for which decay chains and branching is not a factor), the decay calculation is calculated as follows [GENII SDD]:

[17] Inadvertent soil ingestion by animals is not at this time considered in GENII. Although the equation is coded into GENII including the inadvertent soil ingestion pathway, the user interface does not request input of any values for the animal soil ingestion rate, and the GENII variable (SLCONA) for this parameter is set to zero [Napier 2003e].

$C_{asi}(T_{yr})$ = $C_{hai}(T_{yr})\, e^{-\ ?i\ Tha\ 2.74E-3}$

Where $C_{asi}(T_{yr})$ = concentration of radionuclide i in animal product a at usage location s at the time of consumption over a one-year period (Bq/kg wet weight)

Th_a = holdup delay time between harvest and consumption for animal product a (d)

$?_i$ = radiological decay constant for radionuclide i (y^{-1})

2.74E-3 = Conversion factor, years per day (1 year /365 days).

D.3.4.2.3 Tritium and ^{14}C Calculations

Tritium. HTO concentrations in animals are assumed to equal the average weighted tritium concentration of ingested water based on the fraction of water supplied by each source, including skin absorption, inhalation, drinking water, and food (from plant water and digested organically bound molecules).

Concentrations of tritium as HTO in animal products are calculated as [GENII SDD]:

$$C_{HTOap}(T_{yr}) = F_{Wa} \frac{C_{wH}(T_{yr}) U_{wa}\, d_{aw} + \sum_{f=1}^{N_{fa}} C_{cfH}(T_{yr}) U_{af}\, d_{af}}{U_{wa} + \sum_{f=1}^{N_{fa}} F_{fw_pp} RF_{pp} U_{af}}$$

Where:

$C_{HTOap}(T_{yr})$ = concentration of tritiated water in animal product a at time of consumption by humans over a one-year period (Bq/kg)

F_{Wa} = fraction of water in animal product a (dimensionless)

$C_{wH}(T_{yr})$ = average concentration of tritium in water consumed by animal type a over a one-year period (Bq/L)

U_{aw} = daily water intake rate for animal type a (L/d)

d_{aw} = fraction of animal type a water intake that is contaminated (dimensionless)

$C_{cfH}(T_{yr})$ = concentration of tritium, calculated as the sum of the water and organic portions (see above), in animal feed type f at the time of consumption for a one-year period (Bq/kg wet weight)

U_{af} = daily intake rate for animal type a of feed type f (kg/d)

d_{af} = fraction of animal type a feed type f intake that is contaminated (dimensionless)

N_{fa} = number of feed crops eaten by animal type a.

Other constants are previously defined. Tritium (as HTO) concentrations in animal feed is evaluated using the above equations with values defined for the animal feed crops.

Regarding tritium as OBT, the relationship used to calculate concentrations in animal products was created under the assumption that the specific activity in organic material equals the specific activity in the aqueous phase apart from a discrimination factor. It is given, after the derivation of Peterson and Davis [P&D 2001] as:

$$C_{ap_OBT} = C_{ap_HTO} F_{dm_ap} / F_{fw_ap} W_{eq_ap}$$

Default values for the parameters needed for the above equations (9.30a and 9.30b) are listed in Table D-7.

Table D-7 Parameter Values for Calculating HTO and OBT Concentrations in Animal Products

Parameter Values	Eggs	Milk	Beef	Pork	Poultry
Fresh Weight Fraction (F_{fw_ap})	0.74	0.897	0.668	0.50	0.67
Dry Matter Fraction (F_{dm_ap})	0.26	0.103	0.332	0.50	0.33
Water Equivalent Factor (W_{eq_ap})	0.835	0.669	0.795	0.904	0.796

Source: [GENII SDD].

Carbon-14. GENII calculates the concentration of ^{14}C in animal products as [GENII SDD]:

$$C_{caC}(t) = F_{Ca} \frac{\sum_{f=1}^{N_{fi}} C_{efC} U_{af} d_{af}}{\sum_{f=1}^{N_{fi}} F_{Ca} U_{af}}$$

Where $C_{caC}(T_{yr})$ = concentration of ^{14}C in animal product a at time of consumption by humans (Bq/kg)

F_{Ca} = fraction of carbon in animal product a (dimensionless)

$C_{efC}(T_{yr})$ = concentration of ^{14}C in animal feed type f at time of consumption for a year (Bq/kg wet weight)

U_{af} = daily feed intake rate for animal type a of feed type f (kg/d)

d_{af} = fraction of animal type a feed type f intake that is contaminated (dimensionless)

F_{Cf} = fraction of carbon in animal feed type f (dimensionless)

N_{fa} = number of feed crops eaten by animal type a.

D.3.4.2.4 Ingestion of radioactive Material

Once average concentrations of radionuclides in animal products are determined, the quantity of radioactive material ingested over a given period of time is [GENII SDD]:

$I_{asig}(T)$ = $C_{asi}(T)$ U_{asg} T_{asg} ED_{asg}

Where $I_{asig}(T)$ = total intake of radionuclide i in animal product a over the period T from ingestion at agricultural location s for individuals in age group g (Bq)

$C_{asi}(T)$ = average concentration in animal product a at agricultural location s for radionuclide i (Bq/kg)

U_{asg} = ingestion rate (animal product consumption rate) of animal product a at agricultural location s by an individual in age group g (kg per day on the days that the food is eaten)

T_{asg} = annual intake factor (animal product consumption period) giving the number of days

per year that animal product a is eaten (at the average rate) at agricultural location s by individuals in age group g (d/y)

ED_{asg} = exposure duration for consumption of animal product a at agricultural location s for individuals in age group g (y).

As for ingestion of food crops, the exposure duration (ED_{asg}) is assumed to be one year. Assumed values for the ingestion rate and annual intake factor are provided for each receptor in Appendix E.

D.3.4.3 Aquatic Food Ingestion

Fish, crustaceans, mollusks, and other possible aquatic food products may become contaminated with radionuclides and cause radiation doses to humans when food products are consumed.

D.3.4.3.1 Radionuclide Concentration in Aquatic Foods

The radionuclide concentration in a particular type of aquatic food is given as the radionuclide concentration in water multiplied by a bioaccumulation factor. The basic equation to describe accumulation is [GENII SDD]:

$C_{hqi}(T_{yr})$ = $C_{wi}(T_{yr})\ B_{qi}$

Where $C_{hqi}(T_{yr})$ = concentration of radionuclide i in aquatic food type q at the time of harvest (Bq/kg).

$C_{wi}(T_{yr})$ = average concentration of radionuclide i in water over the year.

B_{qi} = bioaccumulation factor for radionuclide i in aquatic food type q (Bq/kg in wet fish per Bq/L of water).

D.3.4.3.2 Radioactive Decay

Radionuclide concentrations in aquatic food products may be reduced by means of radioactive decay between food product harvesting and food product consumption. Radioactive decay is accounted for using the GENII decay processor in a similar manner as that for food crops and animal products. For most radionuclides (those without decay chains or branching), radioactive decay is considered in the following manner [GENII SDD]:

$C_{fwi}(T_{yr})$ = $C_{hqi}(T_{yr})\ e^{-\ ?i\ Tha\ 2.74E-3}$

Where $C_{fwi}(T_{yr})$ = concentration of radionuclide i in aquatic food type q at water location w at the time of consumption over a one-year period (Bq/kg wet weight)

Th_a = holdup delay time between harvest and consumption of aquatic food type q (d)

$?_i$ = radiological decay constant for radionuclide i (y^{-1})

2.74E-3 = Conversion factor, years per day (1 year /365 days).

D.3.4.3.3 Ingestion of Radioactive Material

Once the concentration of a radionuclide in aquatic food products are calculated (fish, mollusks, invertebrates, and water plants), the radionuclide quantity (Bq) ingested is calculated as [GENII SDD]:

$I_{fwig}(T)$ = $C_{fwi}(T)\ U_{fwg}\ T_{fwg}\ ED_{fwg}$

Where $I_{fwig}(T)$ = total intake of radionuclide i from ingestion of aquatic food f over the period T at aquatic food location w for individuals in age group g (Bq)

$C_{fwi}(T)$ = average concentration in aquatic food f at aquatic food location w for radionuclide i (Bq/kg)

U_{fwg} = ingestion rate (aquatic food product consumption rate) of aquatic food f at aquatic food location w by an individual in age group g (kg per day on the days that the food is eaten)

T_{fwg} = annual intake factor (aquatic food product consumption period) giving the days per year that aquatic food f is eaten (at the average rate) at aquatic food location w by individuals in age group g (d/y)

ED_{fwg} = exposure duration for consumption of aquatic food f at aquatic food location w for individuals in age group g (y).

The exposure duration (ED_{fwg}) in this equation is assumed in this report to be one year. Assumed values for the ingestion rate and annual intake factor are provided as a function of receptor in Appendix E.

D.3.5 Sedimentation Pathways

Individuals involved in sun bathing, fishing, or other recreational shoreline activities along contaminated surface water may be exposed to radiation from radionuclides that have built up over the years in sediment. The build up over time is evaluated as an integral that considers the deposition of radionuclides from the water. The concentration in sediment built up over a single year is [GENII SDD]:

$$C_{sri}(T_{yr}) = \frac{TC\, C_{ri}(T_{yr})\left(1 - e^{-l_i T_{yr}}\right)}{l_i}$$

Where $C_{sri}(T_{yr})$ = concentration of radionuclide i in sediment after one year of accumulation from deposition on the shoreline at recreational water usage location r (Bq/m^2)

TC = transfer rate constant from water to sediment (L/m^2/y)

$C_{ri}(T_{yr})$ = average (constant) annual water concentration for radionuclide i at recreational water usage location r (Bq/L)

T_{yr} = one-year integrating period for deposition to sediments (y).

The concentration over several years would be determined by integrating over the appropriate time period (say five years), considering the average concentration in the water over that time period.

In the above equation, the transfer rate constant (TC) is a parameter that describes the transfer of radionuclides to sediment (Bq/m^2) from water (Bq/L) during a year (L/m^2/y). In GENII, a transfer rate constant of 35,400 L/m^2/y is used, a value chosen from consideration of data obtained for several radionuclides that compared concentrations in river water and sediment. River and sediment samples were obtained from the Columbia River between Richland, Washington, and the river mouth, and from Tillamock Bay, Oregon, 75 km south of the river mouth [GENII SDD].

The exposure to an individual in any year is the time-integral of the shoreline sediment concentration during that year, considering the amount of time spent on the shoreline. The average concentration (Bq per kg of sediment) is determined using a model of the following form [GENII SDD]:

$$C_{sri}(T_{yr}) = \int_0^{T_{yr}} C_{sri}(t)dt / (T_{yr}\, d_{ed}\, r_{sed})$$

Where $C_{sri}(T_{yr})$ = shoreline sediment time integral of exposure for radionuclide i evaluated at the recreational usage location r (Bq/kg)

d_{ed} = thickness of shoreline sediments (m)

$?_{sed}$ = density of shoreline sediments (kg/m^3)

T_{yr} = one-year exposure period (y).

In this case, the concentration within the integral is integrated over a one-year period starting from the total concentration in sediment at the beginning of the year. For example, if one wishes to evaluate the exposure during the 6th year of operations for a given radionuclide, one would calculate the total average radionuclide concentration over the year considering the concentration that had built up over the previous five years, as well as the concentration as enhanced in sediment over the course of the 6th year.

In addition, neither D_{sed} nor $?_{sed}$ is input into the GENII calculations. Rather, to use GENII one inputs the shoreline areal density, in units of kg/m^2, which is the product of D_{sed} with $?_{sed}$ (see Section F.5).

Recreational shoreline exposures are then calculated using the average radionuclide concentration in shoreline sediment as [GENII SDD]:

$I_{srig}(T)$ = $C_{sri}(T)\ SW_r\ FE_{srg}\ TE_{srg}\ T_{srg}$

$I_{srig}(T)$ = average exposure factor over the period T for radionuclide i from shoreline exposure at recreational shoreline location r for individuals in age group g (Bq/kg)

C_{sri} = average shoreline sediment concentration of radionuclide i at recreational shoreline location r (Bq/kg)

SW_r = shoreline width factor for recreational shoreline location r (dimensionless)

FE_{srg} = shoreline use event frequency (frequency of shoreline use) at recreational shoreline location r for individuals in age group g (events/d)

TE_{srg} = duration of each shoreline exposure event at recreational shoreline location r for individuals in age group g (h/event)

T_{srg} = annual exposure factor (shoreline days) for shoreline exposure at recreational shoreline location r for individuals in age group g (number of days in a year that the shoreline exposure location is visited).

The annual exposure factor for shoreline exposure, T_{srg}, is assumed to be 365 days for chronic exposures, which is the situation considered for this report. The daily exposure factor is the product of the event frequency, FE_{srg}, and the event duration, TE_{srg}. Assumed values for these parameters, and for T_{srg}, are provided as a function of receptor in Appendix E. The shoreline width factor (SW_r) is assumed to be 0.2 for the base case evaluation (see Section F.5).

D.3.6 Recreational Exposures from Surface Water Pathways

Recreational exposures to contaminated water are considered for two cases: swimming and boating. Exposure pathways considered for swimming include immersion in a contaminated plume of water, and inadvertent ingestion of small quantities of water. The exposure pathway considered for boating is

external exposure to a volume-contaminated source. The starting point for all pathways is the concentrations of radionuclides in water, given as Bq/L.

D.3.6.1 External Exposure From Immersion in Water (Swimming)

Recreational swimming exposures are calculated in GENII as [GENII SDD]:

$I_{wrig}(T) = C_{wri}(T)\ FE_{wrg}\ TE_{wrg}\ T_{Cs}$

$I_{wrig}(T)$ = average exposure factor over time period T for radionuclide i from swimming at recreational swimming location r for individuals in age group g (Bq/L)

$C_{wri}(T)$ = average water concentration over time period T for radionuclide i in surface water at recreational swimming location r (Bq/L)

FE_{wrg} = frequency of swimming events at recreational swimming location r for individuals in age group g (events per day on the days when swimming occurs)

Tc_s = time correction set to T_{wrg}/8760 h/y for chronic releases

TE_{wrg} = duration of an average swimming event at recreational swimming location r for individuals in age group g (h/event)

T_{wrg} = annual exposure factor (swimming days) for swimming at recreational swimming location r for individuals in age group g (number of days in a year that swimming occurs).[18]

Here, the daily exposure factor is the product of the event frequency, FE_{wrg}, and the event duration, TE_{wrg}. Assumed parameter values for FE_{wrg}, TE_{wrg}, and T_{wrg} are provided in Appendix E as a function of receptor.

D.3.6.2 Ingestion of Surface Water While Swimming

Inadvertent consumption of surface water while swimming is calculated as [GENII SDD]:

$I_{wwig}(T) = C_{wri}(T)\ FE_{wrg}\ TE_{wrg}\ T_{Cs}\ U_{swg}$

$I_{wwig}(T)$ = average exposure factor over time period T for radionuclide i from ingestion at swimming location w for individuals in age group g (Bq)

$C_{wri}(T)$ = average water concentration over time period T for radionuclide I in surface water at the recreational swimming location r (Bq/L)

FE_{wrg} = frequency of swimming events at water use location r for individuals in age group g (events/d

TE_{wrg} = duration of an average swimming event at water use location r for individuals in age group g (h/event)

T_{Cs} = time correction, set equal to T_{wrg}/8760 h/y for chronic releases

T_{wrg} = annual exposure factor (swimming days) for swimming at water use location r for individuals in age group g (number of days in a year that swimming occurs)

U_{wwg} = uptake rate of water while swimming (ingestion rate of water while swimming) for age group g (L during an hour of swimming).[19]

[18] On each of the days it is assumed for purposes of the GENII calculations that the individual swims the number of times specified by the frequency of swimming event and for the duration of swimming event for each of these events.

Here, the daily exposure factor is the product of the event frequency, FE_{wrg}, and the event duration, TE_{wrg}, in units of h/d. The ingestion rate of water while swimming (U_{wwg}) is provided in Appendix E as a function of receptor. Otherwise, one assumes the same usage factors (FE_{wrg}, TE_{wrg}, and T_{wrg}) as those used to calculate direct radiation exposure while swimming (Section D.3.6.2).

D.3.6.3 External Exposure While Boating

Exposure of humans during recreational boating may be calculated as [GENII SDD]:

$$I_{brig}(T) = C_{bri}(T)\ SB\ FE_{brg}\ TE_{brg}\ T_{Cb}$$

$I_{brig}(T)$ = average exposure factor over time period T for radionuclide I from boating at recreational boating location r for individuals in age group g (Bq/L)

$C_{bri}(T)$ = average water concentration of radionuclide i at recreational boating location r (Bq/L)

SB = shielding factor for boating exposures (dimensionless)[20]

FE_{brg} = average frequency of daily boating events at recreational boating location r for individuals in age group g (events/d)

TE_{brg} = duration of an average boating event at recreational boating location r for individuals in age group g (h/event)

T_{Cb} = time correction set equal to T_{brg}/8760 h/y for chronic releases

T_{brg} = annual exposure factor (boating days) for boating at recreational boating location r for individuals in age group g (number of days in a year that boating occurs).[21]

Here, the daily exposure factor is the product of the event frequency, FE_{brg}, and the event duration TE_{bgr}, in units of h/d. Assumed values for SB, Fe_{brg}, Te_{brg}, and T_{brg} are provided as a function of receptor in Appendix E. The shielding factor for boating exposures (SB) is assumed to be 0.5 as addressed in Section F.6.

D.4 Dose and Risk Principles

Additional information about radiation assessment and protection principles, and terminology, can be obtained from Internet sites on radiation established by EPA (http://www.epa.gov/radiation) and the University of Michigan (http://www.umich.edu/~nradinfo).

D.4.1 Types of Radiation

Decaying radionuclides such as those considered for this portion of the SRS Dose Reconstruction Study can each emit up to three basic types of ionizing radiation:

- *Alpha particles*: These particles are essentially the nuclei of helium atoms. Each particle contains two protons and two neutrons. Because of their relatively large size, alpha particles lose energy quickly as

[19] Despite the terminology used by the GENII SDD and the documentation for the FRAMES interface, this parameter is used as a quantity rather than a rate.

[20] The shielding factor for boating accounts for the shielding to direct radiation that may be provided by the structure of the boat. It is different from the geometry factor, which accounts for the location of the receptor above the surface of the water (rather than being immersed in the water). The geometry factor is assumed by the GENII authors to be a factor of 2 reduction, and is incorporated into the dose and risk equations for boating exposures that are addressed in Section D.4.3.

[21] During each of the boating days, the individual is assumed for purposes of the GENII calculations to be involved in the number of events given by the frequency of boating events with each event lasting for the duration of boating events hours.

they collide with matter. They will not penetrate human skin. Therefore, human skin can be impacted by alpha particles (i.e., the human receives an *external exposure* to alpha particles) without harm. However, alpha particles can damage cells within the human body if they are taken into the body by breathing or by swallowing. In this case, a human receives *internal exposure* to alpha particles.

- *Beta particles*: These particles are electrons identical to those that surround the nuclei of atoms. They are much smaller than alpha particles and can penetrate up to a few centimeters of water or human flesh. Therefore, both external and internal exposure to beta particles can damage human cells.
- *Gamma rays and X-rays*: These rays are forms of electromagnetic energy. (Ordinary light is another form of electromagnetic energy, as are microwaves and radio waves). Gamma rays and X-rays are virtually identical except that gamma rays tend to have more energy and are emitted by atomic nuclei, while X-rays tend to have less energy and are emitted from the electrons surrounding atomic nuclei. Gamma rays and X-rays have considerable penetrating power. Both external and internal exposure to gamma rays and X-rays can damage human cells.

Ionizing radiation damages cells by imparting energy to the cells. Energy absorbed by the cells can break chemical bonds, among other impacts.

D.4.2 Radiation Dose

To estimate the effects of radiation on human (or other) tissue, one must estimate the *dose* that the human receives. A radiation dose is a measure of the amount of energy imparted to tissue (absorbed) by the radiation. However, a strict calculation of the *absorbed dose* —e.g., in units of joules of energy absorbed by a kilogramof tissue (J/kg)—is insufficient. Different particles of radiation —alpha, beta, gamma— impart energy to tissue in different ways. One accounts for these differences through the concept of an *equivalent dose*,[22] which may be considered as:

$$H = D\ W_R$$

Where H = equivalent dose (Sievert)

D = absorbed dose (Gray)[23]

W_R = weighting factor (dimensionless)

The unit of equivalent dose, called the *Sievert* (Sv), is therefore defined as:

1 Sievert = 1 J/kg = 100 rem, and

1 milliSievert (mSv) = 1/1000 Sv = 100 millirem (mrem)

Where a "*rem*," or "Roentgen equivalent man," is a dose unit commonly used in the United States, and, as indicated, is one one-hundredth of a Sievert. A *millirem* (mrem) is one one-thousandth of a rem.

The weighting factor[24] accounts for differences in how energy is imparted to tissue by different types of radiation. X-rays, gamma rays, and beta particles are generally assigned weighting factors of one, while alpha particles are generally assigned weighting factors of twenty.

One difficulty of estimating radiation doses to humans is that human bodies are variable. To achieve agreement on standards for radiation protection, and to help comparisons of different radiation dose assessments, a concept was developed called a *standard man*, a surrogate human having organs of both

[22] Except where noted, ICRP-60 terminology is used in this chapter.
[23] A *Gray* is a unit of absorbed dose equal to 1 Joule/kilogram (1 J/kg).
[24] In ICRP-60 and other ICRP recommendations preceding ICRP-60, a weighting factor was called a quality factor.

sexes of reference radii and masses. Risk assessments are commonly performed using these standard physiological assumptions.

Doses from internal exposures, such as those from inhalation or ingestion of radioactive material, are determined using models describing the movement and retention of the material in the body. Some radionuclides may build up in the body as a person inhales or ingests the radionuclides year after year. A radionuclide retained in the body will impart a dose to a person not only for the first year of intake, but in following years until the radionuclide decays or is eliminated. This phenomenon causes a *committed dose.* It may be considered as:

$$H_C = ? \; H(t)\, dt$$

Where H_C = committed equivalent dose (Sv)

$H(t)$ = equivalent dose rate (Sv/y)

And the integral is evaluated over a specified period of time.[25]

At one time, the usual practice was to calculate doses to individual bodily organs or tissues. But in 1977, the ICRP recommended in ICRP-26 the concept of a weighted mean whole-body dose [ICRP-26]. It provides a measure of the dose across multiple organs or tissues, and is determined by multiplying the dose received by each organ or tissue by a weighting factor, and then adding all of these weighted doses to arrive at a single representative dose. ICRP originally called this dose an *effective dose equivalent* [ICRP-26]. In a more recent recommendation (ICRP-60, issued in 1991), ICRP called this dose an *effective dose*. It may be considered as:

$$H_E = S_T \, W_T \, H_T$$

Where H_E = effective dose (Sv)

W_T = a weighting factor representing the ratio of the stochastic risk from irradiation of tissue T to that for the whole body when irradiated uniformly.

H_T = equivalent dose in tissue T.

Values for tissue weighting factors recommended by ICRP in 1977 [ICRP-26] and 1991 [ICRP-60] are listed in Table D-8. The weighting factors recommended in ICRP-60 are different from those recommended in ICRP-26.[26]

The concept of effective dose is used for doses resulting from both external and internal exposures. To calculate committed effective dose from internal exposures, ICRP in ICRP-60 recommended using an integration time of 50 years following intake for assessments of occupational dose, and 70 years for members of the public.

[25] ICRP-26 recommended a 50-year time period for members of the public as well as radiation workers. ICRP-60 recommends a 70-year time period for members of the public and a 50-year time period for radiation workers.

[26] These weighting factors were calculated under somewhat different assumptions. ICRP-26 weighting factors are based on the risk of fatal cancers and hereditary defects in the first two generations. ICRP-60 weighting factors are based on risks for both fatal and non-fatal cancers, the risk of hereditary defects over all future generations, and the relative loss of live expectancy given a fatal cancer or a severe generic disorder.

Table D-8 ICRP-26 and ICRP-60 Tissue Weighting Factors

Organ or Tissue	ICRP-26 Weighting Factors	ICRP-60 Weighting Factors
Gonads	0.25	0.20
Breast	0.15	0.05
Colon		0.12
Red bond Marrow	0.12	0.12
Lungs	0.12	0.12
Stomach		0.12
Urinary Bladder		0.05
Liver		0.05
Esophagus		0.05
Thyroid	0.03	0.05
Bone Surface	0.03	0.01
Skin		0.01
Remainder	0.30*	0.05[†,‡]

*The value 0.30 is applied to the average dose among the five remaining organs or tissues receiving the entire dose, excluding the skin, lens of the eye, and the extremities.
[†]The reminder consists of: adrenals, brain, small intestine, upper large intestine, kidney, muscle, pancreas, spleen, thymus, and uterus.
[‡]The value 0.05 is applied to the average dose to the remainder tissue group. However, if a member of the remainder receives a dose exceeding the highest dose in any of the 12 organs for which weighting factors are specified, a weighting factor of 0.025 is applied to that organ and weighting factor of 0.025 is applied to the average dose to the rest of the remainder.

D.4.3 Risk from Radiation Exposure

Ionizing radiation was first discovered and used in the last years of the 19th Century. The most urgent need was to avoid exposures causing immediate or near-term effects on the health of individuals. These health effects were seen after individuals had received very large exposures above a *threshold* of received radiation. Below the threshold the health effects did not occur, and above it the severity of the health effects increased. These *nonstochastic* effects were avoided by limiting exposures to levels below the threshold.[27]

Scientists and health providers later observed that exposure to radiation might lead to delayed health effects, either to exposed individuals (called *somatic* effects) or to descendents (called *genetic* effects). These effects are called *stochastic* effects, because they occur with given frequencies in populations receiving radiation exposures rather than predictably to an exposed individual. The severity of stochastic effects, including cancer and hereditary effects, is not related to the level of exposure.

From these observations came the development of procedures for estimating the risks of negative health effects that may occur from exposure to ionizing radiation. One way to express risks is the probability of cancer *fatality* (*mortality*) occurring over a lifetime from exposure to radioactive material. Fatality (mortality) is the risk of dying of cancer. Another way to express risks is the probability of cancer

[27] Radiation exposures that members of the public may have received from SRS operations are several orders of magnitude below those levels that could result in nonstochastic effects.

incidence (morbidity) occurring over a lifetime from exposure to radioactive material. Incidence (morbidity) is the risk of radiogenic cancer whether or not the cancer is fatal.

Modern estimates of risk have, particularly for low-LET ionizing radiation,[28] been largely based on information about Hiroshima and Nagasaki atomic bomb survivors as documented in the Radiation Effects Research Foundation's Life Span Study. The Study cohort was a large, relatively healthy population at the time of exposure. The cohort was exposed to a wide range of reasonably established doses to individuals, and there exists a large, well-matched control group (people who received only small doses of radiation but were present at the time the bombs exploded). Additional information used for estimating radiation risks has come from sources such as: (1) persons who have had large intakes of radium into the body from occupational contamination or supposedly therapeutic administration, (2) persons who have had large intakes of a thorium preparation known as Throtrast as part of diagnostic procedures, and (3) workers in uranium mines and other mines resulting in exposure to radon gas.

Application of the various studies to estimations of risks from low levels of radiation exposure is subject to considerable uncertainty, for a variety of reasons, including:

- Sampling uncertainties
- Latency of health effects such as cancer following radiation
- Transferability of risks from one population to another
- Dose and dose rate dependence (e.g., although risk relationships have been developed based on observation of doses that have tended to be acute and much larger than doses at background levels, they have been primarily applied to assessment of risks from chronic doses at levels in the range of background).

There are also various ways to express risks, such as risks of disease or adverse genetic change, the number of days of life shortening from a given dose, and so forth. A common way to express risks, however, is the probability of a radiogenic cancer fatality (mortality) occurring over a lifetime from exposure to radioactive material. As used here, cancer *fatality (mortality)* refers to the risk of dying of cancer. Another way to express risks is the probability of radiogenic cancer incidence (morbidity) occurring over a lifetime from exposure to radioactive material. Cancer *incidence (morbidity)* refers to the risk of experiencing radiogenic cancer whether or not the cancer is fatal.

In any event, to estimate the consequences of radiation exposures to individuals and populations, and to regulate use of radioactive materials, it is normally assumed that the probability of occurrence of late stochastic effects is proportional to the radiation exposure that is received and that there is no threshold for the probability of health effects. This assumption is commonly known as the *linear no-threshold* assumption. For roughly 50 years it has formed the basis for international recommendations for protection of the public from radiation. As summarized by the IAEA in Publication No. 26 [ICRP-26] in 1977:

- No practice shall be adopted unless it introduction produces a positive net benefit.
- All exposures shall be kept as low as reasonably achievable, economic and social factors being taken into account.
- The dose equivalent limits to individuals shall not exceed the limits recommended for the appropriate circumstances by the [ICRP].

[28] LET stands for "linear effective track." Low-LET radiation refers to radiation such as gamma rays and beta particles. High-LET radiation refers to more massive radiation particles such as alpha particles.

D.4.4 Dose and Risk Coefficients

To calculate doses to individuals from exposure to radioactive materials, most risk assessors normally use standard tables that relate human doses or risks to the quantity of individual radioactive material ingested, inhaled, or exposed to. These tables of *dose coefficients* and *risk coefficients* are based on complicated models of physical and human physiological factors. This avoids the need to repeatedly perform these complicated calculations, and it is easier to compare different assessments.

For this report, ATL used the most up-to-date dose and risk coefficients provided in GENII. These dose and risk coefficients are almost all based on EPA's April 2002[29] Update [FGR-13U] to Federal Guidance Report No.13 [FGR-13].

For exposures of persons from inhaling or ingesting radionuclides, ATL used:

- Age-dependent dose coefficients for 23 organs and bodily tissues, plus effective dose based on ICRP-60 weighting factors (see Table D-8).
- Age-dependent cancer risk coefficients (fatality and incidence) for 15 cancer sites, plus the sum of cancers across all cancer sites.

Table D-9 lists the organs and bodily tissues considered in the dose coefficients, and the cancer sites considered in the risk coefficients. Table D-10 lists the age categories considered for the dose and risk coefficients. (Note that the age categories are different for the dose and risk coefficients.)

Table D-9 Organs, Tissues, and Lung-Compartments, and Cancer Sites, Addressed in Dose and Risk Conversion Factors in the FGR-13 Update

Organs, Tissues and Lung-Compartments Addressed in Dose Conversion Factors			Cancer Sites Addressed in Risk Conversion Factors	
Adrenals	Kidneys	Skin	Esophagus	Breast
Bone Surface	Liver	Spleen	Stomach	Ovary
Brain	ET-Region*	Testes	Colon	Bladder
Breast	Lung	Thymus	Liver	Kidneys
Stomach Wall	Muscle	Thyroid	Lung	Thyroid
SI Wall*	Ovaries	Uterus	Bone	Leukemia
ULI Wall*	Pancreas	UB Wall*	Skin	Residual†
LLI Wall*	Red Bone Marrow	Effective*		Total

*SI: small intestine; ULI: upper lower intestine; LLI: lower lower intestine; ET: extra-thoracic; UB: urinary bladder; effective: effective dose.
†Residual cancer sites.

[29] A supplement was first issued in 2000, but this supplement contained errors in the viewer and was replaced by the April 2002 version.

Table D-10 Age Categories Addressed in Dose and Risk Conversion Factors Presented in the FGR-13 Update

Dose Conversion Factors	Risk Conversion Factors
Infant	0-5 Years
1-Year Old	5-15 Years
5-Year Old	15-25 Years
10-year Old	25-70 Years
15-Year Old	0-110 Years
Adult	

For doses and risks from inhalation, ATL had to specify dose and risk coefficients consistent with assumptions about the physical and chemical form of each inhaled radionuclide. This was done because a radionuclide's chemical and physical form affected the rate that it could be absorbed into blood. ATL assumed most radionuclides were particulates assigned to one of three absorption types:

- Type F: Fast dissolution and a high level of absorption to blood.
- Type M: Intermediate rates of dissolution and levels of absorption to blood.
- Type S: Slow dissolution and a low level of absorption to blood.

ATL assumed some radionuclides existed as a gas or vapor. ATL's assumptions for the lung absorption types used in this report are listed in Table D-11.

For Table D-11, a value of G was selected for carbon assuming that the carbon was released as CO_2. Carbon dioxide was considered the most expected form of carbon that would have been inhaled because it is the most chemically stable of the oxidized forms of carbon. For iodine, a value of G for an organic gas was selected because it provides dose and risk results that are intermediate between particulate and elemental iodine. For ruthenium, a value of M was selected based on EPA's recommended value for particulates. It is also an intermediate value. For sulfur, a value of V was selected, which is EPA's recommended value for sulfur dioxide. Limited data on the chemical form suggested that an oxide would be more likely than the other choice of chemical form, carbon disulfide [Johnson 1962], at least from reactor areas.

For external exposures resulting from (1) immersion in a "cloud" of radionuclides in air, and (2) proximity to a contaminated ground surface, ATL used:

- Adult dose coefficients for 23 organs and bodily tissues, plus effective dose based on ICRP-60 weighting factors (see Table D-8).
- Age-specific cancer risk coefficients (fatality and incidence) for 15 cancer sites, plus the sum of cancers across all cancer sites.

GENII (and FGR-13U) provide only adult dose conversion factors for these types of external exposures. The authors of FGR-13 believe that use of adult external dose coefficients for all age groups should normally result in small errors (usually <30%). The FGR-13 authors believe that these errors are likely to be negligible compared to the errors associated with the simplified exposure scenarios assumed to calculate the dose conversion factors (e.g., the phantoms were in constant position in relation to the radiation source, and shielding was not considered) [FGR-13].

Table D-11 Assumptions for Lung Absorption Classes by Element

Element	Absorption Class*	Comments†
Americium (Am)	M	Default absorption type recommended in ICRP-72.
Argon (Ar)	NA	No absorption occurs for noble gases.
Carbon (C)	G	Type G was assumed because it was recommended in FGR-13 for CO_2.
Cesium (Cs)	F	Default absorption type recommended in ICRP-72.
Hydrogen (^3H)	HT: G HTO: V OBT‡: V	Type G was assumed for tritium released as a gas (HT) in accordance with FGR-13. Type G is also appropriate for tritium released as an organic. Type V is assumed for tritium released as water vapor (HTO) in accordance with FGR-13.
Iodine (I)	G	Iodine was released in several forms. Type G was assumed because it resulted in dose and risk conversion factors between those for a particulate and elemental I.
Plutonium (Pu)	M	Default absorption type recommended in ICRP-72.
Sulfur (S)	V	FGR-13 recommends Type V for sulfur dioxide. (Note that if S is released as a particulate, ICRP-72 recommends Type M.)
Strontium (Sr)	M	Default absorption type recommended in ICRP-72.
Thorium (Th)	S	Default absorption type recommended in ICRP-72.
Uranium (U)	M	Default absorption type recommended in ICRP-72
Xenon (Xe)	NA	No absorption occurs for noble gases.

*F: fast; M: medium; S: slow; G: gas; V: vapor; NA: not applicable.
†Lung absorption classes are not listed for radioactive isotopes of elements released only into surface waters. Although GENII requires that lung absorption class assumptions be input for these isotopes, the assumed values are not used in the dose and risk calculations because inhalation exposure is not assessed for the surface water pathways considered in this report.
‡OBT: organic bound tritium.

The ages considered in the risk coefficients for these types of external exposures are the same as those listed in Table D-10.

For external exposures while swimming in water or while boating, dose and risk coefficients are not available from the update to FGR-13. ATL therefore used dose coefficients for water immersion and boating from FGR-12. These (adult) dose coefficients are provided for fewer organs than those in the FGR-13 update, and the weighting factors used to calculate effective dose equivalent are from ICRP-26 rather than ICRP-60 (see Table D-8). ATL estimated risk by multiplying the calculated doses for water immersion and boating by the following health effects conversion factors:

- Fatality: 0.05 Sv^{-1}
- Incidence: 0.06 Sv^{-1}

Finally, ATL grouped the dose and risk coefficients into four age groups: 0 to 5 years, 5 to 15 years, 15 to 25 years, and 25 to 70 years. This assumption allowed for better correlation between the doses and risks calculated as a function of age group. Dose and risk conversion factors for these calculations were determined by interpolating between appropriate dose and risk conversion factors obtained from the

update to FGR-13 and from FGR-12. The three combined age groups are summarized in Table D-12. Also presented is the assumed duration of exposure for each age group.

Table D-12 Exposure Groupings and Corresponding Combined Dose and Risk Factor Age Groups

Age / Gender	Exposure Group (Duration [years])	Dose and Risk Factor Age Group
<1 male	Infant (male only) [1]	0 – 5
1 – 4 male	Preschool (male only) [4]	0 – 5
5 – 11 male	Schoolage (male only) [7]	5 – 15
12 – 17 male	Teenage (male only) [6]	15 - 25
18 – 70 male	Adult male [varies] *	25 – 70
18 – 70 female	Adult female [varies] *`	25 – 70

*The exposure duration of the adult age groups depends on the year that the individual reaches age 18. Exposure duration lasts from the year of the 18th birthday until the end of 1992, when one child would be 38 and the other 29.

D.4.5 Calculation of Dose and Risk

Annual doses, and doses summed over all years of exposure, are calculated for each member of the exposure scenario families described in Appendix E. In addition, for each year of exposure, the lifetime risk resulting from that exposure is calculated, as well as the total lifetime risk caused by all years of exposure. Total annual doses and risks are the sum of doses and risks from each pathway. The pathways considered for each family member, and other factors important for calculating doses and risks (e.g., food consumption rates) may differ depending on the scenario and family member.

Section D.3 addressed the calculational procedures used by GENII to model each of the exposure pathways considered for this report. The output of these calculations is a set of annual exposure factors as summarized in Table D-13. Each exposure factor is calculated over a period of time, T, which is one year for the scenarios in this report.

Some exposure factors may be calculated several times for each receptor, and the individual calculations summed, to arrive at a total exposure factor for that receptor. This would be the case, for example, for exposure factors involving food crop ingestion, where the exposure factor calculated from consumption of each food product is summed to arrive at a total exposure factor for food crop ingestion.

The exposure factors for each pathway are then used in set of calculational procedures involving multiplication by appropriate dose or risk conversion factors as needed to determine the annual doses and lifetime risks that would result from each of exposure.

Three sets of calculational procedures are used to address effective dose, equivalent dose to various organs, and lifetime risks. Because the calculational procedures are repetitive, they have been summarized in tables. The equations used to calculate effective dose are listed in Table D-14, while definitions for the various parameters listed in these equations are summarized in Table D-15. Similarly, the equations used to calculate equivalent dose are listed in

Table D-16, while the definitions for the various parameters used in these equations are summarized in Table D-17. Finally, the equations used to calculate risk are listed in Table D-18, while the definitions for the various parameters used in these equations are summarized in Table D-19. For these tables, the

assumed values for the surface soil bulk density (?$_s$) and the thickness of the contaminated surface soil layer (d_s) are provided in Section F.7.

Table D-13 Summary of Exposure Factors

Exposure Route	Pathway	Exposure Factor	Definition
External	Plume	$I_{eaig}(T)$	Exposure factor for plume immersion exposure for radionuclide i for an individual in age group g (Bq/m^3) (Sec. D.3.2)
	Ground	$I_{esig}(T)$	Exposure factor for exposure to contaminated ground for radionuclide i for individuals in age group g (Bq/kg) (Sec. D.3.3.2)
	Swim-ming	$I_{wrig}(T)$	Exposure factor for radionuclide i from swimming at recreational swimming location r for individuals in age group g (Bq/L) (Sec. D.3.6.1)
	Boating	$I_{brig}(T)$	Exposure factor for radionuclide i from boating at recreational boating location r for individuals in age group g (Bq/L) (Sec. D.3.6.3)
	Shoreline	$I_{srig}(T)$	Exposure factor for radionuclide i from shoreline exposure at recreational shoreline location r for individuals in age group g (Bq/kg) (Sec. D.3.5)
Ingestion	Farm Crops	$I_{csig}(T)$	Intake of radionuclide i in food crop c from ingestion of agriculture location s for individuals in age group g (Bq) (Sec. D.3.4.1)
	Animal Products	$I_{asig}(T)$	Intake of radionuclide i in animal product a from ingestion at agricultural location s for individuals in age group g (Bq) (Sec. D.3.4.2)
	Aquatic Foods	$I_{fwig}(T)$	Intake of radionuclide i from ingestion of aquatic food f at aquatic food location w for individuals in age group g (Bq) (Sec. D.3.4.3)
	Inadver-tent Soil	$I_{dsig}(T)$	Intake of radionuclide i from inadvertent soil ingestion at soil usage location s for individuals in age group g (Bq) (Sec. D.3.3.4)
	Inadver-tent Swim	$I_{wwig}(T)$	Intake of radionuclide i from inadvertent water ingestion at swimming location w for individuals in age group g (Bq) (Sec. D.3.6.2)
Inhalation	Air	$I_{aaig}(T)$	Intake of radionuclide i from air inhalation at air usage location a for individuals in age group g (Bq) (Sec. D.3.1)
	Resus-pended Soil	$I_{saig}(T)$	Intake of radionuclide i from resuspension inhalation at soil usage location a for individuals in age group g (Bq) (Sec. D.3.3.3)

Table D-14 Equations for Calculation of Effective Dose

Exposure Route	Exposure Pathway	Dose Parameter	How Calculated
External	Plume	$IE_{eaig}(T)$	$I_{eaig}(T)$ EC_{iaa} T_{yr} 3.15E+7
	Ground	IEesig(T)	$I_{esig}(T)$ ECiag Tyr 3.15E+7 / (?$_s$ d_s)
	Swimming	$IE_{wrig}(T)$	10^{-3} $I_{wrig}(T)$ $EC_{ia}w$ T_{yr} 3.15E+7
	Boating	$IE_{brig}(T)$	10^{-3} $I_{brig}(T)$ EC_{iaw} T_{yr} 3.15E+7 / 2*
	Shoreline	$IE_{srig}(T)$	$I_{srig}(T)$ EC_{iag} T_{yr} 3.15E+7 / (?$_s$ d_s)
Ingestion	Farm Crops	$IE_{csig}(T)$	$I_{csig}(T)$ EC_{igoc}
	Animal Products	$IE_{asig}(T)$	$I_{asig}(T)$ EC_{igoc}
	Aquatic Foods	$IE_{fwig}(T)$	$I_{fwig}(T)$ EC_{igoc}
	Inadvertent Soil	$IE_{dsig}(T)$	$I_{dsig}(T)$ EC_{igoc}
	Inadvertent Swim	$IE_{wwig}(T)$	$I_{wwig}(T)$ EC_{igoc}
Inhalation	Air	$IE_{aaig}(T)$	$I_{aaig}(T)$ EC_{igrc}
	Resuspended Soil	$IE_{saig}(T)$	$I_{saig}(T)$ EC_{igrc}

*The factor of two devisor reflects the different geometry of the exposure situation for swimming vs. boating. The swimming pathway entails immersion in the radioactive source, while the boating pathway entails being in proximity to it.

Table D-15 Definitions for Calculation of Effective Dose

Parameter	Definition
$IE_{eaig}(T)$	Effective dose from external exposure to radionuclide i from plume immersion at air usage location a for an individual in age group g (Sv)
$IE_{esig}(T)$	Effective dose from external exposure to radionuclide i in contaminated soil at soil usage location s for an individual in age group g for exposure over time period (T)
$IE_{wrig}(T)$	Effective dose from external exposure to radionuclide i in contaminated water at recreational water usage location r for an individual in age group g (Sv)
$IE_{brig}(T)$	Effective dose from external exposure to radionuclide i from boating in contaminated water at recreational water usage location r for an individual in age group g (Sv)
$IE_{srig}(T)$	Effective dose from external exposure to radionuclide i in shoreline sediment at recreational water usage location r for an individual in age group g (Sv)
$IE_{csig}(T)$	Effective dose from ingestion intake of radionuclide i in food crop c at soil usage location s for an individual in age group g for exposure over time period T (Sv)
$IE_{asig}(T)$	Effective dose from ingestion intake of radionuclide i in animal product a at soil usage location s for an individual in age group g for exposure over time period T (Sv)
$IE_{fwig}(T)$	Effective dose from ingestion intake of radionuclide i in aquatic food f at water usage location w for an individual in age group g for exposure over time period T (Sv)
$IE_{dsig}(T)$	Effective dose from ingestion intake of radionuclide i in soil at soil usage location s for an individual in age group g for exposure over time period T (Sv)
$IE_{wwig}(T)$	Effective dose from ingestion intake of radionuclide i in swimming water at water usage location w for an individual in age group g for exposure over time period T (Sv)

$IE_{aaig}(T)$	Effective dose from inhalation intake of radionuclide i in air at air usage location a for an individual in age group g for exposure over time period T (Sv)
$IE_{saig}(T)$	Effective dose from inhalation intake of radionuclide i in resuspended soil at air usage location a for an individual in age group g for exposure over time period T (Sv)
EC_{iaa}	Effective dose coefficient for external exposure from plume immersion for radionuclide i for an adult (Sv m^3 per Bq s)
EC_{iag}	Effective dose equivalent factor for external exposure from ground exposure for radionuclide i for an adult (Sv m^2 per Bq s)
EC_{iaw}	Effective dose equivalent factor for external exposure from water immersion for radionuclide i for an adult (Sv L per Bq s)
EC_{igoc}	Effective dose coefficient for ingestion intake of radionuclide i of class c for an individual in age group g (Sv/Bq)
EC_{igrc}	Effective dose coefficient for ingestion intake of radionuclide i for an individual in age group g (Sv/Bq)
T_{yr}	Time of exposure, one year.
3.15E+7	Factor for correction of units (seconds per year)
10^{-3}	Factor for correction of units (m^3 per liter)
$?_s$	Surface soil bulk density (kg/m^3)
d_s	Thickness of surface soil layer (m)

Table D-16 Equations for Calculation of Equivalent Dose

Exposure Route	Exposure Pathway	Dose Parameter	How Calculated
External	Plume	$IE_{eaig}T(T)$	$I_{eaig}(T)\ HC_{iaa}T\ T_{yr}\ 3.15E+7$
	Ground	$IE_{esig}T(T)$	$I_{esig}(T)\ HC_{iag}T\ T_{yr}\ 3.15E+7 / (?_s\ d_s)$
	Swimming	$IE_{wrig}T(T)$	$10^{-3}\ I_{wrig}(T)\ HC_{iaw}T\ T_{yr}\ 3.15E+7$
	Boating	$IE_{brig}T(T)$	$10^{-3}\ I_{brig}(T)\ HC_{iaw}T\ T_{yr}\ 3.15E+7 / 2$*
	Shoreline	$IE_{srig}T(T)$	$I_{srig}(T)\ HC_{iag}T\ T_{yr}\ 3.15E+7 / (?_s\ d_s)$
Ingestion	Farm Crops	$IE_{csig}T(T)$	$I_{csig}(T)\ HC_{igoc}T$
	Animal Products	$IE_{asig}T(T)$	$I_{asig}(T)\ HC_{igoc}T$
	Aquatic Foods	$IE_{fwig}T(T)$	$I_{fwig}(T)\ HC_{igoc}T$
	Inadvertent Soil	$IE_{dsig}T(T)$	$I_{dsig}(T)\ HC_{igoc}T$
	Inadvertent Swim	$IE_{wwig}T(T)$	$I_{wwig}(T)\ HC_{igoc}T$
Inhalation	Air	$IE_{aaig}T(T)$	$I_{aaig}(T)\ HC_{igrc}T$
	Resuspended Soil	$IE_{saig}T(T)$	$I_{saig}(T)\ HC_{igrc}T$

*The factor of two devisor reflects the different geometry of the exposure situation for swimming vs. boating. The swimming pathway entails immersion in the radioactive source, while the boating pathway entails being in proximity to it.

Table D-17 Definitions for Calculation of Equivalent Dose

Parameter	Definition
$IE_{eaig}T(T)$	Equivalent dose to organ or tissue T from external exposure to radionuclide i from plume immersion at air location a for an individual in age group g (Sv)
$IE_{esig}T(T)$	Equivalent dose to organ T from external exposure to radionuclide i from plume immersion at soil usage location s for an individual in age group g for exposure over time period T (Sv)
$IE_{wrig}T(T)$	Equivalent dose to organ T from external exposure to radionuclide i while swimming at recreational water usage location r for an individual in age group g for exposure over time period T (Sv)
$IE_{brig}T(T)$	Equivalent dose to organ T from external exposure to radionuclide i while boating at recreational water usage location r for an individual in age group g for exposure over time period T (Sv)
$IE_{srig}T(T)$	Equivalent dose to organ T from external exposure to radionuclide i from shoreline sediment at recreational water usage location r for an individual in age group g over time period T (Sv)
$IE_{csig}T(T)$	Equivalent dose to organ T from ingestion intake of radionuclide i in food crop c at soil usage location s for an individual in age group g for exposure over time period T (Sv)
$IE_{asig}T(T)$	Equivalent dose to organ T from ingestion intake of radionuclide i in animal product a at soil location s for an individual in age group g for exposure over time period T (Sv)
$IE_{fwig}T(T)$	Equivalent dose to organ T from ingestion intake of radionuclide i in aquatic food f at water usage location w for an individual in age group g for exposure over time period T (Sv)
$IE_{dsig}T(T)$	Equivalent dose to organ T from ingestion intake of radionuclide i in soil at soil usage location s for an individual in age group g for exposure over time period T (Sv)
$IE_{wwig}T(T)$	Equivalent dose to organ T from ingestion intake of radionuclide i in water at water usage location w for an individual in age group g for exposure over time period T (Sv)
$IE_{aaig}T(T)$	Equivalent dose to organ T from inhalation intake of radionuclide i in air at air usage location a for an individual in age group g for exposure over time period T (Sv)
$IE_{saig}T(T)$	Equivalent dose to organ T from inhalation intake of radionuclide i in resuspended soil at air usage location a for an individual in age group g for exposure over time period T (Sv)
$HC_{iaa}T$	Equivalent dose coefficient for air immersion to an organ T, radionuclide i, for an adult (Sv m^3 per Bq s)
$HC_{iag}T$	Equivalent dose coefficient to organ T for external exposure to ground for radionuclide i for an adult (Sv per Bq s)
$HC_{iaw}T$	Equivalent dose coefficient to organ T for external exposure from water immersion for radionuclide I for an adult (Sv L per Bq s)
$HC_{igoc}T$	Equivalent dose coefficient to organ T for ingestion intake of radionuclide c of class c for an individual in age group g (Sv/Bq)
$HC_{igrc}T$	Equivalent dose coefficient to organ T for inhalation intake of radionuclide i of class c for an individual in age group g (Sv/Bq)

Parameter	Definition
EC_{igrc}	Effective dose coefficient for ingestion intake of radionuclide i for an individual in age group g (Sv/Bq)
T_{yr}	Time of exposure, one year.
3.15E+7	Factor for correction of units (seconds per year)
10^{-3}	Factor for correction of units (m^3 per liter)
$?_s$	Surface soil bulk density (kg/m^3)
d_s	Thickness of surface soil layer (m)

Table D-18 Equations for Calculation of Cancer Risk

Exposure Route	Exposure Pathway	Risk Parameter	How Calculated
External	Plume	$IR_{eaig}T(T)$	$I_{eaig}(T)\ RC_{iga}T\ T_{yr}\ 3.15E+7$
	Ground Contam.	$IR_{esig}T(T)$	$I_{esig}(T)\ RC_{igg}T\ T_{yr}\ 3.15E+7 / (?_s\ d_s)$
	Swimming	$IR_{wrig}T(T)$	$10^{-3}\ I_{wrig}(T)\ HC_{iaw}T\ HC_{gh}\ T_{yr}\ 3.15E+7$
	Boating	$IR_{brig}T(T)$	$10^{-3}\ I_{brig}(T)\ HC_{iaw}T\ HC_{gh}\ T_{yr}\ 3.15E+7 / 2$*
	Shoreline	$RH_{srig}T(T)$	$I_{srig}(T)\ RC_{iag}T\ T_{yr}\ 3.15E+7 / (?_s\ d_s)$
Ingestion	Farm Crops	$RH_{csig}T(T)$	$I_{csig}(T)\ RC_{igoc}T$
	Animal Products	$RH_{asig}T(T)$	$I_{asig}(T)\ EC_{igoc}T$
	Aquatic Foods	$RH_{fwig}T(T)$	$I_{fwig}(T)\ RC_{igoc}T$
	Inadvertent Soil	$RH_{dsig}T(T)$	$I_{dsig}(T)\ RC_{igoc}T$
	Inadvertent Swim	$RH_{wwig}T(T)$	$I_{wwig}(T)\ RC_{igoc}T$
Inhalation	Air	$RH_{aaig}T(T)$	$I_{aaig}(T)\ RC_{igrc}T$
	Resuspended Soil	$RH_{saig}T(T)$	$I_{saig}(T)\ RC_{igrc}T$

*The factor of two devisor reflects the different geometry of the exposure situation for swimming vs. boating. The swimming pathway entails immersion in the radioactive source, while the boating pathway entails being in proximity to it.

Table D-19 Definitions for Calculation of Cancer Risk

Parameter	Definition
$IR_{eaig}T(T)$	Risk to organ or tissue T from external exposure to radionuclide i from plume immersion at air location a for an individual in age group g (risk)
$IR_{esig}T(T)$	Risk to organ T from external exposure to radionuclide i from plume immersion at soil usage location s for an individual in age group g for exposure over time period T (risk)
$IR_{wrig}T(T)$	Risk to organ T from external exposure to radionuclide i while swimming at recreational water usage location r for an individual in age group g for exposure over time period T (risk)
$IR_{brig}T(T)$	Risk to organ T from external exposure to radionuclide i while boating at recreational water usage location r for an individual in age group g for exposure over time period T (risk)
$RH_{srig}T(T)$	Risk to organ T from external exposure to radionuclide i from shoreline sediment at recreational water usage location r for an individual in age group g over time period T (risk)
$RH_{csig}T(T)$	Risk to organ T from ingestion intake of radionuclide i in food crop c at soil usage location s for an individual in age group g for exposure over time period T (risk)
$RH_{asig}T(T)$	Risk to organ T from ingestion intake of radionuclide i in animal product a at soil location s for an individual in age group g for exposure over time period T (risk)
$RH_{fwig}T(T)$	Risk to organ T from ingestion intake of radionuclide i in aquatic food f at water usage location w for an individual in age group g for exposure over time period T (risk)
$RH_{dsig}T(T)$	Risk to organ T from ingestion intake of radionuclide i in soil at soil usage location s for an individual in age group g for exposure over time period T (risk)
$RH_{wwig}T(T)$	Risk to organ T from ingestion intake of radionuclide i in water at water usage location w for an individual in age group g for exposure over time period T (risk)
$RH_{aaig}T(T)$	Risk to organ T from inhalation intake of radionuclide i in air at air usage location a for an individual in age group g for exposure over time period T (risk)
$RH_{saig}T(T)$	Risk to organ T from inhalation intake of radionuclide i in resuspended soil at air usage location a for an individual in age groupg g for exposure over time period T (risk)
$RC_{iga}T$	Risk coefficient for air immersion to an organ T, radionuclide i, for an individual in age group g (m^3 per Bq s)
$RC_{igg}T$	Risk coefficient to organ T for external exposure to ground for radionuclide i for an adult (m^2 per Bq s)
$HC_{iaw}T$	Equivalent dose coefficient to organ T for external exposure from water immersion for radionuclide I for an adult (Sv L per Bq s)
HC_{gh}	Health effects conversion factor for effect h and an individual in age group g (risk/Sv)
$RC_{iag}T$	Risk coefficient to organ T for external exposure to ground (the soil surface factor is used for sediment as well) for radionuclide i for an adult (m^3 per Bq s)
$RC_{igoc}T$	Risk coefficient to organ T for ingestion intake of radionuclide c of class c for an individual in age group g (Bq^{-1})

Parameter	Definition
$RC_{igrc}T$	Risk coefficient to organ T for inhalation intake of radionuclide i of class c for an individual in age group g (Bq^{-1})
$RC_{igrc}T$	Risk coefficient for inhalation of radionuclide i for an individual in age group g (Sv/Bq)
T_{yr}	Time of exposure, one year
3.15E+7	Factor for correction of units (seconds per year)
10^{-3}	Factor for correction of units (m^3 per liter)
$?_s$	Surface soil bulk density (kg/m^3)
d_s	Thickness of surface soil layer (m)

D.5 References

Anspaugh. Anspaugh, L.R., J.H. Shinn, P.L. Phelps, and N.C. Kennedy. Resuspension and Redistribution of Plutonium in Soils. Health Physics. 29:571-582. 1975.

ATL 2003. Gordon, M. Estimation of River Flowrate for Lower Three Runs Creek at Martin. ATL internal document. 28 March 2003.

ATL White Paper on Venison.

B&S 1981. Baes, C.F. and R.D. Sharp. Predicting Radionuclide Leaching from Root Zone Soil From Assessment Applications. CONF-81606. Oak Ridge National Laboratory, Oak Ridge, Tennessee. 1981.

Briggs 1973. Briggs, G.A. Diffusion Estimation for Small Emissions. ATDL Contribution File No. 79. Atmospheric Turbulence and Diffusion Laboratory, NOAA, P.O. Box E, Oak Ridge, TN. 1973.

C&G 1983. Christensen, E.J. and D.E. Gordon, eds. Technical Summary of Groundwater Quality Protection Program at Savannah River Plant. Volume I and II. DPST-83-829. 1983.

E&K 1792. Eimutis, E.C. and M.G. Konicek. Derivations of Continuous Functions for the Lateral and Vertical Atmospheric Dispersion Coefficients. Atmospheric Environment. 6:859-863. 1972.

EPA 1994. U.S. Environmental Protection Agency. Estimating Radiogenic Cancer Risks. EPA 402-R-93-076. June 1994.

EPA 1995. U.S. Environmental Protection Agency. User's Guide for the Industrial Source Complex (ISC3) Dispersion Models, Volume II – Description of Model Algorithms. EPA-454/B-95-003b. Research Triangle Park, NC. 1995.

ERDA-1537. U.S. Energy Research and Development Administration (ERDA). Final Environmental Impact Statement: Waste Management Operations, Savannah River Plant, Aiken, South Carolina. ERDA-1537, September 1977.

FGR-11. Eckerman, K.F., A.B. Wolbarst, and A.C.B. Richardson. Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and

Ingestion. Federal Guidance Report No. 11. EPA-520/1-88-020. Oak Ridge National Laboratory and EPA Office of Radiation Programs. September 1988.

FGR-12. Eckerman, K.F. and J.C. Ryman. External Exposure to Radionuclides in Air, Water, and Soil. Federal Guidance Report No. 12. EPA 402-R-93-081. Oak Ridge National Laboratory and EPA Office of Radiation Programs. September 1993.

FGR-13. Eckerman, K. F., et al. Cancer Risk Coefficients for Environmental Exposure to Radionuclides. Federal Guidance Report No. 13. EPA 402-R-99-001. Oak Ridge National Laboratory and U.S. EPA Office of Radiation and Indoor Air. September 1999.

FGR-13U. U.S. Environmental Protection Agency. Federal Guidance Report 13 Cancer Risk Coefficients for Environmental Exposure to Radionuclides: CD Supplement. EPA 402-C-99-001, Rev. 1. Oak Ridge National Laboratory and U.S. EPA. April 2002.

FRAMES 1.3. FRAMES 1.3 Website. 2002. [cited 23 September 2003] Available from URL: http://mepas.pnl.gov/FRAMESV1/index.html.

GENII Guide. Napier, B.A., GENII Version 2 Users Guide. Prepared for U.S. EPA. April 2002.

GENII SDD. Napier, B.A., et al. GENII Version II Software Design Document. PNNL for U.S. Environmental Protection Agency. November 2002.

Hamby 1991. Hamby DM. Land and Water Use Characteristics in the Vicinity of the Savannah River Site (U). Westinghouse Savannah River Company. WSRC-RP-91-17. March 1991; 7.

Harrison 2003. Harrison K. Georgia Extension Engineer. Telephone Log. March 11, 2003.

Hayes & Marter. Hayes, D.W. and W.L. Marter. Historical Flow Rates for Dose Calculations. SRL-ETS-91057. Westinghouse Savannah River Company, Savannah River Laboratory. 10 June 1991.

IAEA 1994. International Atomic Energy Agency. Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Temperate Environment. Tech. Rep. Ser. No. 364. Vienna, Austria. 1994.

IAEA SS-19. International Atomic Energy Agency. Generic Models for Use in Assessing the Impact of Discharges of Radioactive Substances to the Environment. Safety Series Report No. 19. Vienna, Austria. 2001.

ICRP-26. International Commission on Radiation Protection. Recommendations of the International Commission on Radiation Protection. ICRP Publication 26. Pergamon Press, Oxford. 1977.

ICRP-60. International Commission on Radiation Protection. Recommendations of the International Commission on Radiation Protection. ICRP Publication 60. Pergamon Press, Oxford. 1991.

ICRP-72. International Commission on Radiation Protection. Age-Dependent Doses to Members of the Public from Intake of Radionuclides, Part 5. Compilation of Ingestion and Inhalation Dose Coefficients. ICRP Publication 72. Pergamon Press, Oxford. 1996.

Johnson 1962. Johnson JE. Sulfur-35 Releases from Reactor Areas. Dupont Interoffice Memorandum to CM Patterson. Savannah River Plant. RAC reference no. SKR1994020129. July 19, 1962.

Kennedy and Strenge. Kennedy, W.E., Jr. and D.L. Strenge. Residual Radioactive Contamination from Decommissioning – Technical Basis for Translating Contamination Levels to Annual Total Effective Dose Equivalent. NUREG/CR-5512. PNL-7994. Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission. October 1992.

Lederer and Shirley. Lederer, C.M. and V.S. Shirley. Table of Isotopes. 7th Edition. John Wiley & Sons, Inc., New York. 1978.

McElroy & Pooler. McElroy, J.L. and F. Pooler. The St. Louis Dispersion Study. Report AP-53. U.S. Public Health Service, National Air Pollution Control Administration. 1968.

Moore 2002. Moore MS. Critical Pathway Assessment of the Savannah River Site, Aiken South Carolina. South Carolina Department of Health and Environmental Control. May 2002; 17-18.

Moore 2003. Moore M. SCDHEC. Telephone Log. March 12, 2003.

Napier 2003e. Personal communication between WE Joyce, ATL, Inc., and BA Napier, PNNL. 25 September 2003.

Napier 1980. Napier, B.A., R.L. Roswell, W.E. Kennedy, Jr., and D. L. Strenge. ARRRG and FOOD – Computer Programs for Calculating Radiation Dose to Man from Radionuclides I the Environment. PNL-3180. Pacific Northwest Laboratory, Richland, Washington. 1980.

P&H 1993. Proel, G. and F.O. Hoffman. The Interception, Initial and Post Deposition-Retention by Vegetation of Dry and Wet Deposited Radionuclides. VAMP Terrestrial Working Group, International Atomic Energy Agency, Vienna, Austria. 1993.

P&D 2001. Peterson, S.R. and P.A. Davis. Tritium Doses from Chronic Atmospheric Releases: A New Method Proposed for Regulatory Compliance. Health Physics, 82(2):213-225. 2001.

Phase II. Till, J.E, et al. Savannah River Site Environmental Dose Reconstruction Project, Phase II: Source Term Calculation and Ingestion Pathway Data Retrieval, *Evaluation of Materials Released from the Savannah River Site.* RAC Report No. 1-CDC-SRS-1999-Final, Risk Assessment Corporation (RAC), 30 April 2001.

RG 1.111. U.S. Nuclear Regulatory Commission. Methods for Estimating Atmospheric Transport and Dispersion of Gaseous Effluents in Routine Releases from Light-Water-Cooled Reactors. Regulatory Guide 1.111, Revision 1. Office of Standards Development. July 1977.

SBS 1982. Shor, R.W., C.F. Baes III, and R.D. Sharp. Agricultural Production in the United States by County: A Compilation of Information from the 1974 Census of Agriculture for Use in Terrestrial Food Chain Transport and Assessment Models. ORNL=5768. Oak Ridge National Laboratory, Oak Ridge, Tennessee. 1982.

Strenge 1997. Strenge, D.L. A General Algorith for Radioactive Decay with Branching and Loss from a Medium. Health Physics. 73(6): 953-957. 1997.

Smith & Fledderman. Smith, M. and P. Fledderman. Radiocesium in White-tailed Deer on the Savannah River Site. 14 May 1999. Cited 21 August 2003. Available at:

http://www.uga.edu/srel/Graphics/deer_snapshoot.pdf.

Strenge 1987. Strenge, D.L., T.J. Bander, and J.K. Soldat. GASPAR II – Technical Reference and Use Guide. NUREG/CR-3332. U.S. Nuclear Regulatory Commission, Washington, DC. 1987.

Till & Meyer. Till, J.E. and H.R. Meyer. Radiological Assessment – A Textbook on Environmental Dose Analysis. NUREG/CR-3332. ORNL-5968. U.S. Nuclear Regulatory Commission, Washington, DC. 1983.

USGS 2003c. United States Geologic Survey. USGS Flow Rate at HWY301.

Weber 2001. Weber, A.H., R.L. Buckley, M.J. Parker, R.P. Harvey, and D.M. Hamby. The Creation of an Historical Meterological Database for Dose Construction. WSRC-TR-2001-00275. Westinghouse Savannah River Company, Aiken, GA. 2001.

APPENDIX E RECEPTOR ACTIVITIES AND USAGE RATES

This appendix presents the seven exposure scenarios assumed for Phase III of the Savannah River Site (SRS) Dose Reconstruction Project, along with the derivation of base case values for those radiological assessment parameters that depend on the behaviors of the human receptors comprising the exposure scenarios. Seven human receptors were modeled using the GENII[1] computer code for each exposure scenario (28 receptors total). Assumptions about the behavior of each receptor were used to develop values for many of the parameters comprising the mathematical relationships used in GENII for radiological assessment (see Appendix D). These parameters address human-oriented behavior such as the assumed breathing rates of the four receptors associated with each scenario, their food consumption rates, and the times spent in various exposure locations.

The assessments that were performed were complex. Radiation doses and risks were determined for each receptor for each of years of nuclear material production at the SRS. The behavior of each receptor, as well as the receptor's age, changed over time. Therefore, the radiation exposure calculations were made using GENII and assuming "unit" quantities for receptor-specific parameters such as food consumption rates. This output from GENII was then modified in the post-processor (software created for this Phase III study) to arrive at the proper doses and risks for each receptor. These modifications were performed using a set of receptor- and pathway-specific *exposure* and *adjustment factors*.

To link the exposure scenarios, the computational procedures outlined in Appendix D, the receptor-specific parameters and their values input to GENII, and the exposure and adjustment factors used to modify the output from GENII, this appendix is organized in the following manner:

- Section E.1: Scenarios proposed by the Centers for Disease Control and Prevention (CDC) and considered by the Savannah River Site Health Effects Subcommittee (SRSHES).
- Section E.2: Additional assumptions about scenarios.
- Section E.3: Overview of final exposure scenarios.
- Section E.4: Linkage of GENII variables to exposure and adjustment factors.
- Section E.5: Exposure and adjustment factors for each exposure pathway.

Except for radiation dosimetry assumptions, other GENII parameter values that are not clearly receptor-specific (such as food crop production rates, soil density, etc.) are presented in Appendix F. Radiation dosimetry assumptions are presented in Section D.4 of Appendix D.

E.1 Scenarios Proposed by CDC and Considered by the SRSHES

The exposure scenarios considered for this report evolved over time. Originally, CDC proposed the following six scenarios (1):

- A rural family just downwind of the site boundary.
- An urban/suburban family just downwind of the site boundary.
- A delivery person scenario.
- An outdoors person (hunting, fishing, camping, etc.).
- A family living near the river.
- A migrant worker family living mostly outdoors.

[1] All references to the GENII code in this chapter refer to Version 2 of GENII.

These scenarios were meant to represent hypothetical families that might have lived in the SRS vicinity and engaged in activities that were typical for the area. The activities postulated for these scenarios were intended to represent a broad range of lifestyles.

CDC presented proposed assumptions about these six scenarios to the SRSHES at a meeting of the SRSHES held in January 2002 in Charleston, South Carolina. Shortly thereafter, these assumptions were somewhat modified, and the SRSHES formed a work group to consider the proposed scenarios. On September 6, 2002, a SRSHES meeting was held, and J. Lockridge, the chair of the SRSHES Scenario Work Group, presented comments on the proposed scenarios to the CDC and the preparers of this report (1). Table E-1 summarizes the CDC proposed scenarios (as modified) and the SRSHES Work Group comments on the proposed scenarios. The SRSHES also made suggestions about further modifying the scenarios, and Table E-2 summarizes these suggested modifications (1).

The preparers of this report discussed the proposed scenarios with CDC staff in early 2003. Two key references that address these discussions are memoranda from the preparers of this report to CDC (2,3). These discussions principally addressed overall decisions about the number of exposure scenarios to be considered and where the hypothetical families comprising the exposure scenarios would live, work, attend church and school, obtain food, and recreate.

Table E-1 Summary of CDC Proposed Scenarios and SRSHES Comments

Proposed Scenario	Scenario Description	SRSHES Work Group Comments (1)
Rural	• Use the closest downwind location where there could have been farms in 1955. • Consider an adult, an infant born in 1955, and an infant born in 1964 (year of largest iodine release). Use default consumption values. • Assume a lot of time outdoors working in soil. • Assume they drank milk from a backyard cow. • Assume the crops were irrigated from Savannah River. • Assumption of “working in soil” also included resuspension of soil contaminants in the breathing zone. • In addition to two infants, consider the mother nursing at least one of the infants.	• Farm in rural Burke County, GA. Girard, GA - 3 miles west of Savannah River, SW from SRS. Population about 200 in 1950s. Located in SRS plume path. • In 1950’s, a family of two parents, five children. In 1960’s, a family of two parents, three children. • Schools: Girard Elementary, Waynesboro High School. • Cash crops: peanuts, corn, cotton. Vegetables grown for family consumption. • Religion: Methodist. • In 1950’s, 50% of meat & vegetables grown on farm. In 1960s, 25% grown on farm; most milk from one of two dairies in Girard. Family had a few dairy cows. • Some swimming, but minimal camping. No recreational boating. • Lots of fishing from Briar Creek, 2 miles east of Girard. Significant hunting for deer, quail and dove. Limited trapping.
Urban/ Suburban	• Use the closest downwind location where urban or suburban families could have lived in 1955. • Consider an adult, an infant born in 1955, and an infant born in • 1964 (year of largest iodine release).	• Family resided in Augusta, GA (region of Broad and Greene Streets). • In 1950’s, a family of two parents, two children of varying ages. In 1960’s, a family of two parents, three children. • Schools: Augusta neighborhood schools.

Proposed Scenario	Scenario Description	SRSHES Work Group Comments (1)
	• Use default consumption values. • Assume the adult worked at the nearest industrial location downwind in 1955. • Assume milk drunk from nearest dairy or rural neighbor. • Assume the adult worked onsite at SRS in lieu of the "nearest industrial location." • Assume the onsite work location was associated with higher radiological exposures (e.g., SRS Canyons).	• Assume father to have worked in the SRS F-Area Canyon Building from 1955 to 1992. • Assume the mother to have stayed home to raise the children. Mother worked onsite until well into her pregnancy. • Attended local church in Augusta, GA. • Food and milk were obtained from local grocery stores in Augusta, GA. Milk was supplied to local stores from dairies in the Aiken and Augusta area. • Occasional swimming and boating in Clark's Hill Lake. • No hunting, but fishing in Clark's Hill Reservoir. Fishing two weekends per month.
Delivery	• Same as Urban/Suburban Family. • Use the closest downwind location where urban or suburban families could have lived in 1955. • Consider an adult, an infant born in 1955, and an infant born in 1964 (year of largest iodine release). • Use default consumption values. • Assume the adult worked at the nearest industrial location downwind in 1955. • Assume they drank milk from the nearest dairy or rural neighbor. • Assume that the person spent 8 hours per week onsite.	• Family resided in Barnwell, SC. Father provided weekly beverage deliveries to SRS. • In 1950's, family of two parents, two children of varying ages. In 1960's, a family of two parents, three children. • Schools: Barnwell, SC, school system. • Assume the delivery person worked at the Allendale Coca Cola Bottling Plant in Allendale, SC, and made routine deliveries to SRS (various locations) spending 8 hours per week onsite. • Attended Mount Hope Baptist Church, Martin, SC. • Food Sources: Barnwell, SC, grocery stores, and Furses' Grocery Store, Martin, SC. • Swimming in Lower Three Runs Creek outside Martin, SC. Boating and camping at Little Hell Landing on Savannah River (south boundary of SRS). • Hunting at Lower Three Runs Creek area (known for poaching). Fishing at Lower Three Runs Creek, and Savannah River's Smith Lake. • Family drank lots of carbonated beverages (including beer).
Outdoor	• Assume camping at the nearest downwind location that would make sense with the season (hunting, fishing, etc.). • Assume that the person was always outdoors. • Use default consumption values.	• Family resided in Jackson, SC. • In 1950's, a family of two parents, two children of varying ages. In 1960's, a family of two parents, three children. • Schools: (1950) Jackson Elementary (29,831). (1986) Redcliff Elementary (29,803). Jackson High School.

Proposed Scenario	Scenario Description	SRSHES Work Group Comments (1)
	• Assume the person spent 8 hours per day on the Savannah River in the summer. • Assume the person spent 8 hours per week on site hunting or fishing (in season). • Assume the person obtained fish and meat (deer, game birds, turtles) from hunting and fishing onsite (some authorized, some not—a "poacher" assumption.)	• Worked as a hunter/trapper subcontractor to the primary SRS Contractor (DuPont, WSRC, etc.) or the U.S. Forest Service. • Religion: First Baptist Church, Jackson, SC. • 50% of vegetables locally grown and irrigated from a surface creek. 75% of meat obtained from SRS. Fish obtained from Savannah River. Water obtained from well on home property. • Boating in Savannah River from Jackson, SC, boat ramp. • Obtained deer, hogs from work at SRS trapping. Fished in Savannah River.
Near River	• Use the nearest docking location downwind where people could have lived on the house boats in 1955. • Consider an adult, an infant born in 1955 and an infant born in 1964 (year of largest iodine release). • Use default consumption values. • Assume always outdoors in contact with Savannah River. • Assume they obtained their food from the nearest local farm or grocery store. • Validate with the Citizens Advisory Board that the boat scenario is plausible, and if so, define a location. • If not plausible, replace the boat scenario with a new scenario of a site construction worker living in a trailer.	• Scenario location: Consider Martin-Millet area • Family: To be developed (TBD). • Schools: TBD. • Work: TBD. • Religion: TBD. • Food sources: Shell fishing, shrimping, crabbing. • Swimming, boating, camping, hunting, & fishing: TBD.
Migrant Worker	• Use the closest downwind location. • Consider an adult, an infant born in 1955 and an infant born in 1964 (year of largest iodine release). • Use default consumption values. • Assume always outdoors in contact with the soil. • Assume that crops were irrigated by the Savannah River. • Assume they obtained their food from the nearest local farm or grocery store.	• Scenario location: TBD. • In 1950's, a family of two parents, two children of varying ages. In 1960's, a family of two parents, three children. • Schools: TBD. • Work: TBD. • Religion: TBD. • Food sources: TBD. • Swimming, boating, camping, hunting, & fishing: TBD.

Table E-2 SRSHES Work Group Suggested Modifications to CDC Proposed Scenarios

Proposed Scenario	SRSHES Work Group Suggested Modifications to Scenarios
Rural	• Milk source was most likely the local dairies near Girard, but not to the exclusion of the backyard cow. • Assume the family had dogs for pets. • Assume the family had chickens.
Urban/ Suburban	• Milk was obtained from a local grocery in Augusta, and not the "nearest dairy or a rural neighbor." Backyard cow is also included for the purpose of dose modeling. • Add that the mother also worked at the site during the early months of her first pregnancy (actual anecdotal). Stayed home after birth of her first child. • Include a family pet.
Delivery	• No dosimetry issued for this person. • Consider backyard chickens and/or rabbits at residence.
Outdoor	• Scenario also includes the hypothetical poacher. • Hunting dogs were also family pets. • Some potential onsite exposure from trapping activities, streams, ponds, etc.
Near River	• Scenario modifications to be developed.
Migrant Worker	• Scenario modifications to be developed.

Source: Lockridge, 2002 (1).

E.1.1 Exposure Scenarios and Locations

As discussed in Chapter 6, releases to the air from any SRS source were modeled as being transported in each of 16 sectors defined by the 16 major compass directions, consistent with the meteorological data obtained for the SRS. Figure E-1 shows that, in any sector, at a given distance from a source, concentrations were modeled as being the same along all points of an arc defined by the radial distance from the source. It shows the relative radionuclide concentration from a unit source at a distance of 10 miles from the source. In each sector, the relative concentration is constant across the sector width.

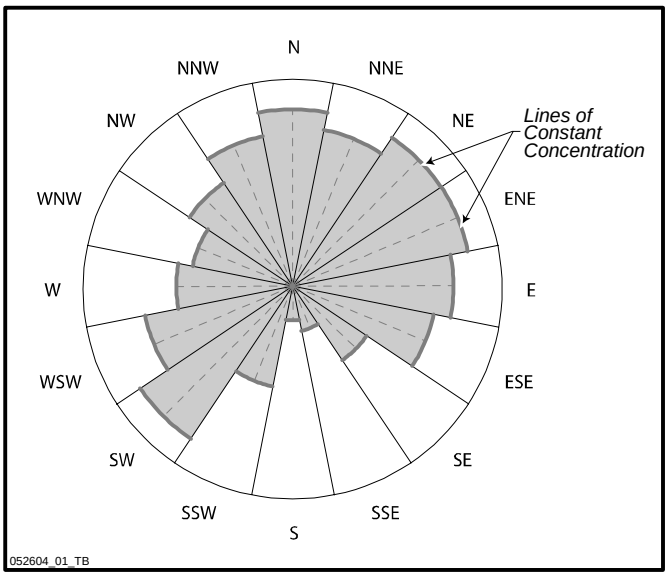

Figure E-1 Example of Modeled Radionuclide Concentration at 10 Miles from a Unit SRS Source

The meaning of this modeling simplification is that at a given distance from a source, the same concentrations will be determined anywhere is a sector.

Thus, two hypothetical exposure locations that are fairly close together will generally not differ significantly in modeled concentrations.

E.1.1.1 Exposure Scenarios and Locations Considered for Phase III

In addition to the six exposure scenarios originally proposed by CDC, a seventh was added. When the scenario locations were plotted on a map of the area surrounding the SRS, it was noted that approximately 90° out of 360°—generally towards the northeast—was without an exposure scenario. Therefore, a seventh—identified as Rural Family Two—was added with concurrence from CDC and the SRSHES.

Each of the seven exposure scenarios consisted of a family living at a designated location. In each scenario, exposure locations were identified to represent where family members lived, worked, attended school, and engaged in recreational activities; where their food was grown; and where other activities were located. For all 7 scenarios, a total of 10 exposure locations were considered for radionuclides that had been transported through the air, while 2 exposure locations were considered for radionuclides that had been transported through surface water.

Figure E-2 shows the exposure locations assumed for the seven exposure scenarios.

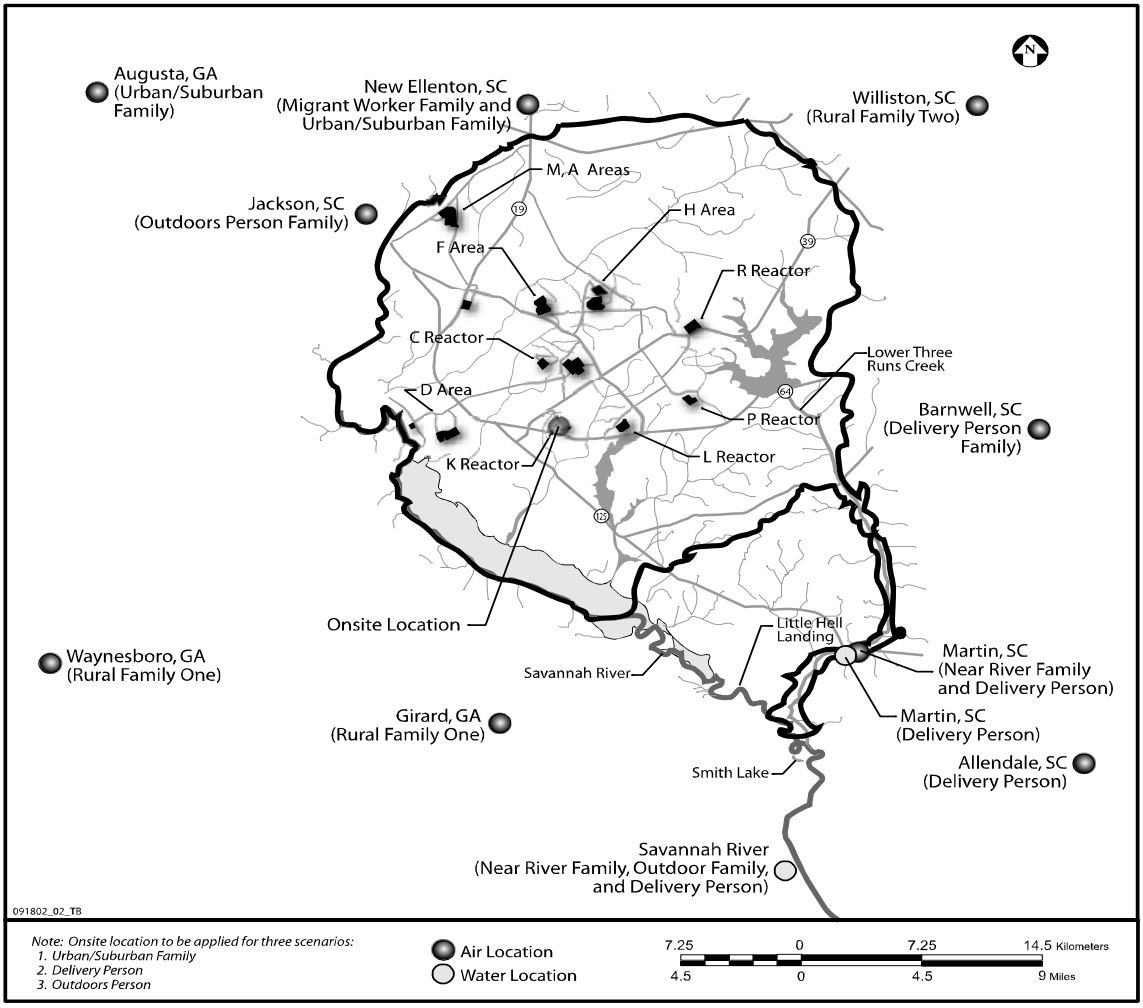

Figure E-2 Exposure Locations for Exposure Scenarios

Tables E-3 and E-4 summarize the exposure locations for contamination released into the air, while Tables E-5 and E-6 summarize the exposure locations for contamination released to surface water. The Lower Three Runs Creek exposure location is in the vicinity of Martin, South Carolina. The downstream Savannah River exposure location is representative of multiple possible locations downstream from the site.

Table E-3 Summary of Exposure Locations for SRS Air Releases

		Exposure Location									
CDC Scenario	**Activity**	**Girard**	**Waynesboro**	**Martin**	**Augusta**	**Williston**	**SRS Onsite**	**Barnwell**	**Allendale**	**Jackson**	**New Ellenton**
Rural Family One	All except high school	X									
	High school		X								
Rural Family Two	All activities					X					
Urban/Suburban Family	All except employment				X						
	Employment						X				
Delivery Person	All except noted below							X			
	Employment						X		X		
	Church, hunting. Partial grocery, swimming, fishing			X							
Outdoors Person	All except employment									X	
	Employment						X				
Near River Family	All activities			X							
Migrant Family	All activities										X

The scenarios and exposure locations are:

- Rural Family One. This family lived on a farm near Girard, Georgia. The Girard exposure location was where the family hunted, fished, and grew or produced much of their food. Although the adults always stayed near the farm, the children attended high school in Waynesboro, Georgia.
- Rural Family Two. This family lived on a farm near Williston, South Carolina. The Williston exposure location was where the family hunted, fished, and grew or produced much of their food. All family members lived at the Williston exposure location for all 39 years, including grade and high school for the children.
- Urban/Suburban Family. This family lived near the intersection of Broad and Greene Streets in Augusta, Georgia. The Augusta exposure location was assumed for most family activities including swimming, boating, and fishing. It was the exposure location where much of the family's food was grown or produced, including half of their milk. The other half of their milk came from cows located

Table E-4 Exposure Locations for Air Releases by Scenario and Pathway

Scenario	Individual	Pathway												
		External Exposure		Inhalation		Ingestion								
		Air	Soil	Air	Resus-pended Soil	Beef	Poultry	Milk	Eggs	Leafy Veg	Root Veg	Fruit	Grain	Soil
Rural Family One	Adult Male	Girard	Girard	Girard	Girard	Girard	Girard	Girard	Girard	Girard	Girard	Girard	Girard	Girard
	Adult Female	Girard	Girard	Girard	Girard	Girard	Girard	Girard	Girard	Girard	Girard	Girard	Girard	Girard
	Child Born 1955	Girard, Waynesboro	Girard, Waynesboro	Girard, Waynesboro	Girard, Waynesboro	Girard	Girard	Girard	Girard	Girard	Girard	Girard	Girard	Girard
	Child Born 1964	Girard, Waynesboro	Girard, Waynesboro	Girard, Waynesboro	Girard, Waynesboro	Girard	Girard	Girard	Girard	Girard	Girard	Girard	Girard	Girard
Rural Family Two	Adult Male	Williston	Williston	Williston	Williston	Williston	Williston	Williston	Williston	Williston	Williston	Williston	Williston	Williston
	Adult Female	Williston	Williston	Williston	Williston	Williston	Williston	Williston	Williston	Williston	Williston	Williston	Williston	Williston
	Child Born 1955	Williston	Williston	Williston	Williston	Williston	Williston	Williston	Williston	Williston	Williston	Williston	Williston	Williston
	Child Born 1964	Williston	Williston	Williston	Williston	Williston	Williston	Williston	Williston	Williston	Williston	Williston	Williston	Williston
Urban/ Suburb Family	Adult Male	Augusta, Onsite SRS	Augusta, Onsite SRS	Augusta, Onsite SRS	Augusta, Onsite SRS	Augusta	Augusta	Augusta, New Ellenton	Augusta	Augusta	Augusta	Augusta	Augusta	Augusta
	Adult Female	Augusta	Augusta	Augusta	Augusta	Augusta	Augusta	Augusta, New Ellenton	Augusta	Augusta	Augusta	Augusta	Augusta	Augusta
	Child Born 1955	Augusta	Augusta	Augusta	Augusta	Augusta	Augusta	Augusta, New Ellenton	Augusta	Augusta	Augusta	Augusta	Augusta	Augusta
	Child Born 1964	Augusta	Augusta	Augusta	Augusta	Augusta	Augusta	Augusta, New Ellenton	Augusta	Augusta	Augusta	Augusta	Augusta	Augusta
Delivery Person	Adult Male	Barnwell, Martin, Allendale, Onsite SRS	Barnwell, Martin, Allendale, Onsite SRS	Barnwell, Martin, Allendale, Onsite SRS	Barnwell, Martin, Allendale, Onsite SRS	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin
	Adult Female	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin
	Child Born 1955	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin
	Child Born 1964	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin	Barnwell, Martin

Scenario	Individual	Pathway												
		External Exposure		Inhalation		Ingestion								
		Air	Soil	Air	Resus-pended Soil	Beef	Poultry	Milk	Eggs	Leafy Veg	Root Veg	Fruit	Grain	Soil
Outdoors Person	Adult Male	Jackson, Onsite SRS	Jackson, Onsite SRS	Jackson, Onsite SRS	Jackson, Onsite SRS	Jackson, Onsite SRS	Jackson	Jackson	Jackson	Jackson	Jackson	Jackson	Jackson	Jackson
	Adult Female	Jackson	Jackson	Jackson	Jackson	Jackson, Onsite SRS	Jackson	Jackson	Jackson	Jackson	Jackson	Jackson	Jackson	Jackson
	Child Born 1955	Jackson	Jackson	Jackson	Jackson	Jackson, Onsite SRS	Jackson	Jackson	Jackson	Jackson	Jackson	Jackson	Jackson	Jackson
	Child Born 1964	Jackson	Jackson	Jackson	Jackson	Jackson, Onsite SRS	Jackson	Jackson	Jackson	Jackson	Jackson	Jackson	Jackson	Jackson
Near River Family	Adult Male	Martin	Martin	Martin	Martin	Martin	Martin	Martin	Martin	Martin	Martin	Martin	Martin	Martin
	Adult Female	Martin	Martin	Martin	Martin	Martin	Martin	Martin	Martin	Martin	Martin	Martin	Martin	Martin
	Child Born 1955	Martin	Martin	Martin	Martin	Martin	Martin	Martin	Martin	Martin	Martin	Martin	Martin	Martin
	Child Born 1964	Martin	Martin	Martin	Martin	Martin	Martin	Martin	Martin	Martin	Martin	Martin	Martin	Martin
Migrant Worker Family	Adult Male	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton
	Adult Female	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton
	Child Born 1955	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton
	Child Born 1964	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton	New Ellenton

Table E-5 Exposure Locations for Water Releases by Scenario and Pathway

	Family Member	External Exposure			Ingestion	
		Shoreline	Swimming	Boating	Fish	Swimming
Rural Family One	Adult Male Adult Female Child Born 1955 Child Born 1964	This family was assumed to do no boating in accordance with Lockridge 2002 (1).				
Rural Family Two	Adult Male Adult Female Child Born 1955 Child Born 1964	This family was assumed to do no boating in accordance with Lockridge 2002 (1).				
Urban/ Suburb Family	Adult Male Adult Female Child Born 1955 Child Born 1964	Activities were unaffected by radionuclides released to surface waters.				
Delivery Person	Adult Male Adult Female Child Born 1955 Child Born 1964	LTRC & SR*	LTRC	Savannah River	LTRC & SR*	LTRC
Outdoors† Person	Adult Male† Adult Female Child Born 1955 Child Born 1964	Savannah River†	Savannah River†	Savannah River†	Savannah River†	Savannah River†
Near River Family	Adult Male Adult Female Child Born 1955 Child Born 1964	Savannah River, all pathways				
Migrant Worker Family	Adult Male Adult Female Child Born 1955 Child Born 1964	Activities were unaffected by radionuclides released to surface waters.				

*LTRC – Lower Three Runs Creek; SR — Savannah River.
†The Adult Male and grown children received external shoreline exposures. The Adult Female did not. Family members received exposures from boating and from eating fish, but not from swimming.

Table E-6 Summary of Exposure Locations for SRS Water Releases

Scenario	Activities / Pathways	Downstream Savannah River	Lower Three Runs Creek	No Exposure to Affected Water*
Rural Family One	All activities†			X
Rural Family Two	All activities†			X
Urban/Suburban Family	All activities†			X
Delivery Person	Fishing, swimming, shoreline		X	
	Boating (and fishing)	X		
Outdoors Person	Fishing, shoreline, boating	X‡		
	Swimming			X§
Near River Family	All activities†	X		
Migrant Worker Family	All activities†			X

*Either the activity occurred in unaffected water or the activity did not occur.
†"All activities" included fishing, boating, swimming, and shoreline.
‡Only the adult male and grown children received shoreline exposures, while working at SRS.
§For entire family while recreating on the Savannah River.

in New Ellenton, South Carolina. The father worked onsite at the SRS. (The children also worked onsite at the SRS when they grew up.) A representative location on the SRS site, near the K-Reactor, was assumed as a work exposure location.

- Migrant Worker Family. This family lived in New Ellenton, South Carolina, for half of any year. The New Ellenton exposure location was assumed for all exposures and activities (home, schools, church, work, recreation, and the source for locally grown vegetables, milk, and meat).
- Delivery Person Family. This family lived in Barnwell, South Carolina, and attended church in Martin, South Carolina. Some of the food eaten by this family was obtained from Barnwell and some from Martin. The father worked in Allendale, South Carolina, and onsite at the SRS. (The children also worked onsite when they grew up.) A representative location on the SRS site, near the K-Reactor, was assumed as a work exposure location. The father hunted deer and wild fowl near Martin. The family engaged in recreation on the shore of Lower Three Runs Creek (at Martin) and on the shore of the Savannah River below its confluence with Lower Three Runs Creek. The family boated on, and ate fish from, the Savannah River at this same exposure location. The family also ate fish caught in Lower Three Runs Creek.
- Outdoors Person Family. This family lived in Jackson, South Carolina, where the family also attended church and the children went to grade and high school. Much of the food eaten by the family was grown in Jackson. The father worked and hunted on the SRS site (as did the children when they grew up). The same location on the SRS site, near the K-Reactor, was assumed for the work exposure location and the hunting exposure location. The father boated on the Savannah River while working and with his family for recreation. The family swam and spent time along the shoreline at the Jackson

Boat Ramp, which is upstream of the SRS discharge to the Savannah River. All family members ate fish that were caught in the Savannah River below its confluence with Lower Three Runs Creek.

- Near River Family. This family lived in Martin, South Carolina.[2] The Martin exposure location was assumed for all activities (home, schools, church, work, recreation, source of milk, and the source of locally grown vegetables). In addition, the family boated in, and ate fish from, the Savannah River below its confluence with Lower Three Runs Creek.

Discussion of Assumptions About Exposure Scenarios and Locations

The following discussion provides additional information about the selection of exposure scenarios and the locations:

- Two rural farming families—Rural Family One and Rural Family Two—were assumed rather than one. Rural Family Two was added to the area near Williston, South Carolina. CDC staff had suggested adding an exposure scenario to the northeast of the SRS to assure that possible radiation exposures in that direction would be considered (3). It was decided that this exposure scenario would be a rural family similar to the farming family located near Girard, Georgia (Rural Family One).
- New Ellenton, South Carolina, was chosen as the exposure location for the Migrant Worker Family. Although a migrant worker scenario had been proposed by CDC, the location where the scenario would be sited was undetermined. (The SRSHES Work Group did not recommend a location [1].) The Migrant Worker Scenario was located in New Ellenton to assure that exposures from radionuclides released to the north from the SRS would be considered and because migrant farm families were probably present in the New Ellenton area during much of the period of interest (2). In addition, the New Ellenton area was chosen as the location of a dairy patronized by the Urban/Suburban Family (2).
- The Urban/Suburban Family was assumed to fish, swim, and boat at the Augusta exposure location. The SRSHES Scenarios Work Group had proposed using Clark's Hill Lake (now called the Strom Thurmond Reservoir) for these activities (1). The Augusta location was chosen as an alternative to help limit the number of exposure locations that had to be modeled. Because both Clark's Hill Lake and Augusta are well above any point of surface water discharge from the SRS, no receptors at either location would have experienced radiological exposures from radionuclides released by the SRS to surface water. The only potential exposures would have been from radionuclides released into the air. Because Augusta is closer to the SRS than Clark's Hill Lake and both locations are northeast of the SRS, Augusta was a more conservative choice than Clark's Hill Lake.
- Any person exposed on the SRS site was assumed not to have been a radiological worker whose radiation exposures would have been routinely measured. This person would have had access to the site but not to areas controlled for purposes of radiation protection. Two candidate locations were identified: (1) near K-Reactor, and (2) the F- and H-Areas. Although hunting was probably more likely near K-Reactor, more people were employed in the F- and H-Areas. The K-Reactor vicinity was chosen to represent the exposure location for all onsite receptors, whether working or hunting.
- For all scenarios, all hypothetical family members stayed in the SRS area over the entire 39-year period. Children born and raised in the area always remained at home except for participating in specified activities such as school and recreation. After finishing high school, the children lived in their home communities. Each child adopted the same occupation and recreational activities as the adult male in their family from age 18 on.
- All radiation exposures associated with the Savannah River (boating, swimming, shoreline, and fishing) were assumed to occur at a location below the confluence of the Savannah River with Lower

[2] Note that Martin, South Carolina, is not directly on the river.

Three Runs Creek. Below the confluence, the Savannah River contained radionuclides that were discharged into the river through the Savannah River Swamp as well as radionuclides that were discharged into the river from Lower Three Runs Creek. The flow rate was not significantly larger than further upstream. For purposes of calculating air exposures while recreating on the Savannah River (e.g., immersion and inhalation doses), the Martin location was assumed as representative. Martin, Smith Lake, and Little Hell Landing are all within a few miles of one another.

E.1.2 Additional Refinements to Proposed Exposure Scenarios

In addition to the overall decisions described above, the following several refinements were made to the specifics of the exposure scenarios proposed by CDC and addressed by the SRSHES:

- Consumption of locally acquired milk. It was assumed for all scenarios that family members drank milk from cows located in the SRS vicinity, meaning that all milk contained radionuclides that had been released into the air from the SRS. This assumption met the intent of the SRSHES Work Group's suggestion that the urban/suburban and rural families should drink milk from family cows (1).
- Consumption of poultry. It was assumed that much of the poultry eaten by all members of all scenarios was produced in the SRS vicinity. This assumption largely met the intent of the SRSHES Work Group's suggestion to include family chickens in some scenarios (1).
- Hunting and similar outdoors activities. It was assumed for several scenarios that the adult male performed outdoor activities such as hunting, trapping, and fishing. Radiation exposures received through consumption of game animals was modeled for the two rural families (i.e., the Delivery Person and Outdoors Person Families) by assuming that meat from game animals could be represented as either a form of beef or poultry (see Section E.2.2 of this appendix and Section D.1.1.3 of Appendix D.) Radiation exposures received through consumption of fish was modeled for the Delivery Person, Outdoor Person, and Near River Families (see Section E.5.2.3).
- Consumption of crustaceans. All radiation exposures from eating aquatic animals were assumed to come from eating fish. The SRSHES Work Group had suggested that shell fishing, shrimping, and crabbing should be considered as food sources for the Near River Family scenario (1). However, the level of contamination at brackish downriver water locations is small and unlikely to add to radiation exposures in the vicinity of the SRS.
- Irrigation. Irrigation with water contaminated with radionuclides from the SRS was not modeled as an exposure pathway. Although the proposed CDC scenario had envisioned that the rural family and migrant families would irrigate crops with water taken from the Savannah River (1), it was determined that such a pathway would be unrealistic for the SRS area.
- Houseboating. The Near River Family was assumed to live in Martin, South Carolina, an exposure location that was consistent with the recommendations of the SRSHES Work Group (1). CDC had proposed that the family living near the river should live on a houseboat (1). Yet there was no evidence that persons lived on houseboats in the SRS area.
- Family composition. Each exposure scenario consists of two adults and two children. The SRSHES Work Group had suggested that five children be assumed for the rural family and three for the delivery person family (1). However, it was determined that this additional information would only confirm the assumptions of the proposed CDC scenarios. Each scenario proposed by CDC included two children who were born during years that SRS released large quantities of radionuclides into the air (1).
- Religion. It was assumed that all family members attended religious services for a few hours each week. This assumption was consistent with the SRSHES Work Group's suggestions (1). For most

scenarios, it was assumed that the place of worship was near the family residence. The scope of the study did not support making distinctions between the specific locations of the structures within a small geographical area.

- Pets. Pets were not modeled as a separate exposure pathway. The SRSHES Work Group suggested that persons living in the SRS vicinity would probably have had pets such as hunting dogs (1). These pets may have brought radionuclides into a house from dust or dirt caught in their fur. However, the Phase III radiological assessment made no distinction between radionuclide concentrations indoors or outdoors, either in the air or deposited on the ground.
- Nursing mothers. The rural family scenario as proposed by CDC called for a mother nursing at least one of the children (1). Separate exposures through this pathway were not modeled because a standard approach could not be used to simulate this pathway. However, the Phase III radiological assessment did consider the consumption of contaminated foodstuffs by infants, including cow's milk.
- *In utero* exposures. It was assumed that the Adult Female for the Urban/Suburban Family scenario always worked at home. The SRSHES Work Group had suggested that the mother of the urban/suburban family be assumed to work onsite until well into her pregnancy (1). It was recognized that the Work Group's proposed assumption was directed at assessing *in utero* exposure to an unborn child. However, neither the modeling approach used nor the dose and risk coefficients that were used as principal components of the analysis address such exposures.[3]

E.2 Additional Assumptions About Scenarios

To perform the Phase III radiological assessments, it was necessary to add several additional assumptions to those provided by CDC and the SRSHES to address specific features of the exposure scenarios. These assumptions are addressed in detail in Appendix E and summarized here.

E.2.1 Composition of Exposure Scenario Families

It was assumed that each of the seven hypothetical families had the same composition:

- A male who was an adult (over age 18) in 1954.
- A female who was an adult (over age 18) in 1954.
- A male child born in 1955.
- A male child born in 1964.

This family composition was chosen to model infant exposures during 1955 and 1964 when releases of radionuclides to the environment were relatively large. Male children were modeled because males receive slightly larger radiation exposures for some pathways than females (e.g., males eat more than females) and therefore provide more conservative estimates of doses and risks. It was desirable to make both children the same sex to allow direct observation of the effect of being born at different times.

Figure E-3 presents the age and gender of each receptor for each year of exposure. A 39-year period was modeled starting at the beginning of 1954 and finishing at the end of 1992. Information about the age and gender of each member of the scenario families was used to determine the ingestion rates of certain foods (Section E.2.2), the times spent performing different activities (Section E.2.3), and other activities. In

[3]The dose and risk coefficients used are up-to-date coefficients issued by the Environmental Protection Agency in their 1992 update to Federal Guidance Report 13, "Cancer Risk Coefficients for Environmental Exposure to Radionuclides" (4).

addition, information about each individual's age and gender was used to convert exposure levels to lifetime radiation dose and cancer risk as discussed in Chapter 10 and Appendix D.

As the children grew from infants to adults, assumptions about parameter values were made that were appropriate for their age. Each child was assumed to grow from a male infant (his first year), to a preschooler (3 years from ages 2-4), to a grade-school aged child (7 years from ages 5-11), to a teenager (6 years from ages 12-17) years), to an adult age (all remaining years from age 18 on). After each child reached age 18, parameter values appropriate for an adult were maintained for the rest of the study period. The Child Born in 1955 became an adult in 1973; the Child Born in 1964 became an adult in 1982.

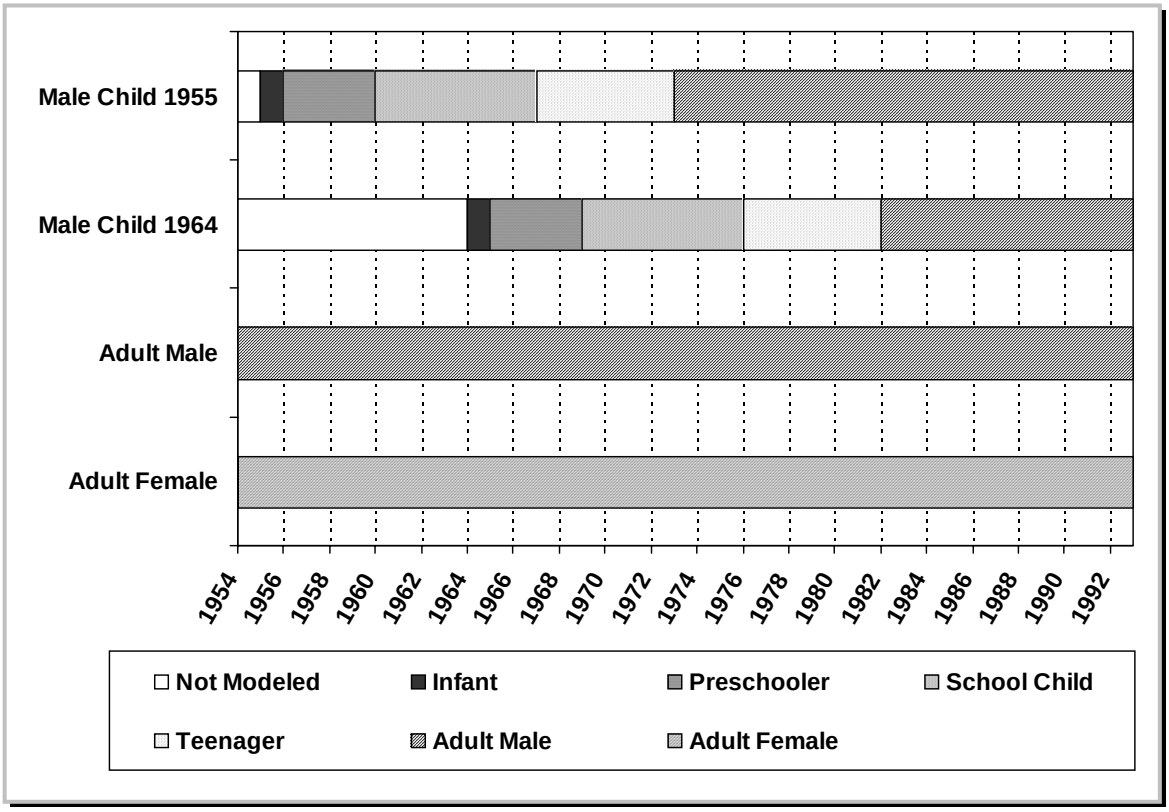

Figure E-3 Age and Gender Categories of Modeled Receptors by Year

E.2.2 Overview of Food Product Consumption

To address radiation exposures through consumption of food and animal products, quantities of each food product eaten by each receptor were estimated as well as the fraction of each food product that had been contaminated with radionuclides released by the SRS. Assumptions were made for each family member about the consumption rates of the food products listed below. The primary data source for these assumptions was EPA's "Exposure Factors Handbook" (5):

- Leafy vegetables
- Root vegetables
- Fruit
- Grain
- Beef
- Poultry
- Milk
- Eggs
- Fish

The quantity of each food product consumed annually depended on the age of the receptor. Adults living in the SRS vicinity at the start of SRS operations in 1954 ate a constant annual quantity of each food product over the 39 years of the study. Adult females generally ate less food than did the adult males. The children ate different quantities of each food product depending on their age. After each child reached age 18, they ate each food product in annual quantities appropriate for an adult male.

Assumptions about food product contamination depended on the food product and scenario. If the food product was grown or produced locally (e.g., from local farms or dairies), then it was assumed that all was contaminated. If the food product was from a local store, then it was assumed that some (generally half) was obtained locally (and therefore contaminated) and the remainder was obtained from sources external to the SRS vicinity.

Radiation exposure from eating game animals taken near the SRS site was modeled by assuming that meat from all game animals could be represented as forms of beef (e.g., venison) or poultry (e.g., wild fowl). Members of Rural Family One and Two, the Delivery Person Family, and the Outdoors Person Family were assumed to eat game animal meat. The total quantities of beef and poultry that these members ate were the same as that eaten by comparable members of the other three scenarios. However, larger fractions of this meat were assumed to be locally produced for these four scenarios compared to the other three scenarios.

E.2.3 Scenario Exposure Time Assumptions

To perform the exposure assessments outlined in Section E.5, it is necessary to document the time spent by each family member performing each of their assumed activities. Each family member was assigned a time spent at home, at work (for the adult male and for the children after they became adults), at church, and while performing other activities including hunting, fishing, swimming, and boating. Times spent performing these activities were determined from Lockridge (1), the 1997 EPA “Exposure Factors Handbook” (5), and Hamby (6). Appendix Q includes a matrix showing the times performing each activity by each member of each family exposure scenario.

Except for the Migrant Worker Family, the total time spent by each family member performing all activities added to 8,760 hours each year (24 hours/day x 365 days/year). This reflects the conservative assumption that no family member was ever away from the SRS vicinity. The total time spent by each member of the Migrant Worker Family was only 4,380 hours/year, reflecting their presence in New Ellenton for only half of any year.

A distinction is made between hours spent indoors vs. hours spent outdoors because the information is used to help determine external radiation exposures from contaminated soil (Section E.5.1.2). For each exposure scenario, the split between indoor and outdoors hours changed for the two children as they grew from infant to adult; however, it was assumed to be constant for the two adults. This assumption was made to reduce modeling complexity despite the expectation that an infant and an Adult Female would have the same number of outside hours. But because each of the children were infants for only a single year, it was determined that adjusting the outside hours of the Adult Female to closely correspond to that of the children as they grew up was not warranted.

The hours spent indoors and outdoors were determined principally based on (1) the definition of the exposure pathways and (2) data from Lockridge (1) and EPA, 1997 (5). For some exposure pathways, the time spent indoors and outdoors was contained within the definition of a receptor’s actions. For example, it was assumed that swimming, boating, or walking a river shoreline were all outdoor activities. When indoor and outdoor hours were not defined under the scenario specifications, assumptions about the split between indoor and outdoor hours were made as addressed below.

- Church. Except for the Migrant Worker Family, all members of all exposure scenarios spent 104 hours per year in church (52 weeks/year x 2 hours/week). All members of the Migrant Worker Family spent 52 hours per year in church. All hours in church were spent indoors.

- School. Except for the Migrant Worker Family, for all exposure scenarios, the school-aged and teenaged children all spent 1,260 hours per year in school (180 days/year x 7 hours/day). (The school-aged children attended grade school and the teenagers attended high school.) Of these 1,260 hours per year, 900 hours were spent indoors and 360 hours were spent outdoors [(5 hours indoors/day, 2 hours outdoors/day) x 180 days/year]. The school-aged and teenaged children of the Migrant Worker Family spent 630 hours per year in school (90 days/year x 7 hours/day). Of these 630 hours/year; 450 hours were spent indoors and 180 hours were spent outdoors [(5 hours indoors/day, 2 hours outdoors/day) x 90 days/year].

- Work. Except for the Migrant Worker Family, the Adult Male of all exposure scenarios spent 2,000 per year at work (40 hours/week x 50 weeks/year).[4] The Adult Male of the Migrant Worker Scenario spent 1,000 hours per year at work. The split between indoors and outdoors hours depended on the nature of the work. The Adult Males of Rural Family One, Rural Family Two, and Migrant Worker Family were farmers, spending one working hour per day indoors, and seven working hours per day outdoors. The Adult Males of the Urban/Suburban Family and Near River Family mainly worked within buildings, spending seven working hours per day indoors, and one working hour per day outdoors. The Adult Male of the Delivery Person Family worked 400 hours per year making deliveries to the SRS and the remaining 1,600 hours per year in Allendale. Of the annual 400 hours working onsite at the SRS, 200 hours were indoors and 200 hours were outdoors. At Allendale, the remaining annual 1,600 hours were divided into 1,350 hours indoors and 250 hours outdoors (1 hr/day for 250 days/year spent outdoors). The Adult Male of the Outdoors Person Family spent all of his 2,000 working hours at the SRS outside. Of these working hours, 260 hours/year were spent along the SRS shoreline (where he was exposed to radionuclides deposited from the Savannah River on the shoreline), and 260 hours/year were spent boating in the Savannah River. The exposures from these working activities were in addition to recreational shoreline and boating activities addressed below. Thus, the following are the annual working hours for the Adult Males of each exposure scenario:

  -- Rural Family One: 250 hours indoors, 1,750 hours outdoors.

  -- Rural Family Two: 250 hours indoors, 1,750 hours outdoors.

  -- Urban/Suburban Family: 1,750 hours indoors, 250 hours outdoors.

  -- Migrant Worker Family: 125 hours indoors, 875 hours outdoors.

  -- Delivery Person Family: Allendale – 1,350 hours indoors, 250 hours outdoors; SRS – 200 hours indoors, 200 hours outdoors.

  -- Outdoors Person Family: 2,000 hours outdoors, including 260 hours on the shoreline and 260 hours boating.

  -- Near River Family: 1,750 hours indoors, 250 hours outdoors.

  Note that all children of all exposure scenarios adopted the same work habits (and annual times spent indoors and outdoors) as did the Adult Male of the exposure scenario when each of the children reached age 18.

- Hunting and fishing. For all receptors, hunting and fishing were outside activities. Except for the Adult Male of the Outdoors Person Scenario, the time spent hunting and fishing was included with

[4] All two-week vacations from work were spent at home.

the residential outside hours (see below). For the Adult Male of the Outdoors Person Scenario, time spent outdoors hunting and fishing was included with his work hours. This assumption also applied to the two children of the Outdoors Person Scenario when they reached age 18 and began working on the SRS site.

- Recreational swimming, shoreline, and boating. Except for members of the Migrant Worker and Near River Family, members of all exposure scenarios (including all members of the Outdoors Person Scenario) spent 21 hours/year swimming and 85 hours/year along a river or creek shoreline. Members of the Migrant Worker Family swam for 11 hours per year and spent 43 hours along a shoreline. Members of the Near River Family swam for 91 hours per year and spent 365 hours per year along a shoreline. (See Section E.5.1.4 for the derivation of the swimming hours, and Section E.5.1.3 for the derivation of shoreline hours.)

  Members of Rural Family One, Rural Family Two, and the Migrant Worker Family did no boating. Members of the Urban/Suburban Family, Delivery Person Family, and Outdoors Person Family recreationally boated for 96 hours per year, while members of the Near River Family boated for 192 hours per year. (See Section E.5.1.5 for the derivation of the boating hours.) All swimming, shoreline, and boating hours were spent outside.

- Home. Times spent at home were determined for each member of each exposure scenario by adding all hours spent while at church, work, and school, and while swimming, boating, and spending time along a shoreline. These summed hours were subtracted from the total hours spent in the SRS vicinity each year (generally 8,760 hours). The remaining hours were distributed between indoors and outdoors hours using data from the EPA "Exposure Factors Handbook" (5) as summarized in Table E-7. This table summarizes data from the EPA "Exposure Factors Handbook" (5) that presents mean values for the times spent indoors and outdoors for various age and gender categories (first column). Table E-7 also shows the corresponding grouping of age and gender categories that were modeled for this study (second column).

Table E-7 Time Spent Outdoors – EPA 1997 Age and Gender Categories and Rate Data, and Corresponding Modeled Age and Gender Categories and Calculated Rates

EPA Age and Gender Categories	Corresponding Modeled Age and Gender Categories	Time Spent Outdoors (minutes/ day)	Calculated Time Spent Outdoors (hours/year)	Time Spent Indoors (minutes/day)	Calculated Time Spent Indoors (hours/year)
1 – 4	Infant (<1)	196	1,190	1,212	7,371
1 – 4	Pre-School (1-7)	196	1,190	1,212	7,371
5 – 11	Child (<7 – 12)	188	1,141	1,005	6,115
12 – 17	Teenager (<12 – 17)	135	823	970	5,898
18 – 64	Adult Male (>17)	144	877	948	5,766
18 – 64	Adult Female (>17)	144	877	948	5,766

Source: Table 15-132 (mean values) from EPA, 1997 (5).

As an example, the Infant of Rural Family One annually spent 104 hours in church, 21 hours swimming, and 85 hours along a shoreline. This leaves (8,760 – 104 – 21 – 85 = 8,550 hours. Using Table 3-7, the hours spent indoors were calculated as 8,550 x 7371/(1190 + 7371) = 7,362 hours. The hours spent outdoors were calculated as 8,850 x 1190/(1190 + 7371) = 1,188 hours.

Hours for the remaining members of the exposure scenarios were calculated in a similar manner and are listed in Appendix Q.

E.3 Overview of Final Exposure Scenarios

The seven scenarios and the assumed home locations for each of the hypothetical families making up these scenarios are described in detail in the following sections.

E.3.1 Rural Family One

This hypothetical family lived in Girard, Georgia. All family members spent much of their work, home activities, and recreation time outdoors. The Adult Male was a farmer, and the Adult Female worked at home. The family hunted, fished, and swam in the Girard area and in the nearby area of Briar Creek. The family did no boating. The children stayed at home until they reached school age; then they attended grade schools in Girard and high school in Waynesboro, Georgia. When not attending school, the children remained in the Girard area. When the children grew to adulthood, they became farmers and fished, hunted, and engaged in recreational activities in the Girard area. All family members remained permanently in the Girard area. Figure E-4 shows the exposure locations of Rural Family One.

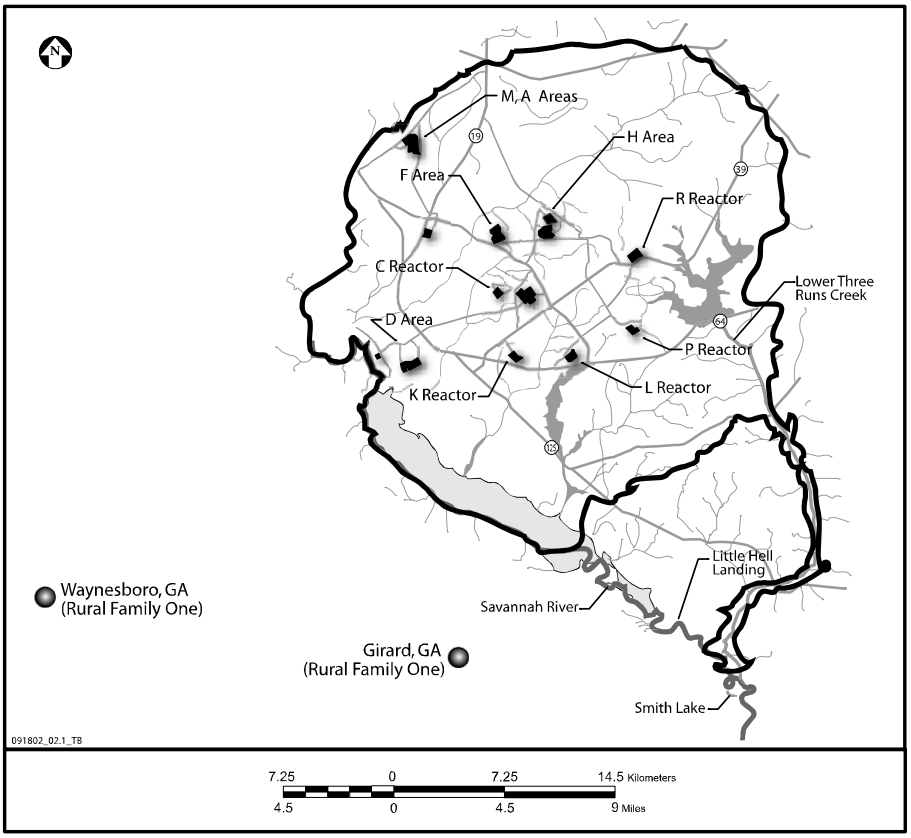

Figure E-4 Exposure Locations of Rural Family One

All the family's milk and eggs came from cows and hens located in Girard. The fish eaten by the family was caught in Briar Creek or other nearby locations. Because Briar Creek is not located hydrologically downstream from the SRS, none of the fish consumed by the family was affected by SRS release of radionuclides to surface water. During the 1950's, half of the beef, poultry, leafy and root vegetables, and fruit eaten by the family was grown or produced on the family farm. The remainder came from other sources such as stores in Girard. Half of this remaining food was locally grown or produced. Beginning in 1960, only 25 percent of their beef, poultry, vegetables, and fruit was grown or produced on the family farm. The remaining 75 percent came from sources such as stores. Half of this remaining food was grown or produced in Girard, and half came from sources outside the SRS. It was assumed that all of the locally grown grain eaten by the family was corn.[5] Drinking water and water used to irrigate the food grown and eaten by the family came from local ground water or surface water sources that were unaffected by SRS releases.

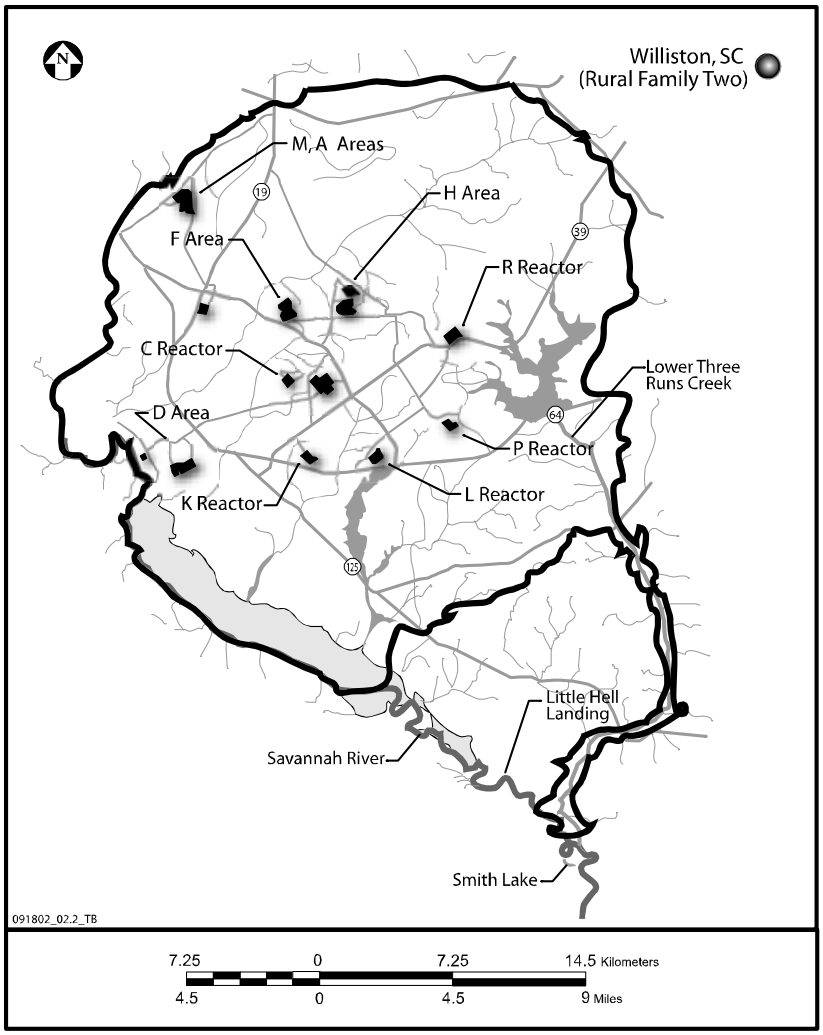

Figure E-5 Exposure Location of Rural Family Two

E.3.2 Rural Family Two

Rural Family Two was a hypothetical family substantially similar to Rural Family One, except that the family lived and spent all their time in Williston, South Carolina. Figure E-5 shows the exposure location of Rural Family Two.

All family members spent much of their work, home activities, and recreation time outdoors. The adult male was a farmer, and the adult female worked at home. The family hunted, fished, and swam in the Williston area. Like Rural Family One, this family did no boating. The children stayed at home until they reached school age, and then they attended schools in Williston. When not attending school, the children

[5] This assumption was made for all receptors and scenarios. Individuals in the SRS vicinity would have consumed grain products such as breads, pasta, or flours; however, most of these grain products were likely grown or produced out of the SRS vicinity and therefore were not contaminated by SRS operations. But it is plausible to assume that individuals in the SRS vicinity consume locally grown corn. Such consumption could occur for those persons living in a suburban as well as a rural environment. Therefore, corn was treated as a grain for purposes of this study and as a grain surrogate for purposes of the assessments.

remained in the Williston area. When the children grew to adulthood, they became farmers. The family always lived, engaged in recreational activities, and worked in and around the Williston area.

All of the family's milk and eggs came from cows and hens located in Williston (on the family farm or nearby). All of the fish eaten by the family were caught in streams or ponds in or near Williston. Because these streams and ponds are not hydrologically downstream from the SRS, none of the fish eaten by the family was affected by SRS releases of radioactive material to surface water.

During the 1950's, half of the beef, poultry, leafy and root vegetables, and fruit eaten by the family was grown or produced on the family farm. The remaining half came from other sources such as stores in Williston. Half of this remaining food (i.e., food not grown or raised on the family farm) was grown or produced in Williston and the other half came from outside the SRS area. Beginning in 1960, only 25 percent of their beef, poultry, vegetables, and fruit was grown or produced on the family farm. The remaining 75 percent was obtained from other sources such as stores in Williston. Half of this remaining food was locally grown or produced, and half came from outside the SRS area.

All locally grown grain eaten by the family was corn. Drinking water and water used to irrigate any food grown and eaten by the family came from ground- or surface-water sources assumed to be unaffected by SRS releases

E.3.3 Urban/Suburban Family

This hypothetical family lived in Augusta, Georgia, and all family members were present there for most activities including school and church. The Adult Male worked onsite at the SRS for the duration of the study period (39 years). The children worked onsite at the SRS beginning in 1973 for the Child Born in 1955 and 1982 for the Child Born in 1964. All family members swam, boated, and fished in the Savannah River flowing through the Augusta area, a location well upstream of any point of radionuclide discharge to surface water from the SRS. Figure E-6 shows the exposure locations of the Urban/Suburban Family.

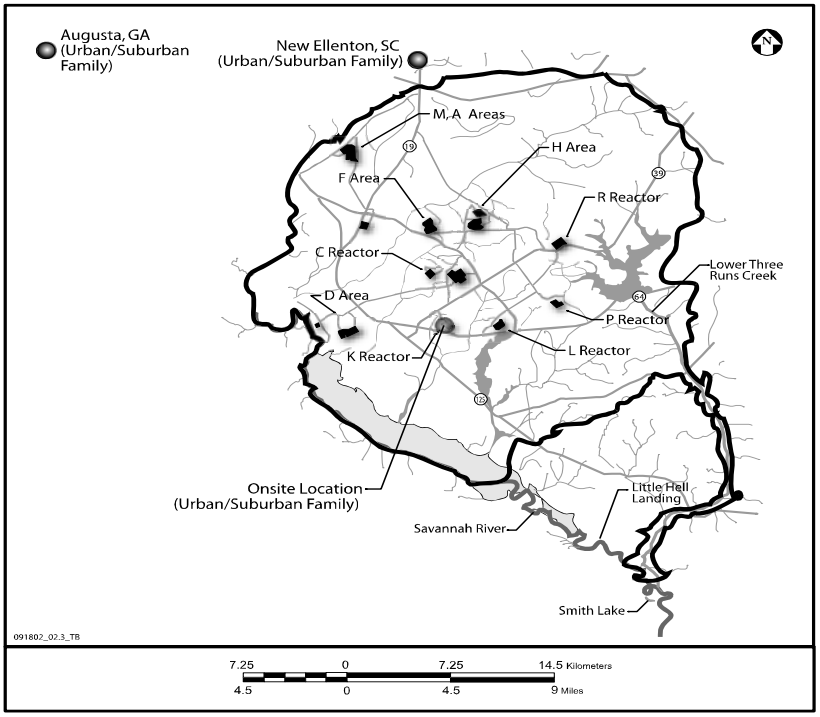

Figure E-6 Exposure Locations of Urban/Suburban Family

Half the family's milk came from cows in the Augusta area and half from cows in the New Ellenton area. All eggs came from hens located in the Augusta area. Half of their beef, poultry, leafy vegetables, root vegetables, and fruit was grown or produced in the Augusta area, and half came from unaffected nonlocal sources. All locally grown grain eaten by the family was corn. Fish came from sources unaffected by liquid releases from the SRS (e.g., from the nearby Savannah River). Drinking water and water used to irrigate any food grown and eaten by the family came from ground- or surface-water sources assumed to be unaffected by SRS releases

E.3.4 Migrant Worker Family

All family members spent much of their work, home activities, and recreation time outdoors in New Ellenton, South Carolina. Figure E-7 shows the exposure location of the Migrant Worker Family. Because the Adult Male and Adult Female worked as migrant farm workers, the family lived in New Ellenton for only half of any year. While living in New Ellenton, the family participated in hunting, trapping, and other outdoor activities. The family did no boating but did participate in other water sports such as fishing and swimming in local pools, ponds, and creeks. The children stayed at home until they reached school age and attended schools in New Ellenton. When the children grew to adulthood, they became migrant farmers spending half the year in New Ellenton and half the year away from the SRS vicinity.

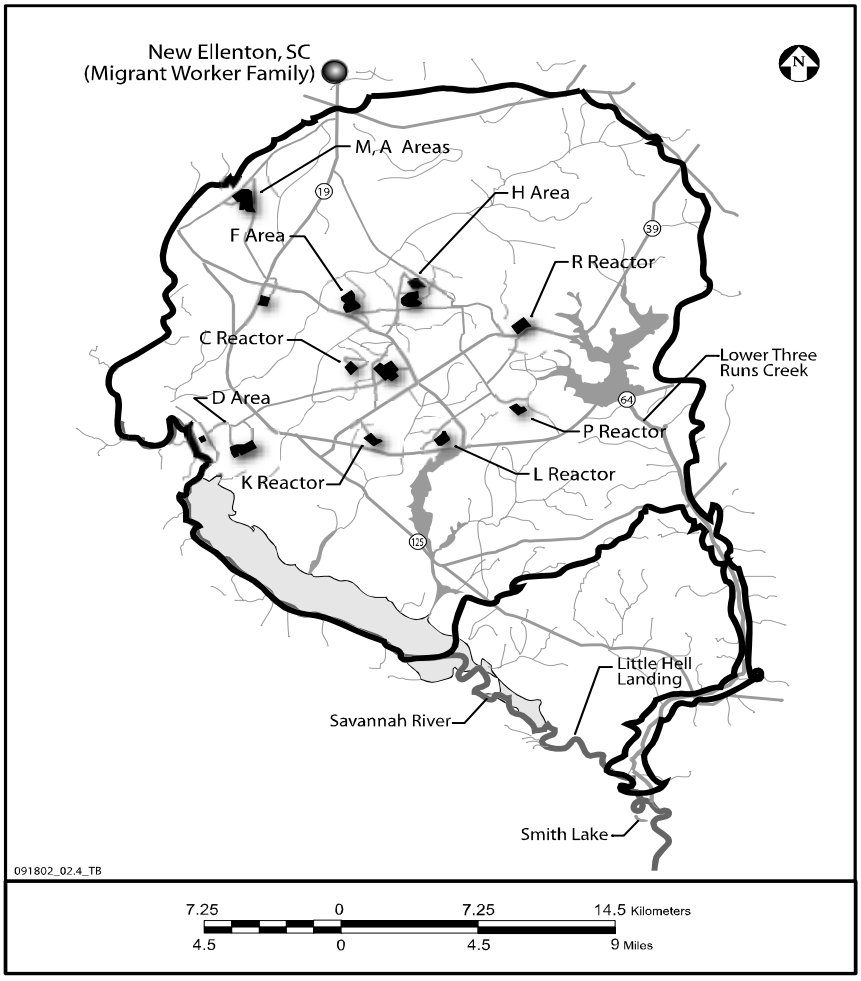

Figure E-7 Exposure Location of Migrant Worker Family

During the six months of each year that the family lived in New Ellenton, all of their milk and eggs were produced or collected in or near New Ellenton. Half of the family's beef, poultry, leafy vegetables, root vegetables, and fruit was grown or produced in the New Ellenton area and half came from sources outside the SRS vicinity. All of their corn was grown in the New Ellenton area. Because ponds and creeks in the vicinity of New Ellenton are not hydrologically downstream from the SRS, none of the fish eaten by the family was affected by SRS releases. Drinking water and water used to irrigate foods eaten by the family came from ground water or surface water sources unaffected by SRS liquid releases.

E.3.5 Delivery Person Family

This hypothetical family lived in Barnwell, South Carolina, where the children attended grade and high school. Because the Adult Male worked as a delivery driver for a bottling plant located in Allendale, South Carolina, he spent portions of his time in Allendale and portions onsite at the SRS where he made periodic deliveries. (When the children reached 18, they lived in Barnwell and became delivery drivers like the Adult Male.) All family members attended religious services in Martin, South Carolina, for two hours each week. All family members swam, fished, and spent time along the shoreline at Lower Three Runs Creek near Martin. The adult male hunted for deer and fowl in the Martin vicinity. Figure E-8 shows the exposure locations of the Delivery Person Family.

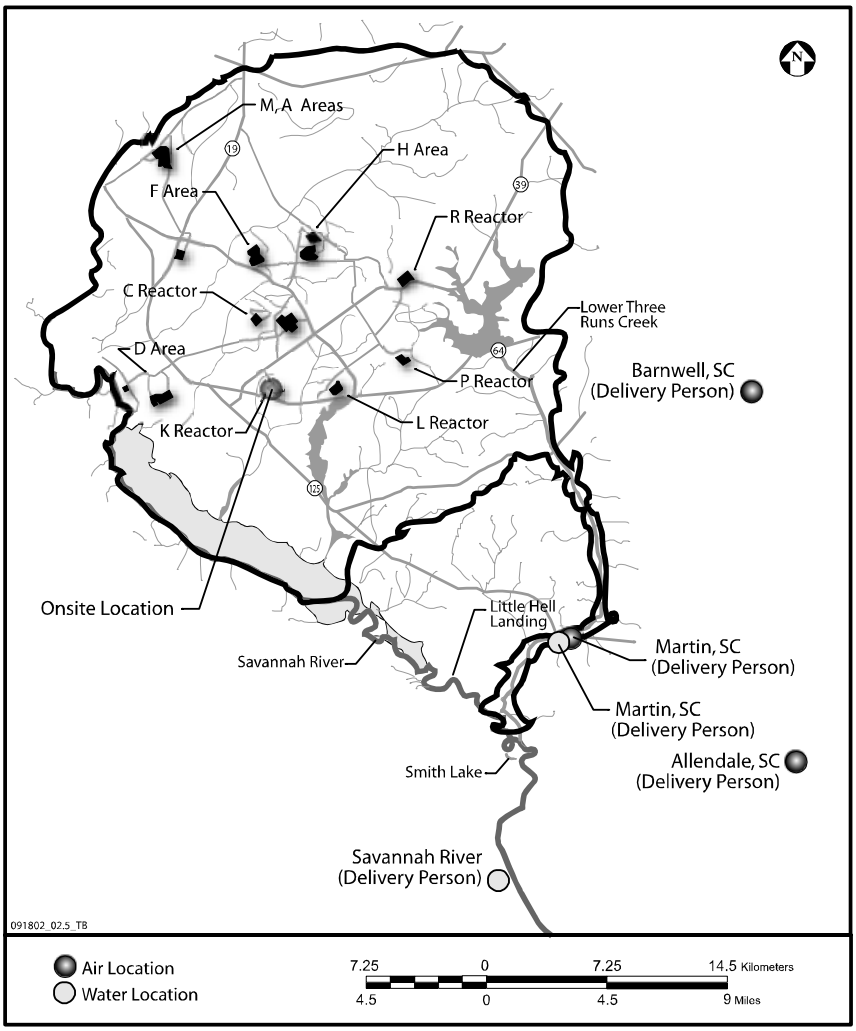

Figure E-8 Exposure Locations of Delivery Person Family

The family boated on the Savannah River using the boat ramp at Little Hell Landing, which is upstream of the confluence of the Savannah River with Lower Three Runs Creek. The family then moved the boat to the Smith Lake area for fishing and activities along the Savannah River shoreline. Smith Lake is located just below the confluence of the Savannah River with Lower Three Runs Creek. The family did not swim in the Savannah River.

Half of the family's milk and eggs came from cows and hens in the Barnwell area and half came from cows and hens in the Martin area. In addition, half the family's beef and poultry came from Barnwell and half from Martin. Half of the beef and poultry from Barnwell was actually produced in the Barnwell area, and half was acquired from sources away from the SRS area. Of the beef and poultry from Martin, 25 percent consisted of meat from hunting deer and wild fowl. That is, 25 percent of the beef from Martin consisted of locally hunted venison while 25 percent of the poultry from Martin consisted of locally hunted wild fowl. Of the remaining 75 percent of the beef and poultry from Martin, half was produced in the Martin area and half was acquired (e.g., by stores) from sources well away from the SRS.

Half the leafy vegetables, root vegetables, and fruit came from Barnwell, and half came from Martin. Half of the produce obtained in the Barnwell area was grown in areas away from the SRS vicinity and half of the produce obtained in the Martin area was grown in areas away from the SRS vicinity. Half of the corn eaten by the family was grown in Barnwell and half in Martin.

Half of the fish eaten by the family was caught in Lower Three Runs Creek at Martin and half was caught in the Savannah River.

E.3.6 Outdoors Person Family

This hypothetical family lived in Jackson, South Carolina, and all family members were present there for most activities including school and religious services. When the children grew to adulthood, they continued to live in Jackson. Family members were not present in Jackson during employment for the Adult Male and employment for the children when they each reached age 18. The Adult Male worked onsite at the SRS as a hunter, as did the children when they grew up. During the time the Adult Male spent onsite at the SRS annually, he took game animals in the form of deer and birds, and caught fish from the Savannah River. His job required him to spend 260 hours per year along on the Savannah River shoreline as well as 260 hours per the year boating on the Savannah River. Figure E-9 shows the exposure locations of the Outdoors Person Family.

All family members (including the Adult Male) engaged in recreational swimming in the Savannah River and spent time along the Savannah River shoreline near the Jackson boat ramp (upstream of sources of SRS radionuclide release to the Savannah River). All family members boated in the Savannah River downstream of the SRS.[6]

All milk and eggs came from cows and hens located in Jackson. Half the leafy and root vegetables and fruit were grown in Jackson, and half came from sources away from the SRS area. All of the family corn was grown in Jackson.

Three-quarters of the family's beef and poultry consisted of venison and wild fowl that was hunted by the Adult Male on the SRS site. Their remaining beef and poultry came from other sources such as stores. Of this, half was produced in Jackson and half came from sources away from the SRS area. All fish taken from the Savannah River contained radionuclides from SRS operations.

[6] After putting the boat in the water at the Jackson boat ramp, the family moved the boat to an area downstream of the confluence of the Savannah River with Lower Three Runs Creek. Therefore, the Adult Male received radiation exposures while recreationally boating as well as while working at the SRS.

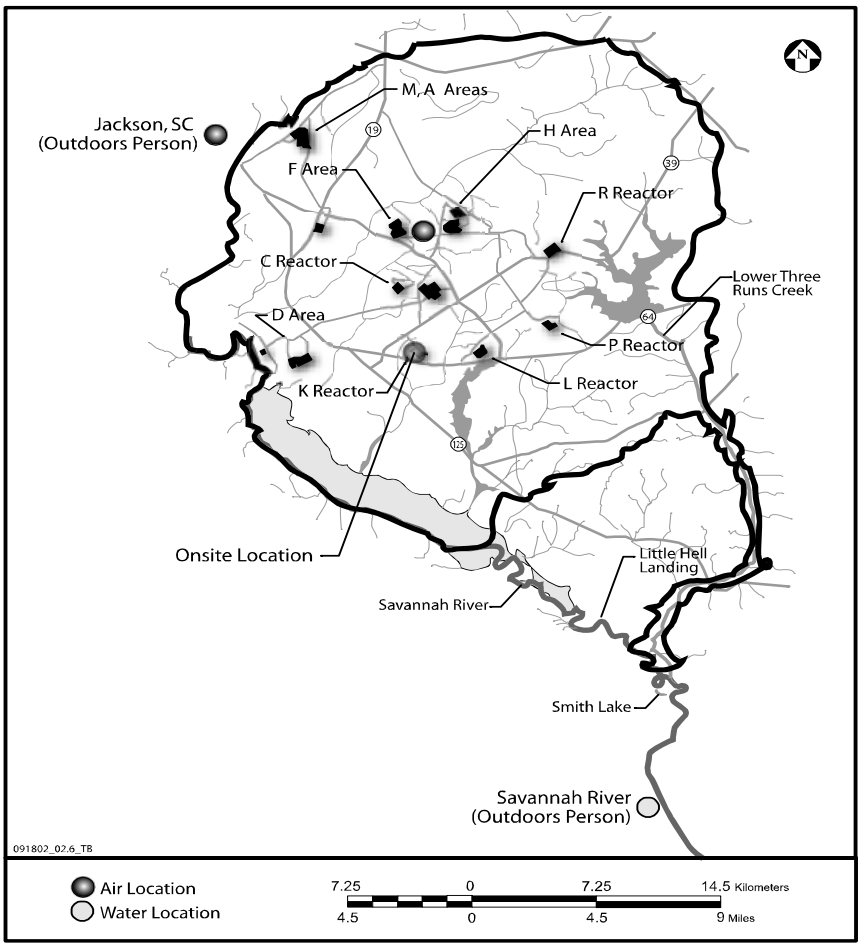

Figure E-9 Exposure Locations of Outdoors Person Family

E.3.7 Near River Family

This hypothetical family lived in Martin, South Carolina. All members spent much of their work, home activities, and recreation time outdoors. The family lived, worked, and went to school and church in Martin, and participated in outdoor activities such as hunting, fishing, and boating. Figure 3-10 shows the exposure locations for the Near River Family.

This family spent twice as much time boating (in the Savannah River) as did other families. Each family member spent an average of an hour per day of each year on the Savannah River shoreline and an average of an hour a day swimming during the summer in the Savannah River. When the children grew up, they continued to live in Martin. The family's milk and eggs all came from cows and hens located in Martin. Half of the family's beef, poultry, leafy vegetables, root vegetables, and fruit was grown or produced in Martin and half came from sources outside the SRS vicinity. All of the corn eaten by the family was grown in Martin. All of the fish eaten by the family was caught in the Savannah River below its confluence with Lower Three Runs Creek. Drinking water and any irrigation used to produce the food eaten by the family came from sources unaffected by SRS releases.

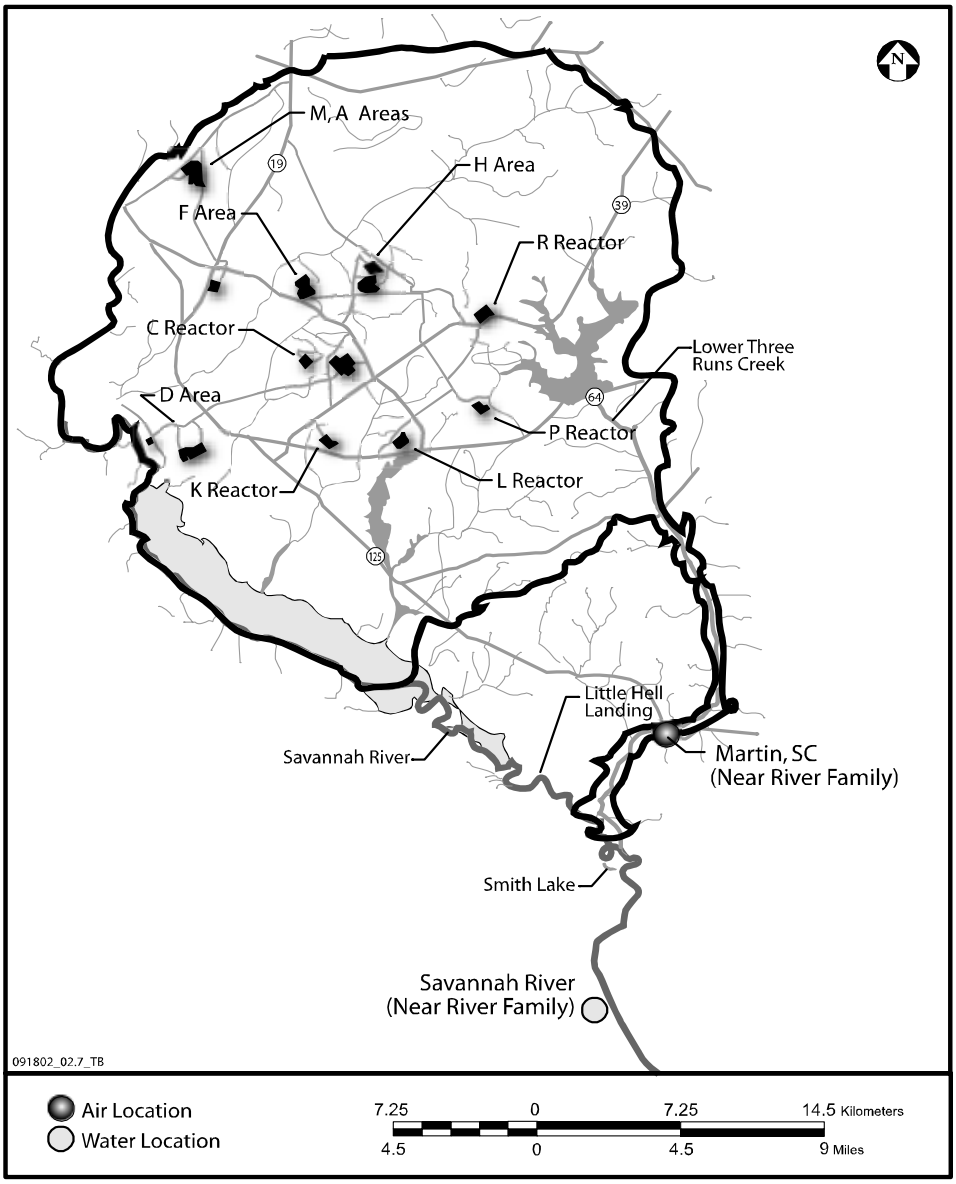

Figure E-10 Exposure Locations for Near River Family

E.4 Linkage of GENII Variables to Exposure and Adjustment Factors

Because of the size and complexity of the computational requirements, radiological assessment calculations were performed using the GENII code assuming "unit" quantities for receptor-specific usage factors such as food consumption rates. The output from the GENII code was then modified in the post-processor (software specially created for this Phase III study) to arrive at the proper doses and risks as a function of year for each receptor. These adjustments were performed using a series of receptor- and pathway-specific *exposure* and *adjustment factors* that were multiplied by the GENII output. Mathematically, the use of the exposure and adjustment factors to calculate annual dose may be envisioned as follows:

$$D_{PPrp} = D_{Grp}\ EF_{rp}\ AF_{rp}$$

Where D_{PPrp} = The dose (Sv) calculated from the post-processor for each receptor and for each pathway.

D_{Grp} = The dose (Sv) calculated from GENII for each receptor and for each pathway, assuming unit quantities for usage factors.

EF_{rp} = A receptor- and pathway-specific exposure factor.

AF_{rp} = A receptor- and pathway-specific adjustment factor.

A similar relationship may be envisioned to calculate the use of exposure and adjustment factors to link risks calculated from GENII runs and those calculated using the post-processor.

Exposure and adjustment factors are discussed in Sections E.4.1 and E.4.2, respectively.

E.4.1 Creation of Exposure Factors

An *exposure factor* was created for each pathway by multiplication of two or more GENII variables used to describe receptor-specific usage factors. The creation of an exposure factor may be illustrated using the example provided below.

The mathematical relationship used in the GENII code to calculate radiation exposures received by a receptor from inhaling air containing radionuclides is presented in the GENII Software Design Document (Napier, 2002) and summarized in Section D.3.4.1 of Appendix D. The total amount of radioactive material inhaled over a period of time (in this case one year) is given as follows (7):

$$I_{aaig}(T) = C_{aag} \; U_{aag} \; T_{aag} \; ED_{aag}$$

Where $I_{aaig}(T)$ = total intake of radionuclide i from air inhalation over the period T at air usage location a for individuals in age group g (Bq)

C_{aag} = average air concentration for radionuclide i at air usage location a over time period T (Bq/m^3)

U_{aag} = inhalation rate at air usage location a for individuals in age group g (m^3/d)

T_{aag} = annual intake factor giving days per year that air inhalation occurs at air usage location a for individuals in age group g (d/y)

ED_{aag} = exposure duration for the air inhalation pathway at air usage location a for individuals in age group g (y).

The total intake of radionuclide i, or $I_{aaig}(T)$, was then input to the dose and risk computational module described in Section D.4, and doses and risks were calculated for each receptor for each year of SRS operation. To calculate $I_{aaig}(T)$, C_{aag}, U_{aag}, T_{aag}, and ED_{aag} had to be numerically specified. The exposure duration (ED_{aag}) was one year in all cases. The average concentration (C_{aag}) was determined for each year and receptor location using the Gaussian plume air dispersion model described in Section D.2.

The remaining parameters, U_{aag} and T_{aag}, had to be input to GENII for each code run using the FRAMES interface. The GENII variable names for these parameters are UINH and TINH, respectively (7). Under

normal circumstances, assuming year-round presence of an adult male at the location of interest, one would have input a value for UNIH of 15.2 m^3/ day, which is the average daily breathing rate of an adult male according to EPA data in its 1997 Exposure Factors Handbook (5). One would have also input 365 days per year for TINH. (The product of UINH and TINH is 15.2 x 365 = 5,548 m^3/year.)

But to address computational needs as discussed above, GENII was run (determining values for $I_{aaig}(T)$) assuming that UINH and TINH both equaled unity (i.e., UINH = TINH = 1). After completing the GENII computer runs, the output from GENII was fed into the postprocessor, and the GENII calculations were adjusted using appropriate exposure factors. For this example, the exposure factor was calculated as the product of the above example values for UINH and TINH. For an adult male, the exposure factor would have been 5,548 m^3/year. The exposure factor for another person (say, an infant or an adult female) would have been different because that person would have had a different average daily breathing rate.

Similar procedures were performed for each of the pathways. Table E-8 lists, for each pathway, the GENII variables that were input as unit values to the GENII calculations. This table also identifies the computational parameter that the GENII variable represents, as well as that section in Appendix D where the use of the parameter in the mathematical expressions codified in GENII can be found.

Table E-8 GENII Variables Input as Unit Values and Adjusted in Post-Processor

Trans-port	Transfer Process or Activity	Exposure Pathway (Section)	Param-eter	GENII Variable Name and Description
Air	Plume Immersion	External Exposure (Section D.3.2.1)	U_{eag} T_{eag}	UEXAIR – Daily exposure factor (h/d) TEXAIR – Annual exposure factor (d/y)
Air	Ground Contamination	External Exposure (Section D.3.2.2)	SH_h SH_o U_{esg} T_{esg} FT_{hg} FT_{og}	SHIN – Indoor shielding factor (dimensionless)* SHOUT – Outdoor shielding factor (dimensionless)* UEXGRD – Daily external exposure time (h/d) TEXGRD – Yearly external exposure time (d/y) FTIN – Fraction of time indoors (dimensionless)* FTOUT – Fraction of time outdoors (dimensionless)*
Surface Water	Concentration in Sediment	External Exposure (Section D.3.2.3)	FE_{srg} TE_{srg} T_{srg}	EVSHOR – Frequency of shoreline use (event/d) TESHOR – Duration of shoreline use (h/event) TSHOR – Shoreline days (d/y)
Surface Water	Recreational Swimming	External Exposure (Section D.3.2.4)	FE_{wrg} TE_{wrg} T_{wrg}	EVSWIM – Frequency of swimming (event/d) TESWIM – Duration of swimming event (h/event) TSWIM – Swimming days (d/y)
Surface Water	Recreational Boating	External Exposure (Section D.3.2.5)	FE_{brg} TE_{brg} T_{brg}	EVBOAT – Frequency of boating event (event/d) TEBOAT – Duration of boating event (h/event) TBOAT – Boating days (d/y)
Air	Food Crop Concentration	Leafy Veg. Ingest. (Section D.3.3.1)	U_{csg} T_{csg}	UCRP 1 – Leafy vegetable consumption rate (kg/y) TCRP 1 – Leafy vegetable consumption period (d/y)

Trans-port	Transfer Process or Activity	Exposure Pathway (Section)	Param-eter	GENII Variable Name and Description
		Root Veg. Ingest. (Section D.3.3.1)	U_{csg} T_{csg}	UCRP 2 – Root vegetable consumption rate (kg/y) TCRP 2 – Root vegetable consumption period (d/y)
		Fruit Ingestion (Section D.3.3.1)	U_{csg} T_{csg}	UCRP 3 – Fruit consumption rate (kg/y) TCRP 3 – Fruit consumption period (d/y)
		Grain Ingestion (Section D.3.3.1)	U_{csg} T_{csg}	UCRP 4 – Grain consumption rate (kg/y) TCRP 4 – Grain consumption period (d/y)
Air	Animal Product Concentration	Beef Ingestion (Section D.3.3.2)	U_{asg} T_{asg}	UNAM 1 – Beef consumption rate (kg/y) TANM 1 – Beef consumption period (d/y)
		Poultry Ingestion (Section D.3.3.2)	U_{asg} T_{asg}	UNAM 2 – Poultry consumption rate (kg/y) TANM 2 – Poultry consumption period (d/y)
		Milk Ingestion (Section D.3.3.2)	U_{asg} T_{asg}	UNAM 3 – Milk consumption rate (kg/y) TANM 3 – Milk consumption period (d/y)
		Egg Ingestion (Section D.3.3.2)	U_{asg} T_{asg}	UNAM 4 – Egg consumption rate (kg/y) TANM 4 – Egg consumption period (d/y)
Surface Water	Aquatic Accumulation	Fish Ingestion (Section D.3.3.3)	U_{fwg} T_{fwg}	UAQU 1 – Fish consumption rate (kg/y) TAQU 1 – Fish consumption period (d/y)
Air	Ground Contamination	Soil Ingestion (Section D.3.3.4)	U_{dsg} T_{dsg}	USOIL – Daily soil consumption rate (mg/d) TSOIL – Days of ingestion in a year (d/y)
Surface Water	Recreational Swimming	Ingestion (Section D.3.3.5)	FE_{wrg} TE_{wrg} T_{wrg} U_{wwg}	EVSWIM – Frequency of swimming (event/d) TESWIM – Duration of swimming event (h/event) TSWIM – Swimming days (d/y) USWIM – Ingestion rate while swimming (L/h)
Air	Contaminated Plume	Inhalation (Section D.3.4.1)	U_{aag} T_{aag}	UINH – Air inhalation rate (m^3/d) TINH – Intake factor (d/y)
Air	Ground Contamination	Inhalation (Section D.3.4.2)	U_{sag} T_{sag} F_{sag}	UINHR – Resuspended soil inhalation rate (m^3/d) TINHR – Resuspended soil inhalation period (d/y) FRINHR – Fraction of day resuspended inhalation occurs

* SHIN and FTIN were both set equal to zero. SHOUT and FTOUT were both set equal to unity (see Section E.5.1.2).
Source: Napier, 2002 (7).

The exposure factors that were used in the post-processor to modify the GENII output from the calculations performed assuming unit quantities for these GENII variables are presented for each pathway in Section E.5.

E.4.2 Creation of Adjustment Factors

Adjustment factors were created as needed for certain pathways and receptors. The adjustment factors were created when the use of a single factor to modify GENII exposures using the post-processor was insufficient for computational needs. Therefore, an adjustment factor supplements an exposure factor.

Adjustment factors were most commonly used to correct for the consumption of foods that were grown or produced outside the vicinity of the SRS and therefore could not be contaminated by SRS operations. GENII does not include any direct mechanism to address this situation except for reducing the amounts of certain foods consumed during the year. This approach was not taken, however, because it would have been more difficult to compare assumptions taken for Phase III with those for other studies. It was clearer to separate the two considerations: (1) food quantities consumed and (2) the fraction of the consumed food that was contaminated. Each consideration could then be considered separately, and compared to other studies separately.

Section E.5 addresses the derivation of adjustment factors for each receptor and pathway.

E.5 Exposure and Adjustment Factors for Each Exposure Pathway

Exposure and adjustment factors are presented for each exposure pathway in the same order as the pathways summarized in Table E-8. That is, they are organized by exposure route:

- Section E.5.1: External Exposure Route
  E.5.1.1 Immersion in a Plume of Contaminated Air
  E.5.1.2 Exposure to Contaminated Soil
  E.5.1.3 Exposure to a Contaminated Shoreline
  E.5.1.4 Exposure to Contaminated Water While Swimming
  E.5.1.5 Exposure to Contaminated Water While Boating
- Section E.5.2: Ingestion Exposure Route
  E.5.2.1 Ingestion of Food Crops
  E.5.2.2 Ingestion of Animals and Animal Products
  E.5.2.3 Aquatic Food Ingestion
  E.5.2.4 Inadvertent Soil Consumption
  E.5.2.5 Inadvertent Ingestion of Water While Swimming
- Section E.5.3: Inhalation Exposure Route
  E.5.3.1 Inhalation of a Contaminated Plume of Air
  E.5.3.2 Inhalation of Resuspended Soil

E.5.1 External Radiation Exposure Route

E.5.1.1 Immersion in a Plume of Contaminated Air

This exposure pathway accounts for external radiation exposure from immersion in a plume of contaminated air. The following are GENII variables for this exposure pathway:

- UEXAIR: Daily plume immersion exposure time (hours/day).
- TEXAIR: Yearly plume immersion exposure time (days/year).

The combination of these two variables resulted in an exposure factor in units of hours/year. It was assumed that each receptor spent 8,760 hours out of the year in the SRS vicinity at one or more exposure locations (i.e., 365 days/year x 24 hours/day = 8,760 hours/year). Similar to that for inhalation of

contaminated air (Section E.5.3.1), no adjustments in exposure factors were assumed for receptors being indoors for a portion of each day. That is, indoor air concentrations were equal to outdoor air concentrations. Because indoor air concentrations would likely contain lower concentrations of airborne radioactivity, this assumption contributed to conservative (i.e., increased) estimates of dose and risk.

The exposure factors for the teenagers of Rural Family One were split between Girard and Waynesboro, where the teenagers attended high school. Assuming a total of 1,260 hours per year spent in high school, out of a total 8,760 hours in a year, the teenagers' exposure factors were 1,260 hours/year for the time spent in high school, and 7,500 hours/year for the remaining time spent in Girard. For the remaining family members, exposure factors were calculated assuming that they spent the entire year in Girard.

The split in exposure factors between Girard and Waynesboro for the teenagers was applied for the entire time they were teenagers (i.e., for the six years comprising 1967 through 1972 for the Child Born in 1955 and the six years comprising 1976 through 1981 for the Child Born in 1964). Thus, these teenagers spent six years partially in the Waynesboro area rather than four.[7]

Exposure factors for the Adult Male of the Urban/Suburban Family were split between Augusta and his job onsite at the SRS. The adult male exposure factors were 2,000 hours/year for the time spent at work and 6,760 hour/year for the remaining time spent in Augusta. Exposure factors for the Adult Female of this family were calculated assuming that she spent all her time in Augusta. The two children spent all their time in Augusta until they each age 18, and then they each worked onsite for 2,000 hours per year.

For the Delivery Person Family, the Adult Male worked in Allendale (1,600 hours/year) and also occasionally came onsite at the SRS for deliveries (400 hours/year). The remainder of his time was spent between Barnwell, where he lived with his family, and Martin, where he and his family recreated and attended church.

For the Outdoors Person Family, exposure factors for the adult male were split between Jackson and his job onsite at the SRS. Exposure factors for the Adult Female of this family were calculated assuming that she spent all her time in Jackson. The two children were assumed to spend all their time in Jackson until they each reached age 18, and then they each worked onsite for 2,000 hours per year.

Exposure factors for all members of the Near River Family were calculated assuming that each member spent all their time in Martin. The exposure factors for the members of the Migrant Worker Family were calculated assuming that each member spent all their time in New Ellenton, and that they were only in the SRS vicinity for half of any year.

Table E-9 lists the calculated exposure factors for Rural Family One, and Table E-10 lists the calculated exposure factors for all other exposure scenarios. While the children were teenagers, each spent six years in the Waynesboro area. For the remaining years, they stayed in Girard.

Adjustment factors were assumed to be unity for all receptors.

[7] This was assumed to reduce the complexity of the computational procedures.

Table E-9 Exposure Factors (hours/year) for Air Immersion Pathway for Rural Family One

Individual	Girard	Waynesboro
Adult M	8,760	0
Adult F	8,760	0
Child Born in 1955	7,500 for 1967-72; 8,760 for other years	1,260 for 1967-72; 0 for other years
Child Born in 1964	7,500 for 1976-81; 8,760 for other years	1,260 for 1976-81; 0 for other years

Table E-10 Exposure Factors (hours/year) for Air Immersion Pathway for Remaining Scenarios

Individual	Rural Family Two	Urban/Suburban Family		Delivery Family		
	Williston	Augusta	Onsite SRS	Martin	Onsite SRS	Allendale
Adult Male	8,760	6,760	2,000	306	400	1,600
Adult Female	8,760	8,760	0	306	0	0
Child Born in 1955:						
Thru 1972	8,760	8,760	0	306	0	0
Starting 1973	8,760	6,760	2,000	306	400	1,600
Child Born in 1964:						
Thru 1981	8,760	8,760	0	306	0	0
Starting 1982	8,760	6,760	2,000	306	400	1,600

Individual	Delivery Family (continued)	Outdoors Person Family		Near River Family	Migrant Worker Family
	Barnwell	Onsite SRS	Jackson	Martin	New Ellenton
Adult Male	6,454	2,000	6,760	8,760	4,380
Adult Female	8,454	0	8,760	8,760	4,380
Child Born in 1955:					
Thru 1972	8,454	0	8,760	8,760	4,380
Starting 1973	6,454	2,000	6,760	8,760	4,380
Child Born in 1964:					
Thru 1981	8,454	0	8,760	8,760	4,360
Starting 1982	6,454	2,000	6,760	8,760	4,380

E.5.1.2 Exposure to Contaminated Soil

This exposure pathway accounts for external radiation exposure resulting from standing on the ground at a specified exposure location contaminated by the deposition of radionuclides from the air. Exposures may occur either indoors or outdoors. The following are GENII variables for this exposure pathway:

- UEXGRD (U_{esg}): Daily external ground exposure time (hours/day).
- TEXGRD (T_{esg}): Yearly external ground exposure time (days/year).
- SHIN (SH_h): Indoor shielding factor (unitless).
- SHOU (SH_o): Outdoor shielding factor (unitless).
- FTIN (FT_{hg}): Fraction of time spent indoors (unitless).
- FTOUT (FT_{og}): Fraction of time spent outdoors (unitless).

For each exposure location, exposure and adjustment factors were calculated as follows:

$$\text{Exposure Factor} = U_{esg}\, T_{esg} \quad \text{(hours/year)}$$

$$\text{Adjustment Factor} = [(SH_h\ FT_{hg}) + (SH_o\ FT_{og})] \quad \text{(units are dimensionless)}$$

Exposure factors represented the total hours spent out of the year by each receptor at each location where the receptor may have been exposed. The amount of time that receptors spent at each location exposed to external radiation from contaminated ground surfaces was similar, but not equal, to the amount of time that the receptors spent at those locations exposed to external radiation from immersion in a plume of contaminated air. External radiation exposures from surface-contaminated soil did not occur when the receptor was either swimming or boating. A matrix by which exposure factors were determined for each scenario and receptor in accordance with these considerations is presented in Appendix Q. Table E-11 summarizes these exposure factors for Rural Family One, and Table E-12 summarizes the exposure factors for the remaining scenarios.

To determine adjustment factors, because structures provide shielding against ionizing radiation, the fraction of a year that each receptor spent inside and outside had to be determined. That is, values had to be determined for FT_{hg} and FT_{og} , where $FT_{hg} + FT_{og} = 1$.

Appendix Q provides a matrix that lists the hours spent indoors and outdoors for each receptor and exposure location. This matrix also provides the indoor and outdoor fractions calculated from these hours as well as the total hours spent “out of the water” (total hours out of the year excluding swimming and boating times). The following example illustrates the calculation of indoors and outdoors fractions.

The infant for Rural Family One was exposed to ground contamination at Girard for 8,739 hours out of the year (8,760 total hours in a year – 21 hours swimming minus – hours boating = 8,739 hours). These 8,739 hours were distributed as listed in

Table E-13.

The fraction of the time spent indoors was 7,466/8,739 = 0.85. The fraction of the time spent outdoors was 1,273/8,739 = 0.15.

All church hours were spent indoors. To determine the hours spent indoors and outdoors while at home, the total time spent at home was distributed between indoor and outdoor hours using information from Table E-12. In this case, the infant spent 8,550 hours at home (8,760 hours/yr – 85 hours at the shore – 21 hours swimming – 104 hours at church = 8,550 hours/year at home). Inside hours were taken to be 8,550 x 1190 / (1190 + 7371) = 1188 hours. Outside hours were taken to be 8,550 x 7371 / (1190 + 7371) = 7362 hours.

Table E-11 Exposure Factors (hours/year) for Ground Contamination External Exposure Pathway for Rural Family One

Individual	Girard	Waynesboro
Adult M	8,739	0
Adult F	8,739	0
Child Born in 1955	7,479 for 1967-72;* 8,739 for other years	1,260 for 1967-72;* 0 for other years
Child Born in 1964	7,479 for 1976-81;* 8,739 for other years	1,260 for 1976-81;* 0 for other years

*During the indicated years (1969-1972 for the Child Born in 1955 and 1978-81 for the Child Born in 1964), the children born in 1955 and 1964 are classed as teenagers.

Table E-12 Exposure Factors (hours/year) for Ground Contamination External Exposure Pathway for Remaining Scenarios

Individual	Rural Family Two	Urban/Suburban Family		Delivery Family		
	Williston	Augusta	Onsite SRS	Martin	Onsite SRS	Allendale
Adult M	8,739	6,643	2,000	189	400	1,600
Adult F	8,739	8,643	0	189	0	0
Child Born in 1955:						
Thru 1972	8,739	8,643	0	189	0	0
Starting 1973	8,739	6,643	2,000	189	400	1,600
Child Born in 1964:						
Thru 1981	8,739	8,643	0	189	0	0
Starting 1982	8,739	6,643	2,000	189	400	1,600

Individual	Delivery Family (continued)	Outdoors Person Family		Near River Family	Migrant Worker Family
	Barnwell	Onsite SRS	Jackson	Martin	New Ellenton
Adult M	6,454	1,740	6,643	8,447	4,370
Adult F	8,454	0	8,643	8,447	4,370

Child Born in 1955:					
Thru 1972	8,454	0	8,643	8,447	4,370
Starting 1973	6,454	1,740	6,643	8,447	4,370
Child Born in 1964:					
Thru 1981	8,454	0	8,643	8,447	4,370
Starting 1982	6,454	1,740	6,643	8,447	4,370

Table E-13 Indoor and Outdoor Hours for Infant of Rural Family One

Activity	Hours Indoor	Hours Outdoor
At home	7,362	1,188
At work	0	0
On the shoreline	0	85
At school	0	0
At Church	104	0
Total:	7,466	1,273

This accounting was performed for all receptors as addressed in Appendix Q. Appendix Q presents the total indoor and outdoor hours calculated for each receptor as well as the corresponding overall indoor (FT_{hg}) and outdoor (FT_{og}) fractions. Table E-14 summarizes the indoor and outdoor fractions for each receptor calculated from Appendix Q. (Note that $FT_{hg} + FT_{og} = 1$.)

These fractions were used with the indoor and outdoor shielding factors to create receptor-specific adjustment factors according to the equation listed above. The outdoor shielding factor (SH_o) was set equal to 1.0 for all scenarios, exposure locations, individuals, and years. The value assumed for the indoor shielding factor (SH_h) was conservatively taken to be 0.7.

The authors of this report found occasions where values for the indoor shielding factor of 0.4, 0.5, 0.7, and 0.8 had been used or recommended. Values of 0.5 and 0.7 have been used for modeling population doses resulting from SRS activities (8-10). EPA had at one time recommended using a shielding factor of 0.8, but in 1996 recommended a shielding factor of 0.4 (11). For this recommendation, EPA had reviewed a 1981 EPA report (12) that performed a review of experimentally measured reduction factors from fallout. The authors concluded that “reduction factors of 0.4 to 0.2 are recommended as representative values for above-ground lightly constructed (wood frame) and heavily constructed (block and brick) homes, respectively” (12). From this review, EPA suggested that a default gamma shielding factor of 0.4 based solely on the contribution of terrestrial radiation might be more appropriate for use at sites having soil contaminated with radionuclides than the previous default value of 0.8. This previous default value included the effects of cosmic radiation and the radioactivity inherent in structural materials (11).

But it was assumed that doors and windows of structures tended to remain open (see Section E.5.3.1), which meant that interior surfaces of structures may have been more likely to be contaminated than the situation assumed by EPA. Therefore, a larger value (0.7) was used for the indoor shielding factor than the default value recommended by EPA (0.4), resulting in somewhat larger exposures than would have been the case using the EPA default value.

Adjustment factors calculated from these considerations are presented in Table E-15.

Table E-14 Indoor and Outdoor Fractions for Ground Contamination Pathway

Scenario	Member*	Location†	Out. Frac.	In. Frac.
Rural Family One	Inf.	Girard	0.15	0.85
	Presch	Girard	0.15	0.85
	School	Girard	0.18	0.82
	Teen	Girard	0.13	0.87
	Teen	Wayne	0.29	0.71
	Ad. M	Girard	0.31	0.69
	Ad. F	Girard	0.14	0.86
Rural Family Two	Inf.	Will	0.15	0.85
	Presch	Will	0.15	0.85
	School	Will	0.18	0.82
	Teen	Will	0.15	0.85
	Ad. M	Will	0.31	0.69
	Ad. F	Will	0.14	0.86
Urban/ Suburb. Family	Inf.	Aug	0.14	0.86
	Presch	Aug	0.14	0.86
	School	Aug	0.17	0.83
	Teen	Aug	0.14	0.86
	Ad. M	Aug	0.13	0.87
	Ad. M	SRS	0.13	0.87
	Ad. F	Aug	0.13	0.87
Delivery Person Family	Inf.	Martin	0.45	0.55
	Inf.	Barn	0.14	0.86
	Presch	Martin	0.45	0.55
	Presch	Barn	0.14	0.86
	School	Martin	0.45	0.55
	School	Barn	0.18	0.82
Delivery Person Family (cont.)	Teen	Martin	0.45	0.55
	Teen	Barn	0.15	0.85
	Ad. M	Martin	0.45	0.55
	Ad. M	Barn	0.13	0.87
	Ad. M	SRS	0.50	0.50
	Ad. M	Allen	0.16	0.84
	Ad. F	Martin	0.45	0.55
	Ad. F	Barn	0.13	0.87
Outdoor Person	Inf.	Jack	0.15	0.85
	Presch	Jack	0.15	0.85
	School	Jack	0.18	0.82
	Teen	Jack	0.15	0.85
	Ad. M	Jack	0.14	0.86
	Ad. M	SRS	1.0	0
	Ad. F	Jack	0.14	0.86
Near River Family	Inf.	Martin	0.14	0.86
	Presch	Martin	0.14	0.86
	School	Martin	0.18	0.82
	Teen	Martin	0.15	0.85
	Ad. M	Martin	0.13	0.87
	Ad. F	Martin	0.13	0.87
Migrant Worker Family	Inf.	N E	0.15	0.85
	Presch	N E	0.15	0.85
	School	N E	0.18	0.82
	Teen	N E	0.15	0.85
	Ad. M	N E	0.31	0.69
	Ad. F	N E	0.14	0.86

*Inf - infant; Presch - preschooler; School - school child; Ad M - Adult Male; Ad F - adult female.
†Wayne - Waynesboro; Will -Williston; Aug - Augusta; Barn - Barnwell; Allen - Allendale; Jack - Jackson; N E - New Ellenton.

Table E-15 Adjustment Factors for Ground Contamination External Exposure Pathway

Individual	Years	Rural Family One		Rural Family Two	Urban/Suburban Family		Delivery Person Family	
		Girard	Waynes-boro	Willi-ston	Augusta	Onsite SRS	Martin	Onsite SRS
Adult M	All	0.7927	0	0.7927	0.7386	0.7375	0.8349	0.8500
Adult F	All	0.7417	0	0.7417	0.7388	0	0.8349	0
Children Born in 1955 and 1964	Infant	0.7437	0	0.7437	0.7409	0	0.8349	0
	Preschool	0.7437	0	0.7437	0.7409	0	0.8349	0
	Schoolchild	0.7546	0	0.7546	0.7519	0	0.8349	0
	Teen	0.7392	0.7857	0.7459	0.7431	0	0.8349	0
	Adult	0.7927	0	0.7927	0.7386	0.7375	0.8349	0

Individual	Years	Delivery Person Family (continued)		Outdoors Person Family		Near River Family	Migrant Family
		Allendale	Barnwell	Onsite SRS	Jackson	Martin	New Ellenton
Adult M	All	0.7469	0.7396	1.0	0.7423	0.7391	0.7927
Adult F	All	0	0.7396	0	0.7417	0.7396	0.7417
Child Born in 1955	Infant	0	0.7417	0	0.7437	0.7417	0.7437
	Preschool	0	0.7417	0	0.7437	0.7417	0.7437
	Schoolchild	0	0.7529	0	0.7547	0.7528	0.7547
	Teen	0	0.7440	0	0.7460	0.7440	0.7460
	Adult	0.7469	0.7396	0	0.7423	0.7391	0.7927

E.5.1.3 Exposure to a Contaminated Shoreline

This exposure pathway accounts for external radiation exposure resulting from standing on the shoreline containing radioactive material deposited by contaminated water. The following are GENII variables for this exposure pathway:

- EVSHOR - Frequency of shoreline use (event/day).
- TESHOR - Duration of shoreline use events (hours/event).
- TSHOR - Shoreline days (days/year).

Exposure factors were calculated by multiplying age- and location-specific values for these variables, resulting in a set of exposure factors in units of hours of exposure per year. Exposure factors thus developed are summarized in Table E-16 in accordance with the assumptions described in Sections E.5.1.3.1 through E.5.1.3.3.

Table E-16 Exposure Factors for Shoreline External Exposure Pathway

Scenario	Shoreline External Pathway	Exposure Factors
Rural Family One	No shoreline external exposure. Exposure location (Briar Creek near Girard) is not hydrologically downgradient from release points.	Exposure Factors (hours/year) = 0 (all years and individuals)
Rural Family Two	No shoreline external exposure. Exposure locations (Savannah River upstream of the SRS and farm ponds around Williston) are not hydrologically downgradient from release points.	Exposure Factors = 0 (all years and individuals)
Urban/Suburban Family	No shoreline external exposure. Exposure location (Savannah River at Augusta) is not hydrologically downgradient from release points.	Exposure Factors = 0 (all years and individuals)
Delivery Person	**Lower Three Runs Creek (LTRC) at Martin (50%) and the Savannah River down stream of the LTRC confluence (50%).** All individuals exposed for 85 hours/year for all years, combined from both locations.	Exposure Factors (hours/year) **Receptor** / **LTRC-Martin** / **Savannah River** Adult M: 42.5 / 42.5 Adult F: 42.5 / 42.5 Child 1955: 42.5 / 42.5 Child 1964: 42.5 / 42.5
Outdoors Person	**Savannah River upstream of the SRS:** No shoreline external exposure for the adult female and children. The exposure location is not hydrologically downgradient from release points. **Savannah River Downstream of the SRS:** The adult male is exposed for 260 hours/year for all years.	Exposure Factors (hours/year) **Receptor** / **Savannah River** Adult M: 260 Adult F: 0 Child 1955: 0 Child 1964: 0
Near River Family	**Savannah River Downstream of SRS:** All individuals are exposed for 365 hours/year for all years.	Exposure Factors (hours/year) **Receptor** / **Savannah River** Adult M: 365 Adult F: 365 Child 1955: 365 Child 1964: 365
Migrant Worker Family	No shoreline external exposure. Exposure locations (Savannah River upstream of the SRS and farm ponds around New Ellenton) are not hydrologically downgradient from release points.	Exposure Factors = 0 (all years and individuals)

E.5.1.3.1 Exposure Factors for the Delivery Person Family

Shoreline exposure rates were estimated using the following factors based on South Carolina recreational patterns as cited on pages 6 and 24 of Hamby (6):

- Average number of shoreline usage events/year – 19.15.
- Average hours/shoreline usage event – 4.44.

This resulted in an exposure rate of 85 hours/year which was applied to all members of the Delivery Person Family. The Hamby (6) values are based on Ledbetter (13). The numbers apply to all age groups and represent warm-water fishing activity. This exposure value is larger than default values cited in the Nuclear Regulatory Commission's (NRC) Regulatory Guide 1.109 (14) for a maximum exposed individual (MEI). NRC MEI exposure values for adults, teens, and children are 12, 67, and 14 hours/year, respectively (14). Hamby (6) calculated MEI values for population doses in the area around the SRS using local data and assumptions. The Hamby (6) MEI numbers for adults, teens, and children are 23, 128, and 27 hours/year, respectively.

E.5.1.3.2 Exposure Factors for the Outdoors Person Family

The only family members that were exposed to contaminated shorelines were the Adult Male and the two children when they became adults at age 18. It was assumed the Adult Male was present in shoreline areas along the Savannah River onsite at the SRS as part of his job. This time included time spent fishing and hunting. It was assumed the Adult Male was "on the river" 8 hours/day (40 hours/week) during the summer (13 weeks), as cited in Lockridge (1). It was further assumed that half the time spent "on the river" was spent on the shoreline, and the other half was spent on a boat. This resulted in an exposure factor of 260 hours/year on the shoreline for the Adult Male. The Adult Female always spent time along the shoreline at the Jackson, South Carolina, boat ramp, which is upstream from site discharges. Until they each reached age 18, the two children also spent their shoreline time at the Jackson boat ramp. After reaching age 18, they each spent the same time along the shoreline while working at the SRS as did the Adult Male (260 hours/year).

E.5.1.3.3 Exposure Factors for the Near River Family

For these receptors, Lockridge (1) states, "Assume they were always outdoors in contact with the Savannah River." It was assumed that the shoreline exposure rate would have been well above average values. An average daily exposure level of 1 hour/day (365 hours/year) was assumed for each receptor.

E.5.1.4 Exposure to Contaminated Water While Swimming

This exposure pathway accounts for external radiation exposure resulting from swimming in contaminated water. The following are GENII variables for this exposure pathway:

- EVSWIM - Frequency of swimming use (event/day).
- TESWIM - Duration of swimming events (hours/event).
- TSWIM - Swimming days (days/year).

Exposure factors were calculated taking into account these three variables which, when multiplied, result in receptor- and location-specific exposure factors in units of hours per year. Swimming exposures were determined only for members of the Delivery Person Family, who swam on Lower Three Runs Creek near Martin, South Carolina, and the Near River Family, who swam on the Savannah River downstream of the SRS.

For the Delivery Person Family, swimming water exposure rates were estimated using the following factors based on South Carolina recreational patterns cited on pages 6 and 24 of Hamby (6). The Hamby values are based on Ledbetter (13). Thefollowing values apply to all age groups and represent warm-water fishing activity:

- Average number of lake swimming events per year – 8.12 events/y.
- Average time of lake swimming event – 2.61 h/event.

These data resulted in exposure factors of 21.2 hours/year for each member of the Delivery Person Family.

For the Near River Family, it is stated in Lockridge (1) to "Assume they were always outdoors in contact with the Savannah River." A swimming rate was assumed during the summer months of 1 hour/day, leading to an exposure rate of 91 hrs/yr for each receptor. Table E-17 summarizes swimming water exposure factors.

Table E-17 Exposure Factors for Swimming External Exposure Pathway

Scenario	Swimming Water External Pathway	Exposure Factors
Rural Family One	No swimming water external exposure. Exposure location (Briar Creek near Girard) is not hydrologically downgradient from release points.	Exposure Factors = 0 (all years and individuals)
Rural Family Two	No swimming water external exposure. Exposure locations (farm ponds around Williston) are not hydrologically downgradient from release points.	Exposure Factors = 0 (all years and individuals)
Urban/Suburban Family	No swimming water external exposure. Exposure location (Savannah River at Augusta) is not hydrologically downgradient from release points.	Exposure Factors = 0 (all years and individuals)
Delivery Person	**Lower Three Runs Creek (LTRC) at Martin:** All individuals exposed for 21.2 hours/year for all years.	Exposure Factors (hours/year) **Receptor** / **LTRC-Martin** Adult M 21.2 Adult F 21.2 Child 1955 21.2 Child 1964 21.2
Outdoors Person	No swimming water external exposure. Exposure location (Savannah River upstream of the SRS) is not hydrologically downgradient from release points.	Exposure Factors = 0 (all years and individuals)
Near River Family	**Savannah River Downstream of the SRS:** All individuals exposed for 91 hours/year for all years.	Exposure Factors (hours/year) **Receptor** / **Savannah River** Adult M 91 Adult F 91 Child 1955 91 Child 1964 91

Scenario	Swimming Water External Pathway	Exposure Factors
Migrant Worker Family	No swimming water external exposure. Exposure locations (Savannah River upstream of the SRS and farm ponds around New Ellenton) are not hydrologically downgradient from release points.	Exposure Factors = 0 (all years and individuals)

E.5.1.5 Exposure to Contaminated Water While Boating

This exposure pathway accounts for external radiation exposures received while boating in contaminated water. The following are GENII variables for this exposure pathway:

- EVBOAT – Frequency of boating event (event/d).
- TEBOAT – Duration of boating event (h/event).
- TBOAT – Boating days (d/y).

Exposure factors determined when multiplying these variables resulted in exposure factors in units of hours/year. Boating exposure factors were calculated for members of the Delivery Person Family, the Outdoors Person Family, and the Near River Family. The rationale for these exposure factors, summarized in Table E-18, is presented in Subsections E.5.1.5.1 through E.6.1.5.3.

Table E-18 Exposure Factors for Boating External Exposure Pathway

Scenario	Boating External Pathway	Exposure Factors
Rural Family One	No boating external exposure. No boating performed by receptor.	Exposure Factors = 0 (all years and individuals)
Rural Family Two	No boating external exposure. No boating performed by receptor.	Exposure Factors = 0 (all years and individuals)
Urban/Suburban Family	No boating external exposure. Exposure location (Savannah River at Augusta) is not hydrologically downgradient from release points.	Exposure Factors = 0 (all years and individuals)
Delivery Person	**Savannah River Downstream of the SRS:** All individuals exposed for 96 hours/year for all years.	Exposure Factors (hours/year) **Receptor** / **Savannah River** Adult M 96 Adult F 96 Child 1955 96 Child 1964 96
Outdoors Person	**Savannah River Downstream of the SRS:** The adult male is exposed 356 hours/year for all years, including 260 hours for work and 96 hours for recreation. Boating exposure for all other individuals is 96 hours/year for all years.	Exposure Factors (hours/year) **Individual** / **Savannah River** Adult M 356 Adult F 96 Child 1955 96 Child 1964 96
Near River Family	**Savannah River Downstream of the SRS:** All individuals exposed for 192 hours/year for all years.	Exposure Factors (hours/year) **Receptor** / **Savannah River** Adult M 192

Scenario	Boating External Pathway	Exposure Factors
		Adult F 192 Child 1955 192 Child 1964 192
Migrant Worker Family	No boating external exposure. No boating performed by receptor.	Exposure Factors (hours/year) = 0 (all years and individuals)

E.5.1.5.1 Delivery Person Family

Boating exposure rates were estimated considering South Carolina recreational patterns as cited on pages 6 and 24 of Hamby (6), and summarized in Table E-19. These values are based on Ledbetter (13). The values apply to all age groups and include two categories: canoeing and boating/sailing.

Table E-19 South Carolina Boating Usage Rates (adapted from Hamby [6])

Boating Usage	Canoe Trails	Boating / Sailing
Events / Year (average)	6.13	18.77
Hours / Event (average)	2.25	4.38
Hours / Year	13.8	82.2
Total	96 hours/year	

An exposure factor of 96 hours/year was assumed for all members of the Delivery Person Family.

E.5.1.5.2 Outdoors Person

The Adult Male was exposed to radiation to a greater extent than other family members. The exposure factor for the Adult Male includes two components: one for work and one for recreation. For work, the Adult Male was calculated to boat for 260 hours/year, or half the time spent “on the river” as cited in Lockridge (1). Because the time spent “on the river” was cited (1) as 8 hours/day (i.e., 40 hours/week) during the summer (i.e., 13 weeks), it assumed that the Adult Male boated while at work for 0.5 x 40 x 130 = 260 hours/year. For recreational boating, the same rate (i.e., 96 hours/year adapted from Hamby [6]) was applied to all members of the family, including the Adult Male.

E.5.1.5.3 Near River Family

For these receptors, Lockridge (1) states, “Assume they were always in contact with the Savannah River.” An exposure factor was calculated assuming that these receptors went boating for twice the average rates cited in Hamby (6). An exposure factor of 192 hours/year was assumed for each receptor.

E.5.2 Ingestion Exposure Route

E.5.2.1 Ingestion of Food Crops

Exposures from ingestion of food crops include exposures from ingestion of leafy vegetables, root and other vegetables, fruit, and grain. The following are GENII variables for these exposure pathways:

- UCRP 1 – Leafy vegetable daily consumption rate on days that consumption occurs (kg/d).
- TCRP 1 – Leafy vegetable consumption period: days per year that consumption occurs (d/y).

- UCRP 2 – Root vegetable daily consumption rate on days that consumption occurs (kg/d).
- TCRP 2 – Root vegetable consumption period: days per year that consumption occurs (d/y).
- UCRP 3 – Fruit daily consumption rate on days that consumption occurs (kg/d).
- TCRP 3 – Fruit consumption period: in days out of the year that consumption occurs (d/y).
- UCRP 4– Grain daily consumption rate on days that consumption occurs (kg/d).
- TCRP 4 – Grain consumption period: in days out of the year that consumption occurs (d/y).

Four sets of exposure factors were calculated that were linked to these GENII variables and given in units of kilograms per year for leafy vegetables, root vegetables, fruit, and grain. Section E.5.2.1.1 presents exposure factors for leafy and root vegetables and fruit. Section E.5.2.1.2 presents exposure factors for grain.

E.5.2.1.1 Exposure and Adjustment Factors for Leafy and Root Vegetables and Fruit

Background

Consumption rate data for produce (leafy vegetables, root and other vegetables, and fruit) was assessed from EPA, 1997 (5); Hamby (6); and NRC (14). The first two of these references are secondary sources citing data from U.S. Department of Agriculture (USDA) studies, including National Food Consumption Surveys (NFCS) and the Continuing Surveys of Food Intakes by Individuals (CSFII). Consumption rates are specified in these references for specific age and gender categories, and for produce categories, as shown in Table E-20 (EPA [5]; Hamby [6]; NRC [14]). Data sets listed in Table E-20 consisted of:

- 1989-91 CSFII (EPA [5]).
- 1977-78 NFCS (Data Set No. 1) (EPA [5]).
- 1977-78 NFCS (Data Set No. 2) (EPA [5]).
- 1987-88 NFCS (EPA [5]).
- 1994-95 CFSII (EPA [5]).
- Hamby (6) regional estimates.
- NRC defaults from Regulatory Guide 1.109 (NRC [5]).

EPA, 1997 (5) also presents consumption rates based on other factors including geographic region, urbanization, season, and race (see Table E-20). But because age and gender differentiations are not specified for these factors, they were not used to create exposure factors. Although data distinguishing between geographic regions were not reported in EPA, 1997 (5) as a function of age or gender categories, the data do indicate that regional differences in consumption rates are small (i.e., <10%). EPA, 1997 (5) also compared consumption rates over time as illustrated in Table E-21. The data indicate that fruit consumption has gradually increased over time, and that vegetable consumption has fluctuated over time but overall has decreased.

Table E-20 Categories of Produce Consumption Data

Study [rate units]	Age and Gender Categories	Produce Categories*	Other Categories†
1989-91 CSFII (EPA [5]) [g / kg-d]	<5 6 – 11 male / female 12 – 19 male / female >20 male / female All individuals	Total fruits and vegetables Individual fruits and vegetables (28 types) Exposed and protected fruits Exposed and protected vegetables Root vegetables	Geographic region (northeast, midwest, south, west) Urban (city, suburban, nonmetro) Season (spring, summer, fall, winter) Race (White, Black, Asian, Native American, other)
1977-78 NFCS (EPA [5]) [g / d] Data Set #1	<1, 1-2, 3-5, 6-8 9 – 11 male / female 12 – 14 male / female 15 – 18 male / female 19 – 22 male / female 23 – 34 male / female 35 – 50 male / female 51 – 64 male / female 65 – 74 male / female >75 male / female All individuals	Total fruits Total vegetables Total produce	Geographic region (northeast, north central, south, west)
1977-78 NFCS (EPA [5]) [g / d] Data Set #2	<1 1 – 4 5 – 9 10 – 14 15 – 19 20 – 24 25 – 29 30 – 39 40 – 59 >60	Leafy produce Exposed produce Protected produce Other produce	Geographic region (northeast, north central, south, west)
1987-88 NFCS (EPA [5]) [g / d]	<6 6 – 11 male / female 12 – 19 male / female >19 male / female All individuals	Total fruits Total vegetables	None reported
1994-95 CSFII (EPA [5]) [g / d]	<6 6 – 11 male / female 12 – 19 male / female >19 male / female All individuals	Total fruits Total vegetables	None reported
Hamby (6) Regional estimates [kg / yr]	Infant Child Teen Adult	Leafy vegetables Other vegetables	None reported

Study [rate units]	Age and Gender Categories	Produce Categories*	Other Categories†
NRC Defaults (Hamby [6]) [kg / yr]	Infant Child Teen Adult	Other vegetables	None reported

*Data for the listed produce categories are reported by age and gender categories.
†Data for these other categories are not reported by age and gender categories.
Sources: EPA, 1997 (5); Hamby, 1991 (6); NRC, 1977 (14).

Table E-21 Comparison of Produce Consumption Rates Over Time

Produce Category	1977-78 NFCS	1987-88 NFCS	1989-91 CSFII	1995 CSFII
Fruits	142	142	156	173
Vegetables	201	182	179	188

Source: Tables 9-12 of EPA, 1997 (5).

Selection of data sets

The two data sets from the 1977-78 NFCS in EPA, 1997 (5) were chosen as the bases for the produce consumption rates. The following provided the rationale for this selection:

- The time period covered by this data set (1977-1978) was closer to the midpoint of the 1954-1992 period being modeled than the other data sets, which occur near or after 1992.
- This data set provided numerous age and gender categories that could be more easily aligned with the CDC and GENII age and gender categories.
- This data set was expressed in units that more easily converted to units required by GENII (g/day to kg/year). Additional conversions considering consumption rate variations by body weight were not needed.

Consumption rates

Consumption rates for the three different produce categories (leafy vegetables, root vegetables, and fruit) and the six different age and gender-specific categories modeled in GENII were derived from the NFCS data in the following manner:

- Leafy Vegetables. Age- and gender-specific consumption rates were calculated by averaging the NFCS age-specific categories for leafy vegetables in NFCS Data Set #2 using an approach similar to that used for meat consumption (see Section E.5.2.2.1). The data did not distinguish between male and female consumption of leafy vegetables.
- Root Vegetables. Age- and gender-specific consumption rates for root vegetables were determined using a two-step calculation. First, age- and gender-specific rates were calculated by averaging the NFCS age and gender categories for total vegetables in the NFCS Data Set #1, using an approach similar to that used for meat ingestion (see Section E.5.2.2.1). Second, the calculated leafy vegetable rates were subtracted from the total vegetable rates to yield age- and gender-specific consumption rates for root vegetables.
- Fruit. Age- and gender-specific consumption rates for fruit were calculated by averaging the NFCS age and gender categories for fruit in the NFCS Data Set #1 using an approach similar to that used for meat consumption.

For all three cases, the calculated rates were converted from g/day to kg/yr. Table E-22 presents the results of these calculations and the categories that were used for averaging.

Table E-22 GENII-Modeled Age and Gender Categories for Leafy and Root Vegetables and Fruit, Corresponding EPA 1997 (5) Age and Gender Categories, and Calculated Rates

Modeled Age Categories	Corresponding EPA 1997 Categories Averaged		Calculated Value – Average Consumption (kg/year)			
	Data Set #1 (used for total vegetables and fruit)	Data Set #2 (used for leafy vegetables)	Leafy Vegetables	Total Vegetables	Root Vegetables*	Fruit
Infant (<1)	<1	<1	1.2	27.7	26.6	61.7
Pre-School (1 – 4)	1 – 2 3 – 5	1 – 4	4.1	35.2	31.1	50.7
Child (5 – 11)	6 – 8 9 – 11 male	5 – 9 10 – 14	8.1	50.0	41.9	52.0
Teenager (12 – 17)	12 – 14 male 15 – 18 male	15 – 19	10.6	73.8	63.2	49.4
Adult Male (>18)	19 – 22 male 23 – 34 male 35 – 50 male 51 – 64 male 65 – 74 male >75 male	20 – 24 25 – 29 30 – 34 40 – 59 >=60	16.7	95.9	79.21	55.2
Adult Female (>18)	19 – 22 female 23 – 34 female 35 – 50 female 51 – 64 female 65 – 74 female >75 female	20 – 24 25 – 29 30 – 34 40 – 59 >=60	16.7	73.9	57.2	56.6

*Root vegetables are calculated by difference (total vegetables – leafy vegetables = root vegetables).
Source: Data adapted from Tables 9-14. 9-16, and 9-22 of EPA, 1997 (5).

Information from this table was used to calculate exposure and adjustment factors for consumption of leafy vegetables, root vegetables, and fruit. For many receptors, some of the consumed vegetables and fruit were obtained from sources external to the SRS vicinity and therefore did not contain radionuclides from SRS operations.

Table E-23 lists exposure factors. Exposure factors reflect the assumptions that (1) half the leafy vegetables, root vegetables, and fruit consumed by the Delivery Person Family were obtained from the Barnwell area and half from the Martin area, and (2) the Migrant Worker Family was in the SRS vicinity for only half of any year.

Table E-24 lists adjustment factors. For Rural Families One and Two, during the 1950s, half of the vegetables and fruit was grown on the farm, and all of this farm-grown produce had the potential for contamination. The remaining vegetables and fruit were obtained from local stores. Of this produce, it

was assumed that half was grown locally and half was grown outside the SRS vicinity. But beginning in 1960, only 25 percent of their vegetables and fruit was grown on the farm. Of this produce, all had the potential for contamination. The remaining 75 percent was obtained from local groceries. It was assumed that half of this store-bought produce was grown locally, and half was obtained from outside the SRS vicinity.

Table E-23 Exposure Factors (kg/yr) for Three Produce Ingestion Pathways

Individual	Rural Families One and Two, Urban/Suburban Family, Outdoors Person Family, Near River Family			Delivery Person Family (Barnwell/Martin)†			Migrant Worker Family		
	LV*	RV*	F*	LV	RV	F	LV	RV	F
Adult Male	16.7	79.2	55.2	8.35/ 8.35	39.6/ 39.6	27.6/ 27.6	8.35	39.6	27.6
Adult Female	16.7	57.2	56.6	8.35/ 8.35	28.6/ 28.6	28.3/ 28.3	8.35	28.6	28.3
Children Born in 1955 and 1964:									
Infant	1.2	26.6	61.7	0.6/ 0.6	13.3/ 13.3	30.85/ 30.85	0.6	13.3	30.85
Preschool	4.1	31.1	50.7	2.05/ 2.05	15.55/ 15.55	25.35/ 25.35	2.1	15.55	25.35
School	8.1	41.9	52.0	4.05/ 4.05	20.95/ 20.95	26.0/ 26.0	4.05	20.95	26.0
Teen	10.6	63.2	49.4	5.3/ 5.3	31.6/ 31.6	24.7/ 24.7	5.3	31.6	24.7
Adult	16.7	79.2	55.2	8.35/ 8.35	39.6/ 39.6	27.6/ 27.6	8.35	39.6	27.6

*LV: Leafy Vegetables; RV: Root Vegetables; F: Fruit.
†The Delivery Person Family obtained half its produce from Martin and half from Barnwell.

The fraction of vegetables and fruit that may have originated locally and been consumed by receptors was difficult to estimate, particularly over the 39 years considered in this assessment. One could expect, however, that the locally grown fraction had decreased over the years as marketing networks built up in the SRS vicinity. Lockridge (1) had recommended that for the rural family, the study should assume that 50 percent of the vegetables and meat originated from the farm during the 1950's, and only 25 percent thereafter. This recommendation was followed for Rural Families One and Two for all vegetables and fruit. It was reasoned that fruit was about as likely as vegetables to be grown locally or imported from outside the SRS vicinity.

For all other scenarios, it was assumed that half of the receptors' vegetables and fruit was imported from outside the SRS vicinity. The authors of this report considered this assumption to be conservative in that it corresponded to the recommendation made in Lockridge (1) for the 1950's, but was applied to all years. Note that the same adjustment factors were assumed, for the Delivery Person Family, for vegetables and fruit obtained respectively from Martin and Barnwell.

Table E-24 Adjustment Factors (kg/y) for Leafy Vegetable, Root Vegetable, and Fruit Ingestion Exposure Pathways

Individual	Rural Families One And Two	Urban/Suburban Family, Delivery Person Family, Outdoors Person Family, Near River Family, Migrant Worker Family
Adult Male:		
Thru 1959	0.75	0.50
1960 & on	0.625	0.50
Adult Female:		
Thru 1959	0.75	0.50
1960 & on	0.625	0.50
1955 Child:		
Infant 1955	0.75	0.50
Preschool 1956-59	0.75	0.50
School 1960-66	0.625	0.50
Teen 1967-73	0.625	0.50
Adult 1974-92	0.625	0.50
1964 Child:		
All ages (1964 to 1992)	0.625	0.50

E.5.2.1.2 Exposure and Adjustment Factors for Grain

No data regarding grain consumption were identified for the SRS vicinity. Therefore, the authors of this report used data on per-capita intake of corn from EPA, 1997 (5) to generate exposure factors for grain consumption. It was assumed that although individuals in the SRS vicinity would likely have consumed grain products such as breads, pastas, or flours that would not have been derived from locally grown grains, individuals in the SRS vicinity could plausibly have consumed a considerable amount of locally grown corn. In this case, corn was considered to be a grain rather than as a vegetable. Table E-25 shows that consumption rates were combined and averaged for specific age- and gender-categories.

These calculated rates for grain ingestion were used to determine exposure factors for each receptor as summarized in Table E-26.

Exposure factors for the Delivery Person Family reflect the situation that half the grain was obtained half from Barnwell and half from Martin. Exposure factors for the Migrant Worker Family reflect the situation that the family was only in the area for half of the year.

For all receptors and scenarios, adjustment factors were assumed to be unity (i.e., all of the grain [corn] was obtained from the SRS vicinity). It was assumed that because corn was commonly grown in the vicinity, it could have been easily acquired by all receptors, rural or urban.

Table E-25 GENII-Modeled Age and Gender Categories for Grains, Corresponding EPA 1997 Age and Gender Categories, and Calculated Consumption Rates

Modeled Age Categories	Corresponding Averaged EPA 1997 Categories	Average Consumption (kg/year)
Infant (<1)	<1	1.2
Pre-School (1 – 4)	1 – 2 3 – 5	2.9
Child (5 – 11)	6 – 8 9 – 11 male	4.0
Teenager (12 – 17)	12 – 14 male 15 – 18 male	3.6
Adult Male (>18)	19 – 22 male 23 – 34 male 35 – 50 male 51 – 64 male 65 – 74 male >75 male	4.1
Adult Female (>18)	19 – 22 female 23 – 34 female 35 – 50 female 51 – 64 female 65 – 74 female >75 female	3.4

Table E-26 Exposure Factors (kg/y) for Grain Ingestion Exposure Pathway

Individual	Rural Families One and Two, Urban/Suburban Family, Outdoors Person Family, and Near River Family	Delivery Person Family		Migrant Worker Family
		Barnwell	Martin	
Adult Male	4.1	2.05	2.05	2.05
Adult Female	3.4	1.7	1.7	1.7
1955 Child:				
Infant 1955	1.2	0.6	0.6	0.6
Preschool 1956-59	2.9	1.45	1.45	1.45
School 1960-66	4.0	2.0	2.0	2.0
Teen 1967-73	3.6	1.8	1.8	1.8
Adult 1974-92	4.1	2.05	2.05	2.05
1964 Child:				
Infant 1964	1.2	0.6	0.6	0.6
Preschool 1965-68	2.9	1.45	1.45	1.45
School 1969-75	4.0	2.0	2.0	2.0
Teen 1976-82	3.6	1.8	1.8	1.8
Adult 1983-92	4.1	2.05	2.05	2.05

E.5.2.2 Ingestion of Animals and Animal Products

Exposures from ingestion of animals and animal products include exposures from ingestion of beef, poultry, milk, and eggs. The following are GENII variables for these exposure pathways:

- UNAM 1 – Beef daily consumption rate on days that consumption occurs (kg/d).
- TANM 1 – Beef consumption period: days out of the year that consumption occurs (d/y).
- UNAM 2 – Poultry daily consumption rate on days that consumption occurs (kg/d).
- TANM 2 – Poultry consumption period: days out of the year that consumption occurs (d/y).
- UNAM 3 – Milk daily consumption rate on days that consumption occurs (kg/d).
- TANM 3 – Milk period: days out of the year that consumption occurs (d/y).
- UNAM 4 – Eggs daily consumption rate on days that consumption occurs (kg/d).
- TANM 4 – Eggs consumption period: days out of the year that consumption occurs (d/y).

Four sets of exposure factors were determined, linked to these GENII variables, in units of kilograms per year. Exposure factors for beef are presented in Section E.5.2.2.1. Exposure factors for poultry are presented in Section E.5.2.2.2. Exposure factors for milk and eggs are presented in Section E.5.2.2.3.

E.5.2.2.1 Exposure and Adjustment Factors for Beef

The beef pathway was used to represent all non-poultry and non-fish meat that was potentially affected by SRS releases. This pathway includes beef, but serves as a surrogate for wild game, pork, and other non-poultry meats. Several sets of data were evaluated to develop values for meat consumption. The principal source was EPA, 1997 (5), which provides national averages for adult and child meat and beef consumption. Another reference for beef consumption was Hamby (6). Neither of these sources provides values that align exactly with the report scenarios or the age group categories of GENII. Additionally, neither source is based on local (e.g., county- or State-level) data. Therefore, the authors of this report made some adjustments of the raw data to develop values that better corresponded with the scenarios and GENII specifications. EPA, 1997 (5) was selected as a better source than Hamby (6) because it provided separate categories for adult males and females and multiple categories identifying different meat types. Tables E-27 and E-28 present the categories of data included in each of the sources.

Table E-27 Ingestion Categories Presented in EPA 1997 Meat Consumption Data

1987-88 NFCS and 1994/1995 CSFII		1977-78 NFCS	
Age and Gender Categories	**Meat Categories**	**Age and Gender Categories**	**Meat Categories**
<5 6 – 11 male / female 12 – 19 male / female >20 male / female All individuals	Total Meat, Poultry and Fish Beef Pork Lamb, Veal, Game Frankfurters, sausages, luncheon meats Total Poultry Chicken Only Meat Mixtures	<1 1 – 2 3 – 5 6 – 8 9 – 11 male / female 12 – 14 male / female 15 – 18 male / female 19 – 22 male / female 23 – 34 male / female 35 – 50 male / female 51 – 64 male / female 65 – 74 male / female >75 male / female All individuals	Total Meat, Poultry and Fish Beef Pork Lamb, Veal, Game Frankfurters, sausages, luncheon meats Total Poultry Chicken Only Meat Mixtures

Source: EPA, 1997 (5).

Table E-28 Ingestion Categories in Hamby 1991 Meat Consumption Data*

Age and Gender Categories Considered	Meat Categories Considered
Infant, Child, Teen, and Adult	Beef (households in the south only) All meat (nationwide only)

*Hamby, 1991 (6) provides two sets of data: NFCS 1977-78 data for southern households, and NRC defaults.

The meat consumption assumptions used for this report were derived primarily from EPA, 1997 (5) data derived from the 1977-78 NFCS. The 1977-78 NFCS data set was selected for four reasons:

1. This data set included values for a broad range of individual meat categories.
2. The time period covered by this data set (1977-1978) was closer to the midpoint of the 1954-1992 period being modeled than the other data sets, which occur near or after 1992.
3. This data set provides numerous age and gender categories that were more easily aligned with the age and gender categories used for this report.
4. This data set was expressed in units that more easily convert to units required by this report (g/day to kg/year). Additional conversions considering consumption rate variations by body weight were not needed.

To calculate consumption rates for the beef pathway (i.e., meat that is not poultry and not fish), the authors of this report added values from EPA, 1997 (5) for intake of beef, pork, lamb/veal/game, meat mixtures, and processed meats (frankfurters, sausages, luncheon meats, spreads). For non-adult age and gender categories, male and female values were averaged. Table E-29 shows the modeled age and gender categories, the corresponding age and gender categories from EPA, 1997 (5) that were averaged to calculate a comparable input value, and the calculated value that was converted to units of kg consumed per year (or liters per year in the case of milk).

These calculated ingestion rates were used to determine receptor and location-specific exposure factors as summarized in Table E-30. These exposure factors reflected the assumption that (1) the Delivery Person Family consumed beef obtained from both Martin and Barnwell areas, (2) the Migrant Worker Family is in the SRS vicinity for only half the year, and (3) three-quarters of the beef consumed by the Outdoors Person Family originated from the SRS site as venison and one-quarter (not venison) originated from the Jackson area.

Adjustment factors took into account the following assumptions:

- For Rural Families One and Two, ATL assumed that up through the end of 1959, half the beef was grown on the farm and therefore contaminated. The other half came from local grocery stores, of which 50 percent was contaminated. Starting in 1960, 25 percent of the beef was grown on the farm. All this beef contained radionuclides from the SRS. The other 75 percent of the beef came from local grocery stores, of which half was contaminated. These assumptions are consistent with Lockridge (1) and reflect the assumption that half the beef acquired from local grocery stores came from local farms, and half came from sources outside the SRS vicinity.
- For the Urban/Suburban Family, Near River Family, and the Migrant Worker Family, it was assumed that half the consumed beef came from sources local to the SRS, and half did not. (This assumption is equivalent to the assumption that all the beef came from local grocery stores, and that the grocery stores obtained only half their beef locally.) This assumption is conservative, in that it essentially assumed that 1950's conditions for meat consumption, as recommended in Lockridge (1), were applicable for all years for these families. This assumption is consistent with those made for vegetables and fruit for these families (see Section E.5.2.1.1).

- For the Delivery Person Family, half the beef came from the Martin area and half came from the Barnwell area. Of the beef obtained from the Martin area, it was assumed that 25 percent was obtained from hunting deer, and all of this venison contained radionuclides from the SRS. The remaining beef obtained from the Martin area was acquired from stores, of which 50 percent was not contaminated because it was obtained from outside the SRS vicinity. Of the beef obtained from the Barnwell area, half came from sources local to the SRS, and half did not. Combining the venison obtained from hunting with other beef obtained in Martin, it was assumed that 62.5 percent of all beef obtained from Martin potentially contained radionuclides from the SRS.
- For the Outdoors person family, half the beef obtained from stores in the Jackson area came from sources local to Jackson, and half came from sources outside the SRS vicinity. However, it was assumed that all the beef obtained onsite from the SRS was venison and all had the potential for contamination.

Adjustment factors determined according to these assumptions are listed in Table E-31 for Rural Families One and Two. Adjustment factors for the remaining families are listed in Table E-32.

Table E-29 GENII-Modeled Age/Gender Categories for Beef, Poultry, Milk, and Eggs, Corresponding EPA 1997 Age/Gender Categories, and Calculated Consumption Rates

Modeled Age Categories	Corresponding EPA 1997 Categories Averaged	Calculated Value – Average Consumption (kg/year or L/yr)			
		Beef	Poultry	Milk	Eggs
Infant (<1)	<1	25.2	1.5	131.8	1.8
Pre-School (1 – 4)	1 – 2 3 – 5	31.4	6.5	130.2	7.7
Child (5 – 11)	6 – 8 9 – 11 male	50.6	8.0	146.5	8.0
Teenager (12 – 17)	12 – 14 male 15 – 18 male	75.6	11.9	169.5	10.8
Adult Male (>18)	19 – 22 male 23 – 34 male 35 – 50 male 51 – 64 male 65 – 74 male >75 male	78.1	11.3	73.7	13.9
Adult Female (>18)	19 – 22 female 23 – 34 female 35 – 50 female 51 – 64 female 65 – 74 female >75 female	49.7	9.1	55.5	8.4

Source: EPA, 1997 (5).

Table E-30 Exposure Factors (kg/y) for Beef Ingestion Exposure Pathway

Individual	Rural Families One and Two, Urban/ Suburban Family, Near River Family	Delivery Person Family		Outdoors Person Family		Migrant Worker Family
		Martin	Barn-well	Jackson	SRS Onsite	
Adult Male	78.1	39.05	39.05	19.52	58.58	39.05
Adult Female	49.7	24.85	24.85	12.42	37.28	24.85
Children Born in 1955 and 1964:						
Infant	25.2	12.6	12.6	6.3	18.9	12.6
Preschool	31.4	15.7	15.7	7.85	23.55	15.7
School	50.6	25.3	25.3	12.65	37.95	25.3
Teen	75.6	37.8	37.8	18.9	56.7	37.8
Adult	78.1	39.05	39.05	19.52	58.58	39.05

Table E-31 Adjustment Factors for Beef Exposure Pathway, Rural Families One and Two

Individual		Adjustment Factors
Adult Male	Through 1959	0.75
	1960 and on	0.625
Adult Female	Through 1959	0.75
	1960 and on	0.625
1955 Child:	Infant (In 1955)	0.75
	Preschooler (1956 to 1959)	0.75
	School child (1960 to 1966)	0.625
	Teen (1967 to 1973)	0.625
	Adult (1974 to 1992)	0.625
1964 Child:	All ages (1964 to 1992)	0.625

Table E-32 Adjustment Factors for Beef Exposure Pathway, Remaining Scenarios

Individual	Urban/Suburban, Near River, & Migrant Worker Families	Delivery Person Family		Outdoors Person Family	
		Martin	Barnwell	Jackson	SRS Onsite
Adult Male	0.5	0.625	0.5	0.5	1.0
Adult Female	0.5	0.625	0.5	0.5	1.0
1955 Child	0.5	0.625	0.5	0.5	1.0
1964 Child	0.5	0.625	0.5	0.5	1.0

E.5.2.2.2 Exposure and Adjustment Factors for Poultry

For the poultry ingestion exposure pathway, the authors of this report adapted consumption rates from Table 11-10 of EPA, 1997 (5) (citing the 1977-78 NFCS), using the same approach as that for beef (Section E.5.2.2.1). Consumption rates for poultry have been presented in Table E-29. These consumption rates were used to develop exposure factors for poultry ingestion as listed in Table E-33.

Table E-33 Exposure Factors (kg/y) for Poultry Ingestion Exposure Pathway

Individual	Rural Families One and Two, Urban/ Suburban Family, and Near River Family	Delivery Person Family		Outdoors Person Family		Migrant Worker Family
		Martin	Barn-well	Jackson	SRS Onsite	
Adult Male:	11.3	5.65	5.65	2.825	8.475	5.65
Adult Female:	9.1	4.55	4.55	2.275	6.825	4.55
Children Born in 1955 and 1964:						
Infant	1.5	0.75	0.75	0.375	1.125	0.75
Preschool	6.5	3.25	3.25	1.625	4.875	3.25
School	8.0	4.0	4.0	2.0	6.0	4.0
Teen	11.9	5.95	5.95	2.975	8.925	5.95
Adult	11.3	5.65	5.65	2.825	8.475	5.65

Adjustment factors for poultry ingestion were determined in a similar manner as that for beef. It was assumed that both the Outdoors Person Family and the Delivery Person Family obtained some of their poultry as hunted fowl. That is:

- For Rural Families One and Two, it was assumed that up through the end of 1959, half the poultry was grown on the farm. All of this poultry contained radionuclides from the SRS. The other half came from local grocery stores, of which 50 percent was contaminated. Starting in 1960, 25 percent of the poultry was grown on the farm and contained radionuclides from the SRS. The other 75 percent of the poultry came from local grocery stores, of which half was contaminated. These assumptions are consistent with Lockridge (1) in that poultry was assumed to be a form of meat. Table E-34 lists the adjustment factors for Rural Families One and Two.
- For the Urban/Suburban Family, the Near River Family, and the Migrant Worker Family, it was assumed that half the poultry came from sources local to the SRS and half did not. This assumption is conservative: 1950's conditions for poultry consumption, as recommended in Lockridge (1), were assumed to be applicable to all years for these families (Table E-35). This assumption is consistent with those made for vegetables and fruit for these families (see Section E.5.2.1.1).
- For the Delivery Person Family, half the poultry came from the Martin area and half came from the Barnwell area. Of the poultry obtained from the Martin area, 25 percent was obtained from hunting wild fowl, and all of this poultry contained radionuclides from the SRS. The remaining poultry from the Martin area was acquired from stores, of which 50 percent was not contaminated because it was obtained from outside the SRS vicinity. Of the poultry obtained from the Barnwell area, half came from sources local to the SRS and half did not. Combining the wild fowl obtained from hunting with

other poultry obtained in Martin, it was assumed that 62.5 percent of poultry (including wild fowl) obtained from Martin potentially contained radionuclides from the SRS (Table E-35).

- For the Outdoors person family, it was assumed that half the poultry came from sources local to Jackson, and half the poultry came from sources outside the SRS vicinity. However, assumed that all the poultry obtained onsite from the SRS was hunted fowl (e.g., ducks), and all such fowl had the potential for contamination (Table E-35).

Table E-34 Adjustment Factors (kg/y) for Poultry Exposure Pathway, Rural Families One and Two

Individual		Adjustment Factor
Adult Male:	Through 1959	
	1960 and on	0.75
Adult Female:	Through 1959	
	1960 and on	0.75
1955 Child:	Infant (In 1955)	
	Preschooler (1956 to 1959)	0.75
	School child (1960 to 1966)	0.75
	Teen (1967 to 1973)	0.625
	Adult (1974 to 1992)	0.625
1964 Child:	All ages (1964 to 1992)	

Table E-35 Adjustment Factors (kg/y) for Poultry Pathway — Remaining Scenarios

Individual	Urban/ Suburban Family	Delivery Person Family		Outdoors Person Family		Near River Family	Migrant Worker Family
		Martin	Barn-well	Jackson	SRS Onsite		
Adult Male	0.5	0.625	0.5	0.5	1.0	0.5	0.5
Adult Female	0.5	0.625	0.5	0.5	1.0	0.5	0.5
1955 Child	0.5	0.625	0.5	0.5	1.0	0.5	0.5
1964 Child	0.5	0.625	0.5	0.5	1.0	0.5	0.5

E.5.2.2.3 Exposure and Adjustment Factors for Milk and Eggs

For the milk and egg ingestion exposure pathways, the authors of this report adapted consumption rates from Table 11.12 of EPA, 1997 (5), which cited the 1977-78 NFCS. These rates were adapted to the age and gender categories used in this report, using the same approach as that for beef and poultry. Table E-29 presents the consumption rates for milk and eggs (in units of L/y for milk, and kg/y for eggs). Table E-36 summarizes the exposure factors for milk and egg ingestion.

It was assumed that all milk and eggs were obtained from sources local to the SRS. Therefore, the adjustment factors for the milk and egg ingestion pathways were assumed to be unity for all scenarios and receptors.

Table E-36 Exposure Factors (kg/y) for Milk and Egg Ingestion Exposure Pathways

Individual	Rural Family One		Rural Family Two		Urban/Suburban*		Delivery Person	
	Milk	Eggs	Milk	Eggs	Milk	Eggs	Milk	Eggs
Adult Male	73.7	13.9	73.7	13.9	36.85/36.85	13.9	36.85	6.95
Adult Female	55.5	8.4	55.5	8.4	27.75/27.75	8.4	27.75	4.2
Children Born in 1955 and 1964:								
Infant	131.8	1.8	131.8	1.8	65.9/65.9	1.8	65.9	0.9
Preschool	130.2	7.7	130.2	7.7	65.1/65.1	7.7	65.1	3.85
School	146.5	8.0	146.5	8.0	73.25/73.25	8.0	73.25	4.0
Teen	169.5	10.8	169.5	10.8	84.75/84/75	10.8	84.75	5.4
Adult	73.7	13.9	73.7	13.9	36.85/36.85	13.9	36.85	6.95
Individual	**Delivery Person**		**Outdoors Person**		**Near River Family**		**Migrant Worker**	
	Milk	Eggs	Milk	Eggs	Milk	Eggs	Milk	Eggs
Adult Male	36.85	6.95	73.7	13.9	73.7	13.9	36.85	6.95
Adult Female	27.8	4.2	55.5	8.4	55.5	8.4	27.75	4.2
Children Born in 1955 and 1964:								
Infant	65.9	0.9	131.8	1.8	131.8	1.8	65.9	0.9
Preschool	65.1	3.85	130.2	7.7	130.2	7.7	65.1	3.85
School	73.3	4.0	146.5	8.0	146.5	8.0	73.25	4.0
Teen	84.8	5.4	169.5	10.8	169.5	10.8	84.75	5.4
Adult	36.9	6.95	73.7	13.9	73.7	13.9	36.85	6.95

*Although the Urban/Suburban family obtained all of its eggs from the Augusta area, it obtained half its milk from the Augusta area and half from the New Ellenton area. Hence (for example), the adult male annually consumed 36.85 kg of milk from Augusta, 36.85 kg of milk from New Ellenton, and 13.9 kg of eggs from Augusta.

E.5.2.3 Aquatic Food Ingestion

Exposures from ingestion of aquatic food products include exposures from ingestion of fish, mollusks, crustacea, and aquatic plants. The following are GENII variables for these exposure pathways:

- UAQU 1 – Fish daily consumption rate on days that consumption occurs (kg/d).
- TAQU 1 – Fish consumption period: days out of the year that consumption occurs (d/y).
- UAQU 2 – Mollusk daily consumption rate on days that consumption occurs (kg/d).
- TAQU 2 – Mollusk consumption period: days out of the year that consumption occurs (d/y).
- UAQU 3 – Crustacea daily consumption rate on days that consumption occurs (kg/d).
- TAQU 3 – Crustacea consumption period: days out of the year that consumption occurs (d/y).
- UAQU 4– Aquatic plant daily consumption rate on days that consumption occurs (kg/d).
- TAQU 4 – Aquatic plant consumption period: days out of the year that consumption occurs (d/y).

Radiation exposure through the aquatic food consumption pathway was modeled as occurring entirely from eating fish. Therefore, an exposure factor was calculated for fish consumption, in units of kg of fish consumed per year, in a manner linked to the UAQU 1 and TAQI2 GENII variables. Exposure factors for

mollusk, crustacea, and aquatic plant consumption were set equal to zero (UAQU 2 = UAQU 3 = UAQU 4 = 0).

The authors of this report considered fish consumption rate data from several references including EPA, 1997 (5); Hamby (6); EPA, 1991 (11); EPA, 1994 (15); and EPA, 2002 (16). These sources are mainly secondary references citing data from several studies, including the USDA, NFCS, and CSFII studies and several State-level studies. No studies, however, were local to South Carolina and Georgia. EPA, 1997 (5) values were used.

Table E-37 summarizes age- and gender-specific fish consumption rates.

Table E-37 GENII-Modeled Age and Gender Categories and Calculated Consumption Rates for Fish

Modeled Age Categories	Fish Consumption Rate (kg/yr)
Infant (<1)	4.2
Pre-School (1 – 4)	4.2
Child (5 – 11)	5.0
Teenager (12 – 17)	4.5
Adult Male (>18)	9.9
Adult Female (>18)	9.9

Table E-38 summarizes the exposure factors determined using these consumption rates.

Table E-38 Exposure Factors (kg/yr) for Fish Ingestion Exposure Pathway

Individual	Rural Family One	Rural Family Two	Urban/ Suburban Family	Delivery Person Family		Outdoors Person Family	Near River Family	Migrant Worker Family
	Briar Creek	Creeks, ponds near Williston	Savannah River near Augusta	Lower Three Runs Creek	Savannah River (Smith Lake)	Savannah River (various locations)	Savannah River (various locations)	Creeks, etc. near New Ellenton
Adult Male	9.9	9.9	9.9	4.95	4.95	9.9	9.9	4.95
Adult Female	9.9	9.9	9.9	4.95	4.95	9.9	9.9	4.95
Children Born in 1955 and 1964:								
Infant	4.2	4.2	4.2	2.1	2.1	4.2	4.2	2.1
Preschool	4.2	4.2	4.2	2.1	2.1	4.2	4.2	2.1
School	5.0	5.0	5.0	2.5	2.5	5.0	5.0	2.5
Teen	4.5	4.5	4.5	2.25	2.25	4.5	4.5	2.25
Adult	9.9	9.9	9.9	4.95	4.95	9.9	9.9	4.95

All fish eaten by Rural Families One and Two, the Urban/Suburban Family, and the Migrant Worker Family came from sources that are not hydrologically downgradient of any release by the SRS to surface water. For this reason, the adjustment factors for all members of these families were set to zero. However,

it was assumed that all of the fish annually consumed by the members of the Delivery Person Family, the Outdoors Person Family, and the Near River Family had the potential for radionuclide contamination caused by SRS activities. Hence, the adjustment factors for all these receptors were set to unity. Table E-39 summarizes adjustment factors according to these assumptions for the fish ingestion pathway.

Table E-39 Adjustment Factors (dimensionless) for Fish Ingestion Exposure Pathway

Individual	Rural Family One	Rural Family Two	Urban/ Suburban Family	Delivery Person Family		Outdoors Person Family	Near River Family	Migrant Worker Family
	Briar Creek	Creeks, ponds near Williston	Savannah River near Augusta	Lower Three Runs Creek	Savannah River (Smith Lake)	Savannah River (various locations)	Savannah River (various locations)	Creeks, ponds near New Ellenton
Adult Male	0	0	0	1.0	1.0	1.0	1.0	0
Adult Female	0	0	0	1.0	1.0	1.0	1.0	0
Children Born in 1955 and 1964:								
Infant	0	0	0	1.0	1.0	1.0	1.0	0
Preschool	0	0	0	1.0	1.0	1.0	1.0	0
School	0	0	0	1.0	1.0	1.0	1.0	0
Teen	0	0	0	1.0	1.0	1.0	1.0	0
Adult	0	0	0	1.0	1.0	1.0	1.0	0

E.5.2.4 Inadvertent Soil Consumption

This exposure pathway considers exposures from inadvertent ingestion of contaminated soil. The following are GENII variables for this exposure pathway:

- USOIL – Daily soil ingestion rates (milligrams/d), when consumption occurs.
- TSOIL – Soil contact days (days out of the year that soil is consumed).

Exposure factors for this exposure pathway represented the total mass of contaminated soil eaten during each year. They were calculated for each receptor and exposure location by multiplying the daily soil ingestion rate appropriate for that receptor by the days out of the year that the receptor stayed in any exposure location. The results were exposure factors in units of kg/y.

Soil ingestion rates were based on Table 4-23 of EPA, 1997 (5). Daily rates of 100 milligrams per day for children, and 50 milligrams per day for adults, were converted to annual rates (in units of kg/y) as summarized in Table E-40.

Table E-41 summarizes the exposure factors. They were calculated in the same manner as that used to determine exposure factors for the air inhalation exposure pathway (Section E.5.3.1). For example, the Adult Male of the Urban/Suburban family spent 2000 hours out of the year (8,760 hours) working onsite at the SRS. The exposure factor for the time spent at work was 0.0183 x (2000/8,760) = 0.00418 kg/year.

Adjustment factors were unity for all receptors and locations.

Table E-40 GENII-Modeled Age and Gender Categories and Calculated Rates for Soil Ingestion

Modeled Age Categories	Soil Ingestion (g/yr)
Infant (<1)	0.0365
Pre-School (1 – 4)	0.0365
Child (5 – 11)	0.0365
Teenager (12 – 17)	0.0365
Adult Male (>18)	0.0183
Adult Female (>18)	0.0183

Table E-41 Exposure Factors (kg/year) for Soil Ingestion Pathway

Individual	Years	Rural Family One		Rural Family Two	Urban/Suburban Family		Delivery Person Family	
		Girard	Waynes-boro	Willi-ston	Augusta	Onsite SRS	Martin	Onsite SRS
Adult M	All	0.0183	0	0.0183	0.0141	0.00418	0.000693	0.000836
Adult F	All	0.0183	0	0.0183	0.0183	0	0.000393	0
Children Born in 1955 and 1964	Infant	0.0365	0	0.0365	0.0365	0	0.001275	
	Preschool	0.0365	0	0.0365	0.0365	0	0.001275	0
	Schoolchild	0.0365	0	0.0365	0.0365	0	0.001275	0
	Teen	0.03125	0.00525	0.0365	0.0365	0	0.001275	0
	Adult M	0.0183	0	0.0183	0.0141	0.00418	0.00693	0.000836

Individual	Years	Delivery Person Family (continued)		Outdoors Person Family		Near River Family	Migrant Worker Family
		Allendale	Barnwell	Onsite SRS	Jackson	Martin	New Ellenton
Adult M	All	0.00334	0.0135	0.00418	0.0141	0.0183	0.009125
Adult F	All	0	0.0177	0	0.0183	0.0183	0.009125
Children Born in 1955 and 1964	Infant	0	0.0352	0	0.0365	0.0365	0.01825
	Preschool	0	0.0352	0	0.0365	0.0365	0.01825
	Schoolchild	0	0.0352	0	0.0365	0.0365	0.01825
	Teen	0	0.0352	0	0.0365	0.0365	0.01825
	Adult M	0.0034	0.0135	0.00418	0.0141	0.0183	0.009125

E.5.2.5 Inadvertent Ingestion of Surface Water While Swimming

This exposure pathway accounts for ingestion of contaminated water that occurs when an individual swims in contaminated water. The following are GENII variables for this exposure pathway:

- EVSWIM - Frequency of swimming use (event/day).
- TESWIM - Duration of swimming events (hours/event).
- TSWIM - Swimming days (days/year).
- USWIM – Ingestion rate of water while swimming (L/h).

Exposure factors determined in consideration of these variables are in units of L/y.

Swimming water ingestion rates were zero for Rural Families One and Two, the Migrant Worker Family, the Urban/Suburban Family, and the Outdoors Person Family because no swimming occurred in water that was hydrologically downgradient from the site. For the Delivery Person and the Near River Families, swimming water ingestion rates were estimated based on the time spent swimming and the ingestion rates while swimming. The swimming times were 21.2 hours/year for the Delivery Person Family, and 91 hours per year for the Near River Family (see Section E.5.1.4). The ingestion rate while swimming was 0.05 L/hr. This value was equal to EPA's default rate of water ingestion while swimming (5).

Table E-42 summarizes the exposure factors for the swimming water ingestion exposure pathway.

Table E-42 Exposure Factors (L/yr) for Swimming Water Ingestion Exposure Pathway

Individual	Rural Family One	Rural Family Two	Urban/ Suburban Family	Delivery Person Family	Outdoors Person Family	Near River Family	Migrant Worker Family
	Briar Creek	Savannah River	Savannah River	Lower Three Runs Creek	Savannah River	Savannah River	Savannah River
Adult Male	0	0	0	1.06	0	4.6	0
Adult Female	0	0	0	1.06	0	4.6	0
Children Born in 1955 and 1964:							
Infant	0	0	0	1.06	0	4.6	0
Preschool	0	0	0	1.06	0	4.6	0
School	0	0	0	1.06	0	4.6	0
Teen	0	0	0	1.06	0	4.6	0
Adult	0	0	0	1.06	0	4.6	0

E.5.3 Inhalation Exposure Route

E.5.3.1 Inhalation of Contaminated Air

This exposure pathway accounts for radiation exposure resulting from inhalation of airborne contaminants. The following are GENII variables for this exposure pathway:

- UINH: Air inhalation rate (m^3/day).
- TINH: Air inhalation period (days/year).

Exposure factors were created for each receptor by assuming a constant daily inhalation rate that was appropriate for the age and gender of the receptor, and by multiplying it by the number of days in a year that the receptor was at a specified exposure location. The total time that the receptor occupied all specified exposure locations was 365 days. The result was an average air inhalation rate in units of m^3 per year.

The authors of this report conservatively did not consider any differences in radiation exposure based on whether the receptor was inside or outside of a building. This was equivalent to assuming that indoor concentrations for constituents such as fine particulate matter and gasses were roughly equal to the outdoor concentrations. This situation could have existed if the receptors routinely left windows open or spent their time in structures that were not completely sealed.

Exposure factors for each receptor and exposure location were determined using the exposure rates recommended by EPA on Table 5.26 of EPA, 1997 (5), and the assumed days out of the year spent by each receptor at each exposure location. EPA, 1997 (5) provides recommended inhalation values for a more detailed distribution of ages and genders than was assumed for this study. Therefore, the EPA data were grouped into the age and gender categories that were considered in this report, and the EPA data in each group were averaged to align with the modeled categories. Table E-43 specifies the categories and data from this reference and the corresponding modeled categories and rates. Because both the modeled children were male, average exposure rates were calculated for the child (5-11) and teenage (12-17) years assuming male breathing rates (when specified by EPA). (The average annual air inhalation rate for the child was determined by averaging the three 6-8 years with the three 9-11 male years. The average annual air inhalation rate for the teenager was determined by averaging the three 12-14 male years with the four 15-18 male years.)

Table E-43 Air Inhalation Age/Gender Categories and Rates, and Corresponding GENII-Modeled Air Inhalation Age/Gender Categories and Calculated Rates

EPA 1997 Data (Table 5-26)		Corresponding Modeled Exposure Rate Values	
Age/Gender Categories	**Air Inhalation (m^3/day)**	**Modeled Age/Gender Categories**	**Air Inhalation (m^3/year)**
Infants (<1)	4.5	Infant (<1)	1,643
1 – 2 3 – 5	6.8 8.3	Pre-School (1 – 4)	2.,811
6 – 8 9 – 11 Male 9 – 11 Female	10 14 13	Child (5 – 11)	4,380*
12 – 14 Male 12 – 14 Female 15 – 18 Male 15 – 18 Female	15 12 17 12	Teenager (12 – 17)	5,892†
Adult Male 19 – 65+	15.2	Adult Male (>18)	5,548
Adult Female 19 – 65+	11.3	Adult Female (>18)	4,125

*Averaged using the three 6-8 years plus the three 9-11 male years.
†Averaged using the three 12-14 male years and the four 15-18 male years.
Source: EPA, 1997 (5).

Table E-44 lists the exposure factors calculated from the Table E-43 data, and from the assumed location times for each receptor.

The exposure factors for the teenagers of Rural Family One were split between Girard and Waynesboro, where the teenagers attended high school. Assuming a total of 1,260 hours per year spent in high school,

out of a total 8,760 hours in a year, the teenagers' exposure factors were 1260/8760 (5,892) = 847.5 m^3 per year (rounded to 848 m^3 per year) for the time spent in high school, and 5,892 – 847.5 = 5,044.5 m^3 per year (rounded to 5,045 m^3 per year) for the remaining time spent in Girard. For the remaining family members, exposure factors were calculated assuming that they spent the entire year in Girard.

Table E-44 Table E-44 Exposure Factors (m3/y) for Inhalation Exposure Pathway

Individual	Years			Rural Family Two	Urban/Suburban Family		Delivery Person Family	
		Girard	Waynes-boro	Williston	Augusta	Onsite SRS	Martin	Onsite SRS
Adult M	All	5,548	0	5,548	4,281	1,267	194	253
Adult F	All	4,125	0	4,125	4,125	0	144	0
Children Born in 1955 and 1964	Infant	1,643	0	1,643	1,643	0	57	0
	Preschool	2,811	0	2,811	2,811	0	98	0
	Schoolchild	4,380	0	4,380	4,380	0	153	0
	Teen	5,045	848	5,892	5,892	0	206	0
	Adult M	5,548	0	5,548	5,281	1,267	194	128

Individual	Years	Delivery Person Family (continued)		Outdoors Person Family		Near River Family	Migrant Worker Family
		Allendale	Barnwell	Onsite SRS	Jackson	Martin	New Ellenton
Adult M	All	1,013	4,088	1,267	4,281	5,548	2,774
Adult F	All	0	3,980	0	4,125	4,125	2,062
Children Born in 1955 and 1964	Infant	0	1,585	0	1,643	1,643	821
	Preschool	0	2,712	0	2,811	2,811	1,405
	Schoolchild	0	4,227	0	4,380	4,380	2,190
	Teen	0	5,686	0	5,892	5,892	2,946
	Adult M	1,013	4088	1,267	4,281	5,548	2,774

As addressed in Section E.5.1.1, the split in exposure factors between Girard and Waynesboro for the teenagers was applied for the entire time they were teenagers: for the six years comprising 1967 through 1972 for the Child Born in 1955, and the six years comprising 1976 through 1981 for the Child Born in 1964.

The exposure factors for the Adult Male of the Urban/Suburban Family were split between Augusta and his job onsite at the SRS. Assuming a total of 2,000 hours per year spent at work, again out of a total 8,760 hours in a year, the adult male exposure factors were 2000/8760 (5,548) = 1,267 m^3 per year for the time spent at work, and 5,548 – 1,267 = 4,281 m^3 per year for the remaining time spent in Augusta. Exposure factors for the Adult Female of this family were calculated assuming that she spent all her time was spent in Augusta. The two children spent all their time in Augusta until the each reached 18. Both then worked 2,000 hours per year onsite.

For the Delivery Person Family, the Adult Male worked in Allendale and also occasionally came onsite at the SRS for deliveries. The remainder of his time was spent between Barnwell, where he lived with his family, and Martin, where he and his family recreated and attended church. Table E-45 lists the total hours spent at each location for each family member.

Table E-45 Hours Spent by Each Member of the Delivery Person Family at Four Different Exposure Locations

Family Member	Martin	Onsite SRS	Allendale	Barnwell
Adult Male	306	400	1,600	6,454
Adult Female	306	0	0	8,454
Child Born in 1955	306	0	0	8,454
Child Born in 1964	306	0	0	8,454

For the Outdoors Person Family, exposure factors for the Adult Male were split between Jackson and his job onsite at the SRS. The adult male exposure factors were 2,000/8,760 x 5,548 = 1,267 m^3 per year for the time spent at work, and 5,548 – 1,267 = 4,281 m^3 per year for the time spent in Jackson. Exposure factors for the Adult Female of this family were calculated assuming that she spent all her time in Jackson. The two children were assumed to spend all their time in Jackson until they each reached age 18, after which they each worked onsite for 2,000 hours per year.

Exposure factors for all members of the Near River Family were calculated assuming that each member spent all their time in Martin.

The exposure factors for the members of the Migrant Worker Family were calculated assuming that each member spent all their time in New Ellenton, and that they were only in the SRS vicinity for half of any year.

Adjustment factors equaled unity for each receptor and location.

E.5.3.2 Inhalation of Resuspended Soil

This exposure pathway addresses inhalation of resuspended contaminated soil. The following are GENII variables for this exposure pathway:

- UINHR - Resuspended soil inhalation rate (m^3/day).
- TINHR - Resuspended soil inhalation period (days/year).
- FRINHR - Fraction of a day inhalation of resuspended soil occurs (unitless).

Exposure factors were calculated for each receptor and location based on an assumed daily inhalation rate for each receptor, and an assumed time spent at each location. It was assumed that resuspended contamination was breathed for 24 hours out of the day (FRINHR = 1). Therefore, the exposure factors for this exposure pathway were the same as those for inhalation of contaminated air that are listed in Table E-44.

Adjustment factors were assumed to be unity for all receptors and locations.

As discussed previously, no adjustments were made to account for any differences in air concentrations between indoor and outdoor exposures. The indoor and outdoor air concentrations were assumed to be the

same. (This is equivalent to the assumption that individuals left windows and doors of living or working structures open for ventilation, or that the structures were not perfectly sealed.)

E.6 References

1. Lockridge J. CY 2002 status report scenario working group [unpublished]. South Carolina. Savannah River Site Health Effects Site-Specific Advisory Board, Scenario Work Group. September 6, 2002.

2. McDougall V. Receptor locations for atmospheric release [unpublished]. ATL International, Inc. Germantown, Maryland. January 12, 2003.

3. McDougall V. Update on receptor locations for atmospheric releases [unpublished]. ATL International, Inc. Germantown, Maryland. February 26, 2003.

4. U.S. Environmental Protection Agency. Federal guidance report 13, cancer risk coefficients for environmental exposure to radionuclides: CD supplement. EPA 402-C-99-001, Rev. 1. Oak Ridge National Laboratory. April 2002.

5. U.S. Environmental Protection Agency, Office of Research and Development. Exposure factors handbook. EPA/600/P-95/002Fa. Washington, D.C. 1997.

6. Hamby DM. Land and water use characteristics in the vicinity of the Savannah River Site. Westinghouse Savannah River Company, Savannah River Site. Aiken, South Carolina. WSRC-RP-91-17. 1991.

7. Napier BA, Strenge DL, Ramsdell JV Jr., Eslinger PW, Fosmire C. GENII version 2 software design document. Pacific Northwest National Laboratory. Washington. November 2002.

8. Westinghouse Savannah River Company. Savannah River Site environmental report for 1990. WSRC-IM-91-28. Aiken, South Carolina. 1991.

9. Westinghouse Savannah River Company. Savannah River Site environmental report for 1991. Aiken, South Carolina. 1992.

10. Westinghouse Savannah River Company .Savannah River Site environmental report for 1992. WSRC-TR-93-075 and –077. Aiken, South Carolina. 1993.

11. U.S. Environmental Protection Agency, Office of Emergency and Remedial Response, Toxics Integration Branch. Risk assessment guidance for Superfund, volume I: human health evaluation manual, supplemental guidance, standard default exposure factors interim final. OSWER Directive 9285.6-03, NTIS PB91-921314. Washington, D.C. March 25, 1991.

12. U.S. Environmental Protection Agency. Population exposure to external natural radiation background in the United States. 1981.

13. Ledbetter JL. Outdoor recreation assessment and policy plan 1989 in the Georgia recreation planning process. Georgia Department of Natural Resources. Atlanta, Georgia. 1990.

14. U.S. Nuclear Regulatory Commission. Regulatory guide 1.109, calculation of annual doses to man from routine releases of reactor effluents for the purpose of evaluating compliance with 10 CFR Part 50, appendix I. Revision 1. October 1977.

15. U.S. Environmental Protection Agency, Office of Health and Environmental Assessment, Exposure Assessment Group. Estimating exposure to dioxin-like compounds, external review draft. EPA/600/6-88/005Ca. Washington, D.C. June 1994.

16. U.S. Environmental Protection Agency, Office of Science and Technology. Estimated per capita fish consumption in the United States. EPA-821-C-02-003. Washington, D.C. 2002.

APPENDIX F SITE SPECIFIC PARAMETER VALUES USED FOR BASE CASE

This appendix presents values for nearly all parameters used in the GENII code[1] that do not depend on the behavior of the hypothetical receptors (exposure scenario family members) that were modeled for Phase III of the Savannah River Site (SRS) Dose Reconstruction Project. The appendix is in three sections:

- Section F.1: Food Chain Transfer Factors.
- Section F.2: Food Chain Variables.
- Section F.3: Additional Parameter Values.

The discussion refers to those GENII variables that were used for those assessment models and exposure pathways that were considered in Phase III. The GENII Software Design Document may be consulted for a complete list of variables considered in all assessment models and exposure pathways.

Values for parameters needed for human radiation dosimetry assessments (e.g., radionuclide-specific lung clearance classes) are provided in Section D.4 of Appendix D.

F.1 Food Chain Transfer Factors

Transfer factors are needed to model several food-chain pathways. Transfer factors for partitioning between radionuclide concentrations in soil to those in plants are used in the equations set forth in Section D.3.3.1. Transfer factors used to assess the uptake of radionuclides by animals, and the uptake of radionuclides by humans consuming the animals or the animal products, are used in the equations set forth in Section D.3.3.2. Transfer factors that address bioaccumulation of radionuclides in fresh-water fish are used in Section D.3.3 to assess uptake of radionuclides by humans consuming aquatic foods.

F.1.1 Introduction

The three sets of transfer factors used for this report are presented in Table F-1 along with units and GENII variable names. The three sets of transfer factors correspond to the following parameters:

- Bv_{ci}: Concentration ratio for root uptake of radionuclide i in crop type c (Section D.3.3.1).
- Fa_i: ransfer coefficient that relates daily intake rate by an animal to concentration in an edible animal product a (Section D.3.3.2).
- B_{qi}: Bioaccumulation factor for radionuclide i in aquatic food type q (Section D.3.3.3).

Table F-1 shows two sets of units. The first set comprises those units specified for the GENII software and has been simplified from the complete units by eliminating units that cancel each other. For example, the units for the soil-to-plant concentration ratio for animal forage (kg soil/kg dry) are actually a reduction of the ratio [Bq/kg dry forage] / [Bq/kg soil]. The second set comprises the complete units of the factor. These transfer factors are all element-specific (i.e., a single value for each transfer factor identified for a given element or isotope is used for all isotopes of that element). This is a common assumption made in environmental studies involving radionuclides because the chemical behavior in the environment depends on the atomic number rather than the atomic weight.

[1] All references to GENII in this chapter refer to Version 2 of the GENII code.

Table F-1 GENII Transfer Factors in Used in SRS Food Chain Modeling

Category	Variable	GENII Variable Name	GENII Units	Complete Units
Soil-to-Plant Concentration Ratios	Soil to Animal Forage	CLBVAF	kg soil/kg dry	(Bq/kg dry plant matter) / (Bq/kg soil)
	Soil to Grain	CLBVAG		
	Soil to Hay	CLBVAH		
	Soil to Cereal	CLBVCL		
	Soil to Fruit	CLBVFR		
	Soil to Leafy Vegetables	CLBVLV		
	Soil to Other Vegetables	CLBVOV		
	Soil to Root Vegetables	CLBVRV		
Animal-Intake-to-Animal-Product Transfer Factor Ratios	Feed to Egg	CLFEG	d/kg	(Bq/kg eggs) / (Bq/day intake)
	Feed to Animal Milk	CLFMK	d/L	(Bq/L milk) / (Bq/day intake)
	Feed to Animal Meat	CLFMT	d/kg	(Bq/kg meat) / (Bq/day intake)
	Feed to Poultry	CLFPL	d/kg	
Water-to-Aquatic-Food Bioaccumulation Factors (Freshwater)	Bioaccumulation in Freshwater Fish	CLBFF	L/kg	(Bq/kg fish) / (Bq/L water)

Table F-2 summarizes the isotopes and corresponding elements considered in the food-chain assessments.

Table F-2 Elements and Modeled Isotopes Requiring Transfer Factor Values

Atmospheric Release		Liquid Release	
C	(C14)	P	(P32)
Sr	(Sr89, Sr90)	S	(S35)
Y	(Y90)	Co	(Co60)
Ru	(Ru103, Ru106)	Zn	(Zn65)
I	(I129, I131) (both elemental and organic)	Sr	(Sr89, Sr90)
		Y	(Y90) *
Cs	(Cs137)	Nb	(Nb95, Nb95m)
Th	(Th231, Th234) *	Zr	(Zr95)
U	(U234, U235, U236, U238)	Tc	(Tc99)
Pu	(Pu238, Pu239)	Ru	(Ru103, Ru106)
Am	(Am241)	I	(I129, I131)
		Cs	(Cs134, Cs137)
		Ce	(Ce141, Ce144)
		Th	(Th231, Th234)*
		U	(U234, U235, U236, U238)
		Pu	(Pu238, Pu239)

*Transfer factors were needed for these radionuclides because they are decay products of other radionuclides released into air and water pathways from SRS operations.

No transfer factors were selected for tritium, carbon, and noble gases such as argon. For tritium and carbon, GENII determines transfer between compartments and media using special models as summarized in Sections D.3.4.1.7 and D.3.4.2.3. For argon and other noble gases, which do not interact chemically except in unusual circumstances not found in the environment, transfer through the food chain does not occur. Hence, no transfer factors were assumed for noble gasses.

F.1.2 Limitations and Uncertainties in Selecting Transfer Factor Values

In selecting values for transfer factor factors for this study, two limitations became apparent: (1) the use of the same transfer factor in multiple pathways, and (2) limitations in the availability of site-specific transfer factor values.

F.1.2.1 Use of Transfer Factors for Different Pathways

A limitation on selecting values for transfer factors was that GENII requires that certain transfer factors be used for multiple pathways (1). For example, GENII applies the variable used for the soil-to-leafy-vegetable transfer factors (CLBVLV) to four different transport pathways (see Table F-3).[2]

Table F-3 Transfer Factors used in GENII for Multiple Pathways

GENII Transfer Factor	Pathways Covered in GENII
Soil-to-leafy-vegetables (CLBVLV)	• Soil-to-leafy-vegetables (for leafy vegetables that are subsequently consumed by humans, CLBVLV) • Soil-to-beef-cattle-forage (for pasture grass that is subsequently consumed by beef cattle, CLBVAF) • Soil-to-milk-cow-forage (for pasture grass that is subsequently consumed by milk cows, CLBVAF) • Soil-to-milk-cow-feed (for hay that is subsequently consumed by milk cows, CLBVAH)
Soil-to-cereal (CLBVCL)	• Soil-to-cereal (for cereal that is subsequently consumed by humans, CLBVCL) • Soil-to-beef-cattle-feed (for grain that is subsequently consumed by beef cattle, CLBVAG) • Soil-to-poultry-feed (for grain that is subsequently consumed by poultry, CLBVAG) • Soil-to-egg-animal-feed (for grain that is subsequently consumed by egg-producing chickens, CLBVAG)
Soil-to-other-vegetable (CLBVOV)	• Soil-to-other-vegetables (for other vegetables that are subsequently consumed by humans, CLBVOV) • Soil-to-root-vegetables (for root vegetables that are subsequently consumed by humans, CLBVRV)

[2] In this case, the FRAMES software that forms the user interface for GENII lets the user input values for three different transfer factors (CLBVLV, CLBVAF, and CLBVAH). But only CLGVLV is actually read by GENII and it is used for two different pathways. GENII ignores the values input for the other variables.

Because of GENII's calculational simplification, ATL had to select values for the transfer factors listed on the left side of Table F-3 based on its understanding of the type of crop or food product represented in each segment of the food chain involving that transfer factor. For soil-to-plant transfer factors, Table F-4 lists the crops or food products to which the transfer factors were applied. Figure F-1 illustrates how the transfer factor variables are used in the food-chain pathways modeled by GENII.

Table F-4 Crops or Food Products represented by GENII Transfer Factors in SRS Exposure Scenarios

GENII Variable Used in Calculations	Pathway and GENII Variable	Crop or Food Product
CLBVLV	Soil-to-Leafy Vegetables (CLBVLV)	Locally-produced leafy vegetables
	Soil-to-Animal Forage (CLBVAF)	Locally-grown Bermuda grass used as pasture for beef cattle and milk cows as well as stored Bermuda grass green chop consumed by beef cattle
	Soil-to-Hay (CLBVAH)	Locally-produced corn silage used as feed for milk cows
CLBVCL	Soil-to-grain (CLBVAG)	Locally-produced corn grain used as feed for beef cattle, poultry, and egg animals (chickens)
	Soil-to-cereal (CLBVCL)	Locally-produced corn grain consumed by humans
CLBVFR	Soil-to-Fruit (CLBVFR)	Locally-produced fruit
CLBVOV	Soil-to-Other Vegetables (CLBVOV)	Locally-produced non-leafy vegetables
	Soil-to-Root Vegetables (CLBVRV)	Locally-produced non-leafy vegetables

For the CLBVLV transfer factor, Advanced Technologies and Laboratories International, Inc. (ATL) considered three different crops when assigning a value for each element listed in Table F-3. ATL selected values generally considering the most conservative (i.e., largest) values of those available in the literature for the transfer factor as applied to the three pathways. Although this approach may have overestimated the exposure through the different pathways covered by the CLBVLV transfer factor, implementing this approach was relatively straightforward. Otherwise, extensive calculations would have been required to determine the pathways that were the most dominant or representative of the total

exposure to human receptors. Determining the soil-to-plant transfer (soil-to- leafy-vegetable, soil-to-beef-animal-forage, soil-to-milk-animal-forage, and soil-to-milk-animal-feed) that were most representative would have involved calculating the total dose summed up over all soil-to-plant transfer pathways, which would have been calculated using a different transfer factor value for each soil-to-plant transfer pathway.

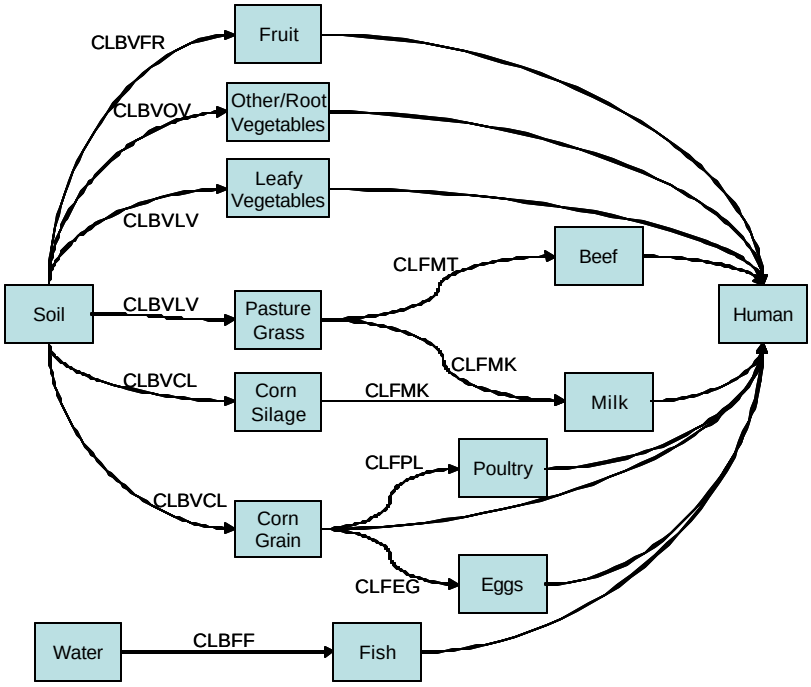

Figure F-1 Exposure Pathways of the Food Chain and Corresponding Transfer Factor Variables Used by GENII

Although the exposure through human consumption of leafy vegetables would have been relatively easy to determine, the exposure through the other pathways would have been more complex to model. It would have required calculations involving the amount of contaminated plant food intake by milk and meat producing animals, the amount of milk and meat consumed by each receptor at each exposure location (including the different amounts consumed by the different age groups), and the values of the other transfer factors that formed the food chain (the animal-intake-to-milk and animal-intake-to-meat factors).

Similar considerations guided ATL's selections of values for the soil-to-cereal transfer factor, CLBVCL, a parameter representing corn consumed by humans, poultry, and egg animals, and corn silage consumed by milk cows. The largest values were again selected from the literature.

F.1.2.2 Limitations in Site-Specific Values for Transfer Factors

A substantial body of literature exists for various transfer factors. This literature includes numerous studies that examine radionuclide transport through the food chain. These studies provide experimental results for specific environmental conditions. For example, soil-to-plant factors are typically specified for individual plant species, soil conditions, and growing conditions. Because transfer factor values cited in the literature often range over several orders of magnitude, there is considerable uncertainty in selecting any single value assigned to a given transfer factor.

ATL used a three-step process—illustrated in Figure F-2—to select transfer factor values for this report. The first step in determining values was to consider data for local or site-specific conditions. Where local data were not available, default values were used. The first reference source used for default values was *Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Temperate Environments*, Technical Reports Series No. 364 (2). For cases where the handbook (2) did not contain a default value, the GENII default was used. Site-specific data and default values were compared where possible. Where site-specific values were selected, the corresponding value from the handbook (2) is provided for information. Where the selected values are considerably different from the handbook (2) values, the 95-percent confidence range, if cited in the handbook (2), is also provided for information.

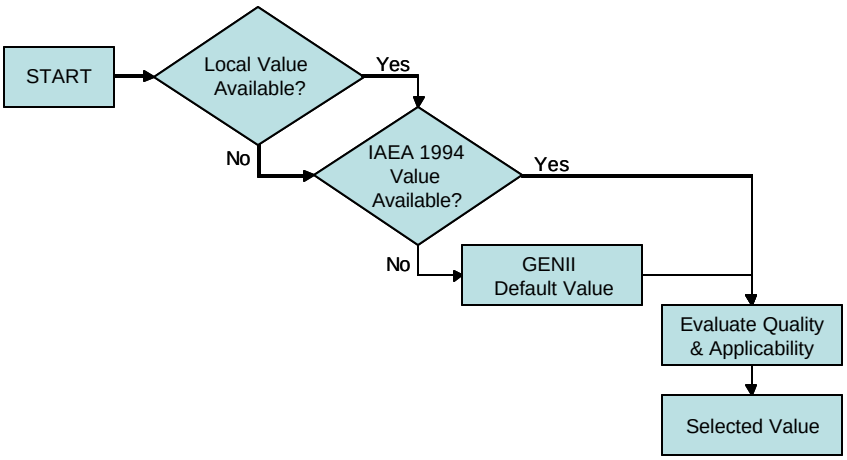

Figure F-2 Process for Selecting Transfer Factor Values

F.1.2.2.1 Site-specific Values

Site-specific data were used to identify values for several transfer factors for four elements being modeled—strontium, cesium, plutonium, and americium. Using data from Friday et al.(3) and, in some cases, a combination of data from Friday et al. (3) and the International Atomic Energy Agency's (IAEA) *Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Temperate Environments* (2), the selected values and the rationale for their determination are described in Table F-5. In general, site-specific values were used without modification if they were within two orders of magnitude of generic values; if the differences were larger, then a geometric mean of the site specific and generic value was usually selected.

In selecting values for some variables, ATL took into account the GENII use of the same values for some transfer factors. In particular, for the soil-to-leafy-vegetable transfer factor (which is also used for beef cattle forage, milk cow forage, and milk cow feed), where the approach was to select the largest values, only a few SRS-specific values were available from the literature. In no case were values cited for more than one plant species for a given radionuclide. For the soil-to-cereal transfer factors, the values selected by ATL corresponded to corn grain. ATL selected corn over other crops (wheat, rice, etc.) because corn is grown in the region (4) and could have been consumed by humans as well as poultry.

Table F-5 Site-Specific Transfer Factor Values Calculated Using Data from Friday 1996

Pathway	Value and Rationale
Strontium	
Water-to-Freshwater-Fish	Value = 450 (Strontium) Friday et al. (3) presents two values for piscivores (3,400) and benthic invertebrate and fish feeders (610). The average value is ~2,000. This value is higher than the IAEA (2) default value (60) by a factor of ~33 and is outside the range of measured values (1 – 1,000) cited in the IAEA report. Because the values from Friday et al. (3) are so high and represent only two data points, the geometric mean (450) of the site-specific average value (2,000) and the generic value (60) was used.
Soil-to-Cereal	Value = 0.15 (Strontium) Friday et al. (3) provides a single value for corn grain of 0.15. Corn grain is consumed by humans and by poultry. This value is smaller than the IAEA (2) default value (0.21) by a factor of ~1.4.
Cesium	
Water-to-Freshwater-Fish	Value = 4,700 (Cesium) Friday et al. (3) presents values for different types of fish muscle. An average of three mean values was taken for surface and midwater insectivores (7,009), insect and bottom invertebrate feeders (911), and piscivores (10,980). The average value (6,300) is larger than the value used by the SRS (3,000) in the Savannah River Site Environmental Report for 2001(5) by a factor of ~2 and the IAEA (2) expected value (2,000) by a factor of ~. It is above the 95 percent confidence range (30 – 3,000) cited by IAEA (2). The value selected by ATL (4,700) was the geometric average of the average of the site-specific values and the IAEA expected value. Friday et al. (3) states "...the relatively high bioconcentration factors of cesium-137 in fish flesh can be largely explained by the low concentrations of potassium in the water" (p.14). Other SRS studies (5,6) have recommended a value of 3000 kg/L.
Soil-to-Leafy-Vegetables	Value = 5.31 (Cesium) Friday et al. (3) provides a mean value for Bahia Grass of 5.31. Bahia grass is the primary forage for cattle, and the soil-to-leafy vegetable factor is used for soil-to-cattle-forage in GENII. This value is larger than the IAEA (2) default value (0.46) by a factor of ~12. Friday et al. (3) states, "The site-specific bioconcentration factors determined for plants and grasses are higher than values reported in the literature and are probably due to the local clay content of the soils at the SRS" (p.18).
Soil-to-Cereal	Value = 0.02 (Cesium) Friday et al. (3) provides a single value for corn grain of 0.01. Corn grain is consumed by humans and by poultry. This value is smaller than the IAEA (2) default value (0.026) by a factor of ~3. However, it is within the 95 percent confidence range (0.0026 – 0.26) cited by IAEA (2). The selected value, 0.02, is the geometric mean of the site-specific and IAEA default values.
Soil-to-Other-Vegetables	Value = 0.9 (Cesium) Friday et al. (3) provides a single value for fresh vegetables of 0.9. This value is higher than the IAEA (2) default value (0.46) by a factor of ~2.

Pathway	Value and Rationale
Plutonium	
Water-to-Freshwater-Fish	Value = 4,700 (Plutonium) Friday et al. (3) provides three values for fish muscle, including two values for piscivores (2,600 and 5,600) and one value for benthic invertebrate and fish feeders (12,000). The average value is ~6,700; the geometric average is 5,600. This value is higher than the IAEA (2) expected value (30) by a factor of ~190 and is higher than the 95 percent confidence range (4 – 300) cited by IAEA (2). The value selected by ATL (4,700) was the geometric average of the average of the site-specific values and the IAEA expected value. Friday et al. (3) states, "Transuranic elements are known to be fixed by clay minerals and complexed by organic matter which may decrease their availability. Zooplankton and benthic insect larvae have high surface to volume ratios. This allows their surfaces as well as their guts to carry sediment and sestonic particles, which adsorb transuranic particles; thus resulting in higher bioconcentration factors... " (p.27). Additionally, for general population dose calculations, the SRS has used a value of 3,000 (5,6).
Soil-to-Cereal	Value = 6E-5 (Plutonium) Friday et al. (3) provides a single value for corn grain of $6x10^{-5}$. This value is larger than the IAEA (2) default value ($8.6x10^{-6}$) by a factor of ~7.
Soil-to-Leafy-Vegetables	Value = 0.0022 (Plutonium) Friday et al. (3) provides maximum and minimum values for Bahia grass of $4.4x10^{-3}$ and $8.9x10^{-5}$. The average of these two values is ~$2.2x10^{-3}$ (the geometric average is $6.3x10^{-4}$). The average value is larger than the IAEA (2) default value ($3.4x10^{-4}$) by a factor of ~6.5; the geometric average is larger by a factor of ~1.8. Both values are within the 95 percent confidence range ($5x10^{-5}$ – 0.65) cited by IAEA (2). The selected value is the average of the site-specific values.
Americium	
Water-to-Freshwater-Fish	Value = 2,400 (Americium) Friday et al. (3) provides two values for fish muscle, including one value for piscivores (2,500) and one value for benthic invertebrate and fish feeders (4,200). The average value is ~3,400; the geometric mean is 3,200. The average value is larger than the IAEA (2) expected value (30) by a factor of ~140, and the geometric mean is larger by a factor of ~110. Both values are larger than the 95 percent confidence range (30 – 300) cited by IAEA (2). The value selected by ATL (2,400) was the geometric average of the average of the site-specific values and the IAEA expected value. The explanation for the higher site-value for Americium is same as that for plutonium (Friday et al. [3]).
Soil-to-Leafy-Vegetables	Value = 0.067 (Americium) Friday et al. (3) provides a mean value for Bahai grass of 0.067. This value is larger than the IAEA (2) default value ($1.2x10^{-3}$) by a factor of ~56.

F.1.2.2.2 IAEA Default Values

Default values from IAEA were found for most radionuclides and pathways (See Table F-6). In general, only a single value was provided for each animal-intake-to-milk, meat, poultry, and egg pathways. However, for soil-to-plant transfer factors, IAEA (2) listed multiple values for different plant species and soil conditions. The following different approaches were used to select from among different plant species:

- For the soil-to-leafy-vegetable transfer factor, different values were considered for both leafy vegetables and grass forage. The available values in each group were averaged, and the highest calculated average value was used. In some cases, only a single value was available, and in other cases multiple values were considered.
- For the soil-to-cereal transfer factor, values for corn grain were preferred over other values. But in cases where no value was available for corn grain, other values for grains and corn fodder were averaged.
- For the soil-to-other vegetable transfer factor, available values were averaged.

In addition, transfer factor values were frequently specified for different soil conditions. In these cases, ATL selected "sand, pH5" because this condition was judged most similar to the soils surrounding the SRS. Other soil conditions (clay, peat) were not considered when data for sandy soil were available. For instances where IAEA (2) cited multiple values, Table F-6 lists the values considered and calculated.

F.1.2.2.3 GENII Default Values

IAEA (2) did not recommend values for some radionuclides and pathways. For these cases, ATL used the default values specified by GENII. The GENII default values are generally specified in both the constituent library included in the GENII software and in Appendix D of the GENII Software Design Document (7). A few of the values were only documented in the constituent library. The GENII default values are not specific to plant species, soil types, or growing conditions.

F.1.2.2.4 References Cited in IAEA (2) and PNNL (7)

For each of the default values taken from IAEA (2), ATL identifies in Table F-7 the previous reference (generally the primary reference) cited by IAEA (2). With a few exceptions, ATL also identifies in Table F-7—for each GENII default value taken from PNNL (7)—the previous reference (generally the primary reference) cited by PNNL (7). These reference citations are provided for information only. ATL's selection of transfer factor values was based on information and recommendations in IAEA (2) and PNNL (7). ATL generally did not research the references cited by these documents.

F.1.3 Transfer Factor Values Used in Report

Table F-8 lists the transfer factor values used by ATL and selected using the process outlined above. The entry "Not Specified" in Table F-8 indicates that the exact species of plant, on which the transfer factor was based, was not provided by the source. The citations in the footnotes of Table F-8 refer to the references listed in Table F-7.

Table F-6 Default Transfer Factor Values Calculated from IAEA 1994

Nuclide and Pathway	Selected Value	Values Cited	
Cobalt – Leafy Vegetables	0.20 (average of cabbage, lettuce, and spinach)	Grass	$5.4x10^{-02}$
		Cabbage	$4.4x10^{-02}$
		Lettuce	$2.8x10^{-01}$
		Spinach	$2.9x10^{-01}$
Cobalt – Other/Root Vegetables	0.11 (average of cited values)	Bean pods	$3.0x10^{-02}$
		Carrot roots	$1.3x10^{-01}$
		Radish roots	$1.2x10^{-01}$
		Potato tubers	$6.0x10^{-02}$
		Mixed green vegetables	$2.x10^{-01}$
Zinc – Cereals	1.0 (average of cited values)	Barley grain	$8.8x10^{-01}$
		Wheat grain	1.6
		Maize fodder	$5.6x10^{-01}$
Zinc – Leafy Vegetables	3.3 (highest value)	Grass	$9.9x10^{-01}$
		Spinach	3.3
Zinc – Other/Root Vegetables	12 (average of cited values)	Bean pod	$7.1x10^{-01}$
		Potato tuber	$3.5x10^{+01}$
		Broccoli	$8.2x10^{-01}$
Strontium – Leafy Vegetables	1.7 (grass in sand pH5)	Grass in sand pH5	1.7
		Grass in peat pH4	$3.4x10^{-01}$
Strontium – Other/Root Vegetables	1.7 (average of values in sand pH5)	Pea/bean pod in clay loam pH6	1.3
		Pea/bean pod in sand pH5	2.2
		Root crops in clay loam pH6	1.1
		Root crops in sand pH5	1.4
		Potato tubers in clay loam pH6	$1.5x10^{-01}$
		Potato tubers in sand pH5	$2.6x10^{-01}$
		Potato tubers in peat pH4	$2.0x10^{-02}$
		Green veg exc. spinach in clay loam pH6	2.7
		Green veg exc. spinach in sand pH5	3.0
		Green veg exc. spinach in peat pH4	$2.6x10^{-01}$
Technetium – Leafy Vegetables	940 (average of cabbage, lettuce, and spinach)	Grass	$7.6x10^{+01}$
		Cabbage	$1.2x10^{+01}$
		Lettuce	$2.0x10^{+02}$
		Spinach	$2.6x10^{+03}$
Technetium – Other/Root Vegetables	28 (average of cited values)	Pea/bean pod	4.3
		Turnip root	$7.9x10^{+01}$
		Potato tuber	$2.4x10^{-01}$
Thorium – Other/Root Vegetables	$6.9x10^{-03}$ (average of cited values)	Bean pod	$1.2x10^{-04}$
		Carrot root	$3.0x10^{-04}$
		Radish root	$3.9x10^{-02}$
		Potato tuber	$5.6x10^{-05}$
		Sweet potato tuber	$2.9x10^{-05}$
		Mixed green vegetables	$1.8x10^{-03}$
Uranium – Other/Root Vegetables	0.011 (average of cited values)	Mixed roots	$1.4x10^{-02}$
		Potato tuber	$1.1x10^{-02}$
		Mixed green vegetables	$8.3x10^{-03}$

Nuclide and Pathway	Selected Value	Values Cited	
Plutonium – Other/Root Vegetables	$8.2x10^{-04}$ (average of cited values)	Bean pod	$6.1x10^{-05}$
		Carrot root	$4.4x10^{-03}$
		Radish root	$7.7x10^{-04}$
		Onion root	$8.7x10^{-05}$
		Mixed roots	$9.1x10^{-04}$
		Potato tuber, swede	$1.5x10^{-04}$
		Cucumber	$9.0x10^{-05}$
		Mixed green vegetables	$7.3x10^{-05}$
Americium – Other/Root Vegetables	$8.4x10^{-04}$ (average of cited values)	Bean pod	$3.9x10^{-04}$
		Carrot root	$2.2x10^{-03}$
		Radish root	$1.4x10^{-03}$
		Onion root	$1.6x10^{-04}$
		Potato tuber flesh	$2.0x10^{-04}$
		Mixed green vegetables	$6.6x10^{-04}$

Table F-7 Previous and Primary References Cited in [IAEA 1994] and [PNNL 2002]

Citation	Reference	Application
Baes 1984 (8)	Baes CF, Sharp RD, Sjoreen AL, Shor RW. A Review and Analysis of Parameters for Assessing Transport of Environmentally Released Radionuclides through Agriculture. ORNL-5786. Oak Ridge National Laboratory, TN. 1984.	Feed-to-Milk
Bishop 1989 (9)	Bishop GP, Beetham CJ, Cuff YS. Review of Literature for Chlorine, Technetium, Iodine and Neptunium, Nirex Radioactive Waste Disposal Safety Studies. Rep. NSS/R193, UK Nirex Ltd. Harwell. 1989.	Feed-to-Beef
CEC 1987 (10)	Commission of the European Communities. 1987. Radionuclide Transfer Factors for Animal Feedingstuffs and Animal Products. Doc. 7682/87. Luxembourg.	Feed-to-Milk
Coughtrey 1983 (11)	Coughtrey PJ, Thorne MC. 1983. Radionuclide Distribution and Transport in Terrestrial and Aquatic Ecosystems, A Critical Review of Data, Vols. 1 – 6. A.A. Balkema, Rotterdam.	Soil-to-Plant
Coughtrey 1990 (12)	Coughtrey, PJ. Radioactivity Transfer to Animal Products. Rep EUR 12608 EN, Commission of the European Communities, Luxembourg. 1990.	Feed-to-Milk, Beef, Poultry, Egg
Cramp 1990 (13)	Cramp TJ, Cuff YS, Davis A, Morgan JE. Review of Data for Uranium, Nickel, and Cobalt. Rep 2150-RI. Associated Nuclear Services Ltd, Epsom. 1990.	Feed-to-Beef
Ennis 1988a (14)	Ennis ME Jr, Ward GM, Johnson JE, Boamah KN. Transfer Coefficients of Selected Radionuclides to Animal Products. II Hen Eggs and Meat, Health Physics 54. pp. 167-170. 1988.	Feed-to-Poultry, Egg
Ennis 1988b (15)	Ennis ME, Johnson JE, Ward GM, Voigt GM. A Specific Activity Effect in the Metabolism of Technetium. Health Physics 54. pp. 157-160. 1988.	Feed-to-Poultry

Citation	Reference	Application
Frissel 1989 (16)	Frissel MJ, van Bergeijk KE. Mean Transfer Values Derived by Simple Statistical Regression Analysis, Sixth Report of IUR Working Group on Soil-to-Plant Transfer Factors, RIVM Bilthoven. 1989.	Soil-to-Plant
Frissel 1992 (17)	Frissel, MJ. An Update of the Recommended Soil-to-Plant Transfer Factors, Eighth Report of the IUR Working Group on Soil-to-Plant Transfer, IUR, Balen, Belgium. 1992.	Soil-to-Plant
Gerzabek 1993 (18)	Gerzabek MH, Horak O, Mohamad S, Muck K. Gefabversuche zum Radionuclidtransfer Boden-Pfanze, Fusionsreaktor – Erste Wand, Rep. OEFZS A-2531, Osterreichisches Forschungszentrum Seibersdorf, 22-31. 1993.	Soil-to-Plant
Handl 1989 (19)	Handl J, Pfau A.. Long-Term Transfer of I-129 into the Food Chain, Sci. Total Environ. 85. 245-252. 1989.	Feed-to-Beef
Hoffman 1988 (20)	Hoffman FO, Amaral E, Mohrbacher DA, Deming E. The Comparison of Generic Model Predictions with Chernobyl Fallout Data on the Transfer of Radioiodine Over the Air-Pasture-Cow-Milk Pathway, J. Environmental Radioactivity 8. 53-71. 1988.	Feed-to-Milk
Johnson 1988 (21)	Johnson JE, Ward GM, Ennis ME Jr, Boamah KN. Transfer Coefficients of Selected Radionuclides to Animal Products. 1. Comparison of Milk and Meat from Dairy Cows and Goats, Health Physics 54, 161-166. 1988.	Feed-to-Milk, Beef
Kennedy 1992 (22)	Kennedy WE Jr, Strenge DL. Residual Radioactive Contamination from Decommissioning: Technical Basis for Translating Contamination Levels to Annual Total Effective Dose Equivalent. Pacific Northwest Laboratory, NUREG/CR-5512. Richland, WA. 1992.	Soil-to-Plant
Morgan 1990 (23)	Morgan JE, Beetham CJ. Review of Literature for Radium, Protactinium, Tin, and Carbon, Nirex Radioactive Waste Disposal Studies, UK Nirex Ltd, Harwell. 1990	Feed-to-Milk
Napier 1988 (24)	Napier BA, Peloquin RA, Strenge DL, Ramsdell JV. GENII – The Hanford Environmental Radiation Dosimetry Software System. Pacific Northwest Laboratory. PNL-6584. Richland, WA. 1988.	Soil-to-Plant
Ng 1977 (25)	Ng YC, Colsher CS, Quinn DJ, Tompson SE. Transfer Coefficients for the Prediction of the Dose to Man via the Forage-Cow-Milk Pathway from Radionuclides Released to the Biosphere. UCRL-51939. Lawrence Livermore National Laboratory, California. 1977.	Feed-to-Milk
Ng 1982a (26)	Ng, YC, Colsher CS, Thompson, SE. Soil-to-Plant Concentration Factors for Radiological Assessments, Rep. NUREG/CR-2975 UCID-19463, Lawrence Livermore National Laboratory, CA. 1982.	Soil-to-Plant
Ng 1982b (27)	Ng, YC. A Review of Transfer Factors for Assessing the Dose from Radionuclides in Agricultural Products, Nucl. Saf. 23. 57-71. 1982.	Feed-to-Milk
Ng 1982c (28)	Ng, YC, Colsher CS, Thompson, SE. Transfer Coefficients for Assessing the Dose from Radionuclides in Meat and Eggs, Final Rep. to USNRC NUREG/CR-2976 UCID-19464 Lawrence Livermore National Laboratory, CA. 1982.	Feed-to-Beef, Poultry, Egg

Table F-8 Selected Values for Transfer, Bioconcentration, and Bioaccumulation Factors

Nuclide	Soil-to-Plant Factors (dry kg/dry kg) [ad]				Animal-Intake-to-Animal Product Factors				
	Cereal and Grain (CLBVCL, CLBVAG)	Leafy Vegetables, Animal Forage, and Hay (CLBVLV, CLBVAF, CLBVAH)	Other Vegetables and Root Vegetables (CLBVOV, CLBVRV)	Fruit (CLBVFR)	Animal Milk (CLFMK) (kg/L)	Animal Meat (CLFMT) (beef) (kg/kg)	Poultry (CLFPL) (kg/kg)	Egg (CLFEG) (kg/kg)	Freshwater Fish (CLBFF) Edible Portions (L/kg)
Phosphorus	3.5 [b]	3.5 [b]	3.5 [y]	3.5 [y]	$1.6x10^{-02}$ [j]	$5x10^{-02}$ [k]	0.19 [a]	1.0 [a]	$5x10^{+04}$ [i]
Sulfur	1.5 [b]	1.5 [b]	1.5 [y]	1.5 [y]	$1.6x10^{-02}$ [j]	$2x10^{-01}$ [l]	2.3 [m]	7.0 [m]	800 [i]
Cobalt	Cereal grain $3.7x10^{-03}$ [c]	Average of 3 values 0.20 [c]	Average of 5 values 0.11 [c]	7 e-03 [y]	Organic cobalt $3xx10^{-04}$ [n]	Organic cobalt $1x10^{-02}$ [k]	2 [k]	0.1 [k]	300 [i]
Zinc	Wheat grain 1.6 [c]	Spinach 3.3 [c]	Average of 3 values 12 [c]	0.9 [y]	0.01 [p]	0.1 [k]	7 [k]	3 [k]	1,000 [i]
Strontium	Site-specific corn grain 0.15 [d]	Grass in sand pH5 1.7 [e]	Average of 4 values 1.7 [e]	Fruit in sand pH5 0.2 [e]	$2.8x10^{-03}$ [o]	$8x10^{-03}$ [o]	0.08 [o]	0.2 [o]	450 [d]
Yttrium	Not specified 0.01 [f]	Not specified 0.01 [f]	Not specified 0.01 [f]	Not specified 0.01 [f]	$2x10^{-05}$ [p]	$1x10^{-03}$ [k]	$1x10^{-02}$ [k]	$2x10^{-03}$ [k]	30 [i]
Niobium	$2.5x10^{-2}$ [g]	$2.5x10^{-2}$ [g]	Bean pod $1.7x10^{-02}$ [h]	$2.5x10^{-02}$ [g]	$4.1x10^{-07}$ [q]	$3x10^{-07}$ [q]	$3x10^{-04}$ [r]	$1x10^{-03}$ [r]	300 [i]
Zirconium	Not specified $1x10^{-03}$ [f]	Not specified $1x10^{-03}$ [f]	Not specified $1x10^{-03}$ [f]	Not specified $1x10^{-03}$ [f]	$5.5x10^{-07}$ [q]	$1x10^{-06}$ [q]	$6x10^{-05}$ [r]	$2x10^{-04}$ [r]	300 [i]
Technetium	Cereals grain 0.73 [c]	Average of 3 values 940 [c]	Average of 3 values 28 [c]	1.5 [y]	$2.3x10^{-05}$ [q]	$1x10^{-04}$ [aa]	0.03 [s]	3 [r]	20 [i]

Nuclide	Soil-to-Plant Factors (dry kg/dry kg) [ad]				Animal-Intake-to-Animal Product Factors				
	Cereal and Grain (CLBVCL, CLBVAG)	Leafy Vegetables, Animal Forage, and Hay (CLBVLV, CLBVAF, CLBVAH)	Other Vegetables and Root Vegetables (CLBVOV, CLBVRV)	Fruit (CLBVFR)	Animal Milk (CLFMK) (kg/L)	Animal Meat (CLFMT) (beef) (kg/kg)	Poultry (CLFPL) (kg/kg)	Egg (CLFEG) (kg/kg)	Freshwater Fish (CLBFF) Edible Portions (L/kg)
Ruthenium	Wheat grain $5x10^{-03}$ [c]	Cabbage 0.2 [c]	Not specified 0.04 [f]	Not specified 0.04 [f]	$3.3\ x10^{-06}$ [o]	0.05 [o]	8 [o]	$5x10^{-03}$ [o]	10 [i]
Iodine	Not specified $2x10^{-02}$ [f]	Grass $3.4x10^{-03}$ [c]	Not specified 0.02 [f]	Not specified 0.02 [f]	0.01 [t]	0.04 [u]	0.01 [r]	3 [r]	40 [i]
Cesium	Corn grain 0.02 [d]	Site-specific Bahai grass 5.31 [d]	Site-specific value 0.9 [d]	Tomato fruit 0.22 [c]	$7.9x10^{-03}$ [o]	0.05 [o]	10 [o]	0.4 [o]	4,700 [d]
Cerium	Not specified $3x10^{-02}$ [f]	Not specified $3x10^{-02}$ [f]	Not specified $3x10^{-02}$ [f]	Not specified $3x10^{-02}$ [f]	$3x10^{-05}$ [v]	$2x10^{-05}$ [v]	$3x10^{-03}$ [w]	$6.5x10^{-05}$ [w]	30 [i]
Thorium	Maize grain $3.4x10^{-05}$ [c]	Grass $1.1x10^{-02}$ [c]	Average of 6 values $6.9x10^{-03}$ [c]	$2.5x10^{-04}$ [y]	$5x10^{-06}$ [p]	$4x10^{-05}$ [x]	$6x10^{-03}$ [x]	$4x10^{-03}$ [ac]	100 [i]
Uranium	Cereals grain $1.3x10^{-03}$ [c]	Grass $2.3x10^{-02}$ [c]	Average of 3 values 0.011 [c]	$4\ x10^{-03}$ [y]	$4x10^{-04}$ [z]	$3x10^{-04}$ [ab]	1 [k]	1 [k]	10 [i]
Plutonium	Site-specific corn grain $6x10^{-05}$ [d]	Site-specific Bahai grass $2.2x10^{-03}$ [d]	Average of 8 values $8.2x10^{-04}$ [e]	$4.5x10^{-05}$ [y]	$1.1x10^{-06}$ [o]	$1x10^{-05}$ [o]	$3x10^{-03}$ [o]	$5x10^{-04}$ [k]	4,700 [d]
Americium	Cereals grain $2.2x10^{-05}$ [e]	Site-specific Bahai grass 0.067 [d]	Average of 6 values $8.4x10^{-04}$ [e]	$2.5x10^{-04}$ [y]	$1.5x10^{-06}$ [o]	$4x10^{-05}$ [o]	$6x10^{-03}$ [o]	$4x10^{-03}$ [k]	2,400 [d]

[a] GENII default value, PNNL 2002 (7), Appx D, which cites a previous reference of Napier 1988 (24).
[b] GENII default value, PNNL 2002 (7), Appx D, which cites a previous reference of Kennedy 1992 (22).
[c] IAEA default value, IAEA 1994 (2), Table VI, p.17-25, which cites a previous reference of Frissel 1989 (16).
[d] Selected value calculated from data in Friday 1996 (3), or from a combination of data taken from Friday 1996 (3) and IAEA 1994 (2).
[e] IAEA default value, IAEA 1994 (2), Table VI, p.17-25, which cites a previous reference of Frissel 1992 (17).
[f] IAEA default value, IAEA 1994 (2), Table VI, p.17-25, which cites a previous reference of Ng 1982a (26).
[g] GENII default value, PNNL 2002 (7), Appx D; which cites a previous reference of Coughtrey 1983 (11).
[h] IAEA default value, IAEA 1994 (2), Table VI, p.17-25, which cites a previous reference of Gerzabek 1993 (18).
[i] IAEA default value, IAEA 1994 (2), p.45, which cites a several previous references.
[j] IAEA default value, IAEA 1994 (2), p.35, which cites a previous reference of Ng 1982b (27).
[k] IAEA default value, IAEA 1994 (2), pp.37, 40, and 41, which cites a previous reference of Ng 1982c (28).
[l] GENII default value, PNNL 2002 (7), Appendix D, which cites a previous reference of IAEA 1987 (?).
[m] GENII default value, GENII V.2 constituent database, unattributed.
[n] IAEA default value, IAEA 1994 (2), p.35, which cites a previous reference of Baes 1984 (8).
[o] IAEA default value, IAEA 1994 (2), pp.35, 37, 40, and 41, which cites a previous reference of Coughtrey 1990 (12).
[p] GENII default value, PNNL 2002 (7), Appx D, which cites a previous reference of Ng 1977 (25).
[q] IAEA default value, IAEA 1994 (2), pp.35 and 37, which cites a previous reference of Johnson 1988 (21).
[r] IAEA default value, IAEA 1994 (2), pp.40 and 41, which cites a previous reference of Ennis 1988a (14).
[s] IAEA default value, IAEA 1994 (2), pp.40 and 41, which cites a previous reference of Ennis 1988b (15).
[t] IAEA default value, IAEA 1994 (2), p.35, which cites a previous reference of Hoffman 1988 (20).
[u] IAEA default value, IAEA 1994 (2), p.37, which cites a previous reference of Handl 1989 (19).
[v] IAEA default value, IAEA 1994 (2), pp.35 and 37, which cites a previous reference of CEC 1987 (10).
[w] IAEA default value, IAEA 1994 (2), pp. 40 and 41, which cites a previous reference of CEC 1987 (10), average of two values for Ce-141 and Ce-144.
[x] GENII default value, PNNL 2002 (7), Appx D, which cites a previous reference of Coughtrey 1990 (12).
[y] GENII default value, PNNL 2002 (7), Appx D, which cites a previous reference of Baes 1984 (8).
[z] IAEA default value, IAEA 1994 (2), p.35, which cites a previous reference of Morgan 1990 (23).
[aa] IAEA default value, IAEA 1994 (2), p. 37, which cites a previous reference of Bishop 1989 (9).
[ab] IAEA default value, IAEA 1994 (2), p. 37, which cites a previous reference of Cramp 1990 (13).
[ac] GENII default value, PNNL 2002 (7), Appx D, which cites a previous reference of Ng 1982c (28).
[ad] GENII requires some of the soil-to-plant bioaccumulation factor variables to have the same value. The values entered for the soil-to-cereal transfer factor (CLBVCL) are also used by GENII for three other soil-to-grain pathways covered by the CLBVAG variable, including soil-to-beef-cattle-feed, soil-to-poultry-feed, and soil-to-egg-animal-feed. Similarly, the values entered for the soil-to-leafy-vegetable transfer factor variable (CLBVLV) are also used by GENII for three other soil-to-plant pathways covered by the CLBVAF and CLBVAH variables, including soil-to-beef-cattle-forage, soil-to-milk-cow-forage, and soil-to-milk-cow-feed (hay). Finally, the values entered for the soil-to-other-vegetable transfer factor variable (CLBVOV) are also used by GENII for the soil-to-root-vegetable transfer factor variable (CLBVRV).

F.2 Food Chain Variables

This section provides assumed values for GENII parameters used for the base-case assessment and needed to assess radiation exposures from ingestion of food (leafy vegetables, root vegetables, fruit, grain) and animal products (beef, poultry, milk, eggs). Table F-9 lists parameter values.

Note that the parameters listed in Table F-9 only address those parameters needed to determine annual ingestion rates of radionuclides. Parameters needed to determine radiation dosimetry from ingestion of radionuclides (e.g., gastro-intestinal absorption fractions) are addressed in Section D.4 (Dose and Risk Assessment) of Appendix D.

Table F-9 Food Chain Variables Other than Transfer Factors

GENII Module – Submodule	Variable Description	Variable Name	Units	Indices	Value and Discussion
Exposure – Agriculture – Animal Feed – Biomass	Animal feed standing biomass (wet) – Beef animal feed	BIOMA2	kg/m^2	1, By exposure location	Value = 1.6 kg/m^2 This pathway is not being modeled. The selected value is the GENII default value (7). The value assigned to this variable should not affect the model calculations because the amount of beef cattle feed consumed is set at Zero (see CONSUM for beef cattle feed).
Exposure – Agriculture – Animal Feed – Biomass	Animal feed standing biomass (wet) – Poultry feed	BIOMA2	kg/m^2	2, By exposure location	Value = 2.4 kg/m^2 Standing biomass for poultry feed is assumed to be locally grown corn consumed by backyard chickens. USDA 1992 Census of Agriculture data for Aiken County, South Carolina, (page 329, Table 28) includes data on corn silage production, which is presumed to include the entire corn plant (all biomass). The published USDA report includes data for both 1987 and 1992 (4): 1987: 4,330 tons / 464 acres = 2.1 kg/m^2 1992: 4,284 tons / 362 acres = 2.6 kg/m^2 The average of these two years (2.4 kg/m^2) was taken as the input value. (conversion factors: 4,047 m^2/acre and 907 kg/ton)
Exposure – Agriculture – Animal Feed – Biomass	Animal feed standing biomass (wet) – Milk animal feed	BIOMA2	kg/m^2	3, By exposure location	Value = 2.4 kg/m^2 The selected value is equal to the value used for poultry feed biomass. It is assumed that milk cattle feed is locally produced corn silage, based on Hamby 1991 (29) (see CONSUM for milk cattle feed).
Exposure – Agriculture – Animal Feed – Biomass	Animal feed standing biomass (wet) – Egg animal feed	BIOMA2	kg/m^2	4, By exposure location	Value = 2.4 kg/m^2 Standing biomass for egg animal feed is assumed to be locally grown corn consumed by backyard chickens (the same as for poultry feed. The selected value is equal to the value used for poultry feed biomass.

GENII Module – Submodule	Variable Description	Variable Name	Units	Indices	Value and Discussion
Exposure – Agriculture – Animal Feed – Biomass	Animal feed standing biomass (wet) – Beef animal forage	BIOMA2	kg/m^2	5, By exposure location	Value = 0.3 kg/m^2 The standing biomass represents the amount of biomass present in the field (e.g., foliage) on which airborne contamination is deposited (see PNNL 2002 [7], pp. 149-154). While different values can be assigned to different exposure locations, all locations are assumed to have the same value. According to Hamby 1991 (29), p.3: "Bermudagrass is the best hay plant for South Carolina and with adequate fertilization and frequent cuttings, yields of up to 8 tons per acre (1.8 kg/m^2) are common." This is based on a Clemson University report on use of Bermudagrass (30). The Hamby value represents total yield and includes multiple cuttings. Hamby 1991 (29) states, "Bermudagrass that is not consumed is cut and bailed every 30 days..." For the Base Case, it is assumed that the 30-day value is a shorter-than-average period between cuttings (spring and summer) and there are 6 cuttings/year. Assuming 6 cuttings/year, the standing biomass value is 1.8 kg/m^2 / 6 = 0.3 kg/m^2.
Exposure – Agriculture – Animal Feed – Biomass	Animal feed standing biomass (wet) – Milk animal forage	BIOMA2	kg/m^2	6, By exposure location	Value = 0.3 kg/m^2 The selected value for milk animal forage biomass is equal to the value used for beef animal forage biomass. Standing biomass for milk animal forage is assumed to be Bermudagrass.
Exposure – Agriculture – Food Crop – Biomass	Standing biomass (wet) – Leafy vegetables	BIOMAS	kg/m^2	1, By exposure location	Value = 0.7 kg/m^2 This value is based on a recommendation in Hamby 1991 (29), p. 4. See explanation for leafy vegetable yield.
Exposure – Agriculture – Food Crop – Biomass	Standing biomass (wet) – Root vegetables	BIOMAS	kg/m^2	2, By exposure location	Value = 0.7 kg/m^2 This value is based on a recommendation in Hamby 1991 (29), p. 4. See explanation for leafy vegetable yield.
Exposure – Agriculture – Food Crop – Biomass	Standing biomass (wet) – Fruits	BIOMAS	kg/m^2	3, By exposure location	Value = 0.7 kg/m^2 This value is based on a recommendation in Hamby 1991 (29), p. 4. See explanation for fruit yield.
Exposure – Agriculture – Food Crop – Biomass	Standing biomass (wet) – Grains	BIOMAS	kg/m^2	4, By exposure location	Value = 0.7 kg/m^2 This value is based on a recommendation in Hamby 1991 (29), p. 4. See explanation for fruit yield.

GENII Module – Submodule	Variable Description	Variable Name	Units	Indices	Value and Discussion
Exposure – Agriculture – Animal Feed	Animal feed consumption rate – Beef animal feed	CONSUM	kg/d	1, By exposure location	Value = 0 kg/day This pathway is not being modeled. According to Hamby 1991 (29) (p.3), "...Farmers in the south rely on year-round grazing of fresh coastal bermudagrass (30)." "The diets of beef cattle in the region generally consist of about 75 percent pasture grass and 25 percent stored grass with total forage consumption averaging 36 kg/day (29)." In the Base Case scenario, the entire beef cattle diet, including both stored and fresh forage, is modeled through the beef animal forage pathway with the beef cattle feed pathway set at zero. Use of the "feed" pathway is eliminated because this pathway is established in GENII using a transfer factor for cereal (i.e., grain) consumption by cattle. The forage pathway is established in GENII to use a transfer factor for leafy vegetable (i.e., grass) consumption by cattle and is therefore more appropriate for beef cattle at the SRS.
Exposure – Agriculture – Animal Feed	Animal feed consumption rate – Poultry feed	CONSUM	kg/d	2, By exposure location	Value = 0.12 kg/day Assume GENII Default Average
Exposure – Agriculture – Animal Feed	Animal feed consumption rate – Milk animal feed	CONSUM	kg/d	3, By exposure location	Value = 13 kg/day According to Hamby 1991 (29): "...Farmers in the south rely on year-round grazing of fresh coastal bermudagrass (30)." "Dairy cattle consume approximately 52 kg/day of which 56 percent is pasture grass, 25 percent is silage, and 19 percent is commercial grain." Milk animal feed for the Base Case is based on the Hamby 1991 (29) figure for silage of 25 percent of 52 kg/day (=13 kg/day (wet)). The commercial grain cited by Hamby is assumed to come from outside the SRS region.
Exposure – Agriculture – Animal Feed	Animal feed consumption rate – Egg animal feed	CONSUM	kg/d	4, By exposure location	Value = 0.12 kg/day Assume GENII Default Average [PNNL 2002].

GENII Module – Submodule	Variable Description	Variable Name	Units	Indices	Value and Discussion
Exposure – Agriculture – Animal Feed	Animal feed consumption rate – Beef animal forage	CONSUM	kg/d	5, By exposure location	Value = 36 kg/day According to Hamby 1991(29), "…Farmers in the south rely on year-round grazing of fresh coastal bermudagrass." (30) "The diets of beef cattle in the region generally consist of about 75 percent pasture grass and 25 percent stored grass with total forage consumption averaging 36 kg/day." The default value from NRC 1971 as cited by Hamby 1991 (29) for beef animal forage consumption is 50 kg/day (wet). Beef animal forage for the Base Case is based on the Hamby 1991 (29) figure including both grazing and stored grass. Both portions of the diet are included in the forage pathway because that pathway uses a transfer factor for leafy vegetables and grass. None of the diet is modeled using the beef feed pathway because that pathway uses a transfer factor for cereal and grain, and the local diet does not include cereal or grain. Including the stored grass portion of the diet in the beef forage pathway has the effect of increasing the dose because the pathway does not include a storage period during which radionuclides would decay.
Exposure – Agriculture – Animal Feed	Animal feed consumption rate – Milk animal forage	CONSUM	kg/d	6, By exposure location	Value = 29 kg/day According to Hamby 1991 (29): "...Farmers in the south rely on year-round grazing of fresh coastal bermudagrass." (30) "Dairy cattle consume approximately 52 kg/day of which 56 percent is pasture grass, 25 percent is silage, and 19 percent is commercial grain." The default value from NRC 1971 as cited by Hamby 1991 (29) for milk animal forage consumption is 50 kg/day (wet). Milk animal feed for the Base Case is based on the Hamby 1991 (29) figure for silage of 56 percent of 52 kg/day (=29 kg/day (wet)). This approach assumes that 1) the silage is locally grown corn silage, and 2) the commercial grain portion of the diet is not locally grown.

GENII Module – Submodule	Variable Description	Variable Name	Units	Indices	Value and Discussion
Exposure – Agriculture – Animal Feed	Fraction of diet that is contaminated – Beef animal feed	DIETFR	fraction	1, By exposure location	Value = 1.0 This pathway is not being modeled. In the Base Case, no portion of the beef animal diet is modeled through the beef animal feed pathway. The value assigned to this variable should not affect the model calculations because the amount of beef cattle feed consumed is set at Zero (see CONSUM for beef cattle feed).
Exposure – Agriculture – Animal Feed	Fraction of diet that is contaminated – Poultry animal feed	DIETFR	fraction	2, By exposure location	Value 0.5 According to Hamby 1991 (29): "...Chickens are housed in covered shelters and eat feed provided by the parent companies responsible for marketing the final product." This indicates a value of Zero for the contaminated fraction of poultry feed and thereby eliminates the poultry and egg pathways. However, because at least one CDC scenario posits "backyard chickens" and because agricultural practices may have changed over the time period of the study, a higher value (contaminated fraction =0.5) is assumed for the exposure scenarios.
Exposure – Agriculture – Animal Feed	Fraction of diet that is contaminated – Milk animal feed	DIETFR	fraction	3, By exposure location	Value = 1.0 In the Base Case, milk animal feed is modeled to represent silage that is locally grown, as described in Hamby 1991 (29). As a result, 100 percent of this portion of the milk animal diet is assumed to be contaminated. (Input value =1)
Exposure – Agriculture – Animal Feed	Fraction of diet that is contaminated – Egg animal feed	DIETFR	fraction	4, By exposure location	Value = 0.5 The value for poultry feed (0.5) is assumed to equal the value for egg animal feed.
Exposure – Agriculture – Animal Feed	Fraction of diet that is contaminated – Beef animal forage	DIETFR	fraction	5, By exposure location	Value = 1.0 In the Base Case, beef animal forage is modeled to represent pasture grass and stored grass, both local, as described in Hamby 1991 (29). As a result, 100 percent of this portion of the beef animal diet is assumed to be contaminated. (Input value =1)
Exposure – Agriculture – Animal Feed	Fraction of diet that is contaminated – Milk animal forage	DIETFR	fraction	6, By exposure location	Value = 1.0 In the Base Case, milk animal forage is modeled to represent pasture grass, as described in Hamby 1991 (29). As a result, 100 percent of this portion of the milk animal diet is assumed to be contaminated. (Input value =1)

GENII Module – Submodule	Variable Description	Variable Name	Units	Indices	Value and Discussion
Exposure – Agriculture – Animal Feed	Animal feed dry/wet ratio – Beef animal feed	DRYFA2	fraction	1, By exposure location	This pathway is not being modeled. The value assigned to this variable should not affect the model calculations because the amount of beef cattle feed consumed is set at Zero (see CONSUM for beef cattle feed).
Exposure – Agriculture – Animal Feed	Animal feed dry/wet ratio – Poultry feed	DRYFA2	fraction	2, By exposure location	Value = 0.91 Assume value for grain (0.91) (adapted from Till 1983 [31])
Exposure – Agriculture – Animal Feed	Animal feed dry/wet ratio – Milk animal feed	DRYFA2	fraction	3, By exposure location	Value = 0.22 Assume value for beef forage (0.22) (adapted from Till 1983 [31])
Exposure – Agriculture – Animal Feed	Animal feed dry/wet ratio – Egg animal feed	DRYFA2	fraction	4, By exposure location	Value = 0.91 Assume value for grain (0.91) (adapted from Till 1983 [31])
Exposure – Agriculture – Animal Feed	Animal feed dry/wet ratio – Beef animal forage	DRYFA2	fraction	5, By exposure location	Value = 0.22 The selected value is based on Till 1983 [31] which cites a fresh-to-dry ratio for fresh forage of 4.5. The dry/wet ratio is the reciprocal of the fresh-to-dry ratio. (1 / 4.5) = 0.22. Hamby 1991 (29) recommends using the NRC Regulatory Guide 1.109 value of 0.25 (NRC 1977 [32]).
Exposure – Agriculture – Animal Feed	Animal feed dry/wet ratio – Milk animal forage	DRYFA2	fraction	6, By exposure location	Assume value for beef forage (0.22) (adapted from Till 1983 [31]).
Exposure – Agriculture – Food Crop	Dry/wet ratio – Leafy vegetables	DRYFAC	fraction	1, By exposure location	Value = 0.10 The selected value is based on Till 1983 (31), which cites two fresh-to-dry ratios for leafy vegetables of 12.6 and 8.5. The dry/wet ratio is the reciprocal of the fresh-to-dry ratio. The selected value was determined by averaging the reciprocals of the cited values. ((1 / 12.6) + (1 / 8.5)) / 2 = 0.10
Exposure – Agriculture – Food Crop	Dry/wet ratio – Root vegetables	DRYFAC	fraction	2, By exposure location	Value = 0.15 The selected value is based on Till 1983 (31), which cites three fresh-to-dry ratios for root vegetables of 4, 8.2, and 13. The dry/wet ratio is the reciprocal of the fresh-to-dry ratio. The selected value was determined by averaging the reciprocals of the cited values. ((1 / 4) + (1 / 8.2) + (1 / 13)) / 3 = 0.15

GENII Module – Submodule	Variable Description	Variable Name	Units	Indices	Value and Discussion
Exposure – Agriculture – Food Crop	Dry/wet ratio – Fruits	DRYFAC	fraction	3, By exposure location	Value = 0.15 The selected value is based on Till 1983 (31), which cites three fresh-to-dry ratios for fruits of 5.7, 15, and 8.3. The dry/wet ratio is the reciprocal of the fresh-to-dry ratio. The selected value was determined by averaging the reciprocals of the cited values. ((1 / 5.7) + (1 / 15) + (1 / 8.3)) / 3 = 0.12
Exposure – Agriculture – Food Crop	Dry/wet ratio – Grains	DRYFAC	fraction	4, By exposure location	Value = 0.91 The selected value is based on Till 1983 (31), which cites a fresh-to-dry ratio for grain of 1.1. The dry/wet ratio is the reciprocal of the fresh-to-dry ratio. The selected value was determined by taking the reciprocal of the cited value. (1 / 1.1) = 0.91
Exposure – Water – Animal Water	Intake rate of water – Beef animal	DWATER	L/d	1, By exposure location	Value = 50 L/day This value is the default from Table E-3 of NRC 1977 (32). IAEA 1994 (2) cites a value of 20 to 60 L/d for a 500 kg beef cattle. (References cited in IAEA 1994 [2] are Coughtrey 1990 [12] and Ng 1982 [33].) Note that the quantity of contaminated water is further adjusted by the DWFACA variable, so the water quantity specified by DWATER represents total water intake, not just contaminated water intake.
Exposure – Water – Animal Water	Intake rate of water – Poultry	DWATER	L/d	2, By exposure location	Value = 0.3 L/day This value is the GENII default. IAEA 1994 (2) cites a value of 0.1 to 0.3 L/d for chickens and laying hens. (References cited in IAEA 1994 [2] are Coughtrey 1990 [12] and Ng 1982 [33].)
Exposure – Water – Animal Water	Intake rate of water – Milk animal	DWATER	L/d	3, By exposure location	Value = 60 L/day This value is the default from Table E-3 of NRC 1977 (32). IAEA 1994 (2) cites a value of 50 to 100 L/d for a dairy cow. (References cited in IAEA 1994 [2] are Coughtrey 1990 [12] and Ng 1982 [33].)
Exposure – Water – Animal Water	Intake rate of water – Egg animal	DWATER	L/d	4, By exposure location	Value = 0.3 L/day This value is the GENII default. IAEA 1994 (2) cites a value of 0.1 to 0.3 L/d for chickens and laying hens. (References cited in IAEA 1994 [2] are Coughtrey 1990 [12] and Ng 1982 [33].)

GENII Module – Submodule	Variable Description	Variable Name	Units	Indices	Value and Discussion
Exposure – Water – Animal Water	Animal water contaminated fraction – Beef animal	DWFACA	fraction	1, By exposure location	Value = 0 for all exposure locations. These values are based on the exposure scenarios. None of the food chain animals consume contaminated water from the Savannah River or Lower Three Runs Creek .
Exposure – Water – Animal Water	Animal water contaminated fraction – Poultry animal	DWFACA	fraction	2, By exposure location	Value = 0 for all exposure locations.
Exposure – Water – Animal Water	Animal water contaminated fraction – Milk animal	DWFACA	fraction	3, By exposure location	Value = 0 for all exposure locations.
Exposure – Water – Animal Water	Animal water contaminated fraction – Egg animal	DWFACA	fraction	4, By exposure location	Value = 0 for all exposure locations.
Exposure – Agriculture – Food Crop	Growing period – Leafy vegetables	GRWP	day	1, By exposure location	Value = 70 days The growing period is the time period over which the food crop is exposed to contamination. For leafy vegetables, the value for the growing period is based on the value cited for unspecified vegetables by Hamby 1991 (29) which states, "The average growing time, or time of exposure, for above-ground vegetables in South Carolina is approximately 70 days." This information is from a 1990 U.S. Department of Agriculture circular (34). This value is longer than the NRC default value (32) of 60 days.
Exposure – Agriculture – Food Crop	Growing period – Root vegetables	GRWP	day	2, By exposure location	Value = 70 days The growing period for root vegetables is based on Hamby 1991 (p.4) (See above discussion for the leafy vegetable growing period.)
Exposure – Agriculture – Food Crop	Growing period – Fruit	GRWP	day	3, By exposure location	Value = 70 days The growing period for fruit is based on Hamby 1991 (29) (See above discussion for the leafy vegetable growing period.)

GENII Module – Submodule	Variable Description	Variable Name	Units	Indices	Value and Discussion
Exposure – Agriculture – Food Crop	Growing period – Grains	GRWP	day	4, By exposure location	Value = 145 days The growing period for grains is based on the growing period for corn in South Carolina, as cited in a 1997 US Department of Agriculture handbook (35). The difference between the peak planting and harvesting dates is ~145 to 150 days. The difference between the earliest planting and harvesting dates is 135 days. The difference between the latest planting and harvesting dates is 145 days.
Exposure – Agriculture – Animal Feed	Growing period for animal feed – Beef animal feed	GRWPA	day	1, By exposure location	This pathway is not being modeled. The value assigned to this variable should not affect the model calculations because the amount of beef cattle feed consumed is set at Zero (see CONSUM for beef cattle feed).
Exposure – Agriculture – Animal Feed	Growing period for animal feed – Poultry feed	GRWPA	day	2, By exposure location	Value = 145 days The growing period for poultry feed is based on the growing period for corn cited in USDA 1997 (35). (See above discussion for the grain growing period.)
Exposure – Agriculture – Animal Feed	Growing period for animal feed – Milk animal feed	GRWPA	day	3, By exposure location	Value = 145 days The growing period for milk animal feed is based on the growing period for corn cited in USDA 1997 (35). (See above discussion for the grain growing period.)
Exposure – Agriculture – Animal Feed	Growing period for animal feed – Egg animal feed	GRWPA	day	4, By exposure location	Value = 145 days The growing period for egg animal feed is based on the growing period for corn cited in USDA 1997 (35). (See above discussion for the grain growing period.)
Exposure – Agriculture – Animal Feed	Growing period for animal feed – Beef animal forage	GRWPA	day	5, By exposure location	Value = 30 days The growing period for beef animal forage is based on Bermudagrass consumption discussed in Hamby 1991 (29), which notes that “Bermudagrass that is not consumed is cut and bailed every 30 days...”

<table>
<tr><th>GENII Module – Submodule</th><th>Variable Description</th><th>Variable Name</th><th>Units</th><th>Indices</th><th>Value and Discussion</th></tr>
<tr><td>Exposure – Agriculture – Animal Feed</td><td>Growing period for animal feed – Milk animal forage</td><td>GRWPA</td><td>day</td><td>6, By exposure location</td><td>Value = 30 days
The growing period for milk animal forage is based on Bermudagrass consumption discussed in Hamby 1991 (29), which notes that “Bermudagrass that is not consumed is cut and bailed every 30 days...”</td></tr>
<tr><td>Exposure – Agriculture – Intake Delays</td><td>Time from harvest to ingestion – Leafy vegetables</td><td>HLDUP</td><td>day</td><td>1, By exposure location</td><td>Value = 1 day (for Rural Family One and Two, Outdoor Person Family, Migrant Family, and Near River Family).
Value = 7 days (for Urban Family and Delivery Person Family)
This corresponds to the assigned value for each exposure location:
<table>
<tr><th>Location</th><th>Value (days)</th></tr>
<tr><td>1. Girard</td><td>1</td></tr>
<tr><td>2. Waynesboro</td><td>NA</td></tr>
<tr><td>3. Augusta</td><td>7</td></tr>
<tr><td>4. Jackson</td><td>1</td></tr>
<tr><td>5. New Ellenton</td><td>1</td></tr>
<tr><td>6. Barnwell</td><td>7</td></tr>
<tr><td>7. Martin</td><td>1</td></tr>
<tr><td>8. Allendale</td><td>NA</td></tr>
<tr><td>9. Williston</td><td>1</td></tr>
<tr><td>10. Onsite</td><td>NA</td></tr>
<tr><td colspan="2">NA - No leafy vegetable production occurs at these locations</td></tr>
</table>
The selected values are based on scenario-specific conditions. For families consuming vegetables from their own gardens, the value is set at 1 day. For families consuming vegetables from local markets, the value is set at 7 days.

NRC recommends a default value of 14 days for both leafy and root vegetables (32) for the general population and 1 day for the maximum exposed individual. The GENII default value is 14 days (7).</td></tr>
</table>

GENII Module – Submodule	Variable Description	Variable Name	Units	Indices	Value and Discussion
Exposure – Agriculture – Intake Delays	Time from harvest to ingestion – Root vegetables	HLDUP	day	2, By exposure location	Value = 14 days A 14-day time period is recommended in Hamby 1991 (29). NRC recommends a default value of 14 days for root vegetables (32) for the general population. The GENII default value is 14 days (7).
Exposure – Agriculture – Intake Delays	Time from harvest to ingestion – Fruits	HLDUP	day	3, By exposure location	Value = 1 day (for Rural Family One and Two, Outdoor Person Family, Migrant Family, and Near River Family) Value = 7 days (for Urban Family and Delivery Person Family) This corresponds to the assigned value for each exposure location: **Location** / **Value (days)** 1. Girard: 1 2. Waynesboro: NA 3. Augusta: 7 4. Jackson: 1 5. New Ellenton: 1 6. Barnwell: 7 7. Martin: 1 8. Allendale: NA 9. Williston: 1 10. Onsite: NA NA - No fruit production occurs at these locations. The selected values are based on scenario-specific conditions. For families consuming vegetables from their own gardens, the value is set at one day. For families consuming vegetables from local markets, the value is set at seven days. NRC recommends a default value of 60 days for produce (32) for the maximum exposed individual. The GENII default value is 14 days (7).

GENII Module – Submodule	Variable Description	Variable Name	Units	Indices	Value and Discussion
Exposure – Agriculture – Intake Delays	Time from harvest to ingestion – Grains	HLDUP	day	4, By exposure location	Value = 1 day (for Rural Family One and Two, Outdoor Person Family, Migrant Family, and Near River Family) Value = 7 days (for Urban Family and Delivery Person Family) This corresponds to the assigned value for each exposure location: **Location** / **Value (days)** 1. Girard: 1 2. Waynesboro: NA 3. Augusta: 7 4. Jackson: 1 5. New Ellenton: 1 6. Barnwell: 7 7. Martin: 1 8. Allendale: NA 9. Williston: 1 10. Onsite: NA NA - No grain production occurs at these locations. The selected values are based on scenario-specific conditions and consider consumption of only locally produced corn. For families consuming corn from their own gardens, the value is set at one day. For families consuming corn from local markets, the value is set at seven days. NRC recommends a default value of 60 days for produce (32) for the maximum exposed individual. The GENII default value is 180 days (7).
Exposure – Agriculture – Intake Delays	Time from harvest to ingestion – Fish	HLDUP2	day	1, By exposure location	Value = 1 day The selected value is based on the GENII default average (7). The NRC default average is seven days for sport fish (32).

GENII Module – Submodule	Variable Description	Variable Name	Units	Indices	Value and Discussion
Exposure – Agriculture – Intake Delays	Time from harvest to ingestion – Slaughter to Beef ingestion	HLDUPA	day	1, By exposure location	Value = 6 days The selected value is based on Hamby 1991 (29), which states, "The commercial slaughtering of beef cattle is generally a six-day process. Cattle are slaughtered the first day, processed and packed the next, and shipped on the sixth day. The beef is cured for the four days between packing and shipping." [Hamby to Mathis, personal communication, Nov. 12, 1990] In the Base Case scenarios, consumption of locally grown beef is assumed, and the six-day slaughter-to-ingestion period is assumed for all receptor scenarios. The NRC default value for this parameter for all meat is 20 days (32) and the GENII default value is 34 days (7). A shorter period is appropriate for the CDC receptors because the ingested beef is locally produced with less time required for long distance transport.
Exposure – Agriculture – Intake Delays	Time from harvest to ingestion – Slaughter to poultry ingestion	HLDUPA	day	2, By exposure location	Value = 6 days The selected value is based on the corresponding value for beef. The NRC default value for this parameter for all meat is 20 days (32) and the GENII default value is 18 days (7). A shorter period is appropriate for the CDC receptors because the ingested poultry is locally produced with less time required for long distance transport.
Exposure – Agriculture – Intake Delays	Time from harvest to ingestion – Harvest to milk ingestion	HLDUPA	day	3, By exposure location	Value = 3 days The selected value is based on Hamby 1991 (29) which states, "Generally, milk is collected every other day from local dairies and shipped to one of several processing plants in the Southeast. The process of homogenizing, pasteurizing, and packing the milk can be completed in about 36 hours. Accordingly, it is assumed that milk is collected and delivered on day one, processed on day two, and shipped, ready for consumption on day three." This is based on a personal communication between Hamby and J. Bailes, Flav-O-Rich, Florence, SC, January 8, 1991, and J. Dawson, Borden, Macon GA, January 7, 1991. The NRC and GENII default values are both four days (32,7).

<table>
<tr><th>GENII Module – Submodule</th><th>Variable Description</th><th>Variable Name</th><th>Units</th><th>Indices</th><th>Value and Discussion</th></tr>
<tr><td>Exposure – Agriculture – Intake Delays</td><td>Time from harvest to ingestion – Harvest to egg ingestion</td><td>HLDUPA</td><td>day</td><td>4, By exposure location</td><td>Value = 1 day (for Rural Family One and Two, Outdoor Person Family, Migrant Family, and Near River Family)
Value = 7 days (for Urban Family and Delivery Person Family)
This corresponds to the assigned value for each exposure location:
<table><tr><th>Location</th><th>Value (days)</th></tr><tr><td>1. Girard</td><td>1</td></tr><tr><td>2. Waynesboro</td><td>NA</td></tr><tr><td>3. Augusta</td><td>7</td></tr><tr><td>4. Jackson</td><td>1</td></tr><tr><td>5. New Ellenton</td><td>1</td></tr><tr><td>6. Barnwell</td><td>7</td></tr><tr><td>7. Martin</td><td>1</td></tr><tr><td>8. Allendale</td><td>NA</td></tr><tr><td>9. Williston</td><td>1</td></tr><tr><td>10. Onsite</td><td>NA</td></tr><tr><td colspan="2">NA - No egg production occurs at these locations.</td></tr></table>
The selected values are based on scenario-specific conditions. For families raising their own chickens, the value is set at one day. For families consuming eggs from local markets, the value is set at seven days. The GENII default value is 34 days (7).</td></tr>
<tr><td>Exposure – Agriculture – Animal Feed</td><td>Storage time – Beef animal feed</td><td>STORTM</td><td>day</td><td>1, By exposure location</td><td>This pathway is not being modeled. The value assigned to this variable should not affect the model calculations because the amount of beef cattle feed consumed is set at Zero (see CONSUM for beef cattle feed).</td></tr>
<tr><td>Exposure – Agriculture – Animal Feed</td><td>Storage time – Poultry feed</td><td>STORTM</td><td>day</td><td>2, By exposure location</td><td>Value = 180 days
The selected value is based on the GENII default average (180 days [7])</td></tr>
</table>

GENII Module – Submodule	Variable Description	Variable Name	Units	Indices	Value and Discussion
Exposure – Agriculture – Animal Feed	Storage time – Milk animal feed	STORTM	day	3, By exposure location	Value = 90 days The value is based on milk cow consumption of corn silage. The value corresponds to the value for beef animal feed (stored grass) cited in Hamby 1991 (29). The GENII default average is 100 days (7).
Exposure – Agriculture – Animal Feed	Storage time – Egg animal feed	STORTM	day	4, By exposure location	Value = 180 days. The value applies to locally produced corn grain that is consumed by egg animals. The selected value is base on the GENII default average of 180 days (7).
Exposure – Agriculture – Animal Feed	Storage time – Beef animal forage	STORTM	day	5, By exposure location	Value = 0 days The value is based on Hamby 1991 (29) which states, "Farmers in the south rely on year-round grazing for fresh, coastal bermudagrass." (Hamby reference is personal communication with T. Mathis, November 12, 1990.)
Exposure – Agriculture – Animal Feed	Storage time – Milk animal forage	STORTM	day	6, By exposure location	Value = 0 days The selected value is based on the corresponding value for beef animal forage (29).
Exposure – Agriculture – Food Crop	Translocation factor – Leafy vegetables	TRANS	fraction	1, By exposure location	Value = 1.0 The translocation factor for food crops is the ratio of the nuclide concentration in the edible portion of the plant and the portion exposed to air-deposited contamination. The selected value is based on Food Chain Models for Risk Assessment, Appendix F. Oak Ridge Risk Assessment Information System, at http://risk.lsd.ornl.gov/homepage/bjcor271/appf.shtml, which cites a translocation factor for leafy vegetables of 1.0 as the default in NCRP 1984 (36). The GENII default average for leafy vegetables also equals 1.0 (7).
Exposure – Agriculture – Food Crop	Translocation factor – Root vegetables	TRANS	fraction	2, By exposure location	Value = 0.1 The selected value is based on the NCRP 1984 (36) as cited in http://risk.lsd.ornl.gov/homepage/bjcor271/appf.shtml. The GENII default average for root vegetables also = 0.1 (7).

GENII Module – Submodule	Variable Description	Variable Name	Units	Indices	Value and Discussion
Exposure – Agriculture – Food Crop	Translocation factor – Fruits	TRANS	fraction	3, By exposure location	Value = 0.1 The selected value is based on NCRP 1984 (36) as cited in http://risk.lsd.ornl.gov/homepage/bjcor271/appf.shtml. The cited value for nonleafy vegetables is 0.1 and is applied to fruit. The GENII default average for fruit equals 0.1 (7).
Exposure – Agriculture – Food Crop	Translocation factor – Grains	TRANS	fraction	4, By exposure location	Value = 0.1 The selected value is based on NCRP 1984 (36) as cited in http://risk.lsd.ornl.gov/homepage/bjcor271/appf.shtml. The cited value for nonleafy vegetables is 0.1 and is applied to grains. The GENII default average for grains equals 0.1 (7).
Exposure – Agriculture – Animal Feed	Translocation factor for animal feed – Beef animal feed	TRANSA	fraction	1, By exposure location	This pathway is not being modeled. The value assigned to this variable should not affect the model calculations because the amount of beef cattle feed consumed is set at Zero (see CONSUM for beef cattle feed). The translocation factor for animal diet is the ratio of the nuclide concentration in the portion of the plant consumed by the animal and the portion exposed to contamination.
Exposure – Agriculture – Animal Feed	Translocation factor for animal feed – Poultry feed	TRANSA	fraction	2, By exposure location	Value = 0.1 The selected value is based on NCRP 1984 (36) as cited in http://risk.lsd.ornl.gov/homepage/bjcor271/appf.shtml. The cited value for nonleafy vegetables is 0.1 and is applied to poultry feed (corn grain). The GENII default average for poultry feed = 0.1 (7).
Exposure – Agriculture – Animal Feed	Translocation factor for animal feed – Milk animal feed	TRANSA	fraction	3, By exposure location	Value = 0.1 The selected value is based on NCRP 1984 (36) as cited in http://risk.lsd.ornl.gov/homepage/bjcor271/appf.shtml. The cited value for nonleafy vegetables is 0.1 and is applied to milk animal feed (corn silage). The GENII default average for milk animal feed = 0.1 (7).
Exposure – Agriculture – Animal Feed	Translocation factor for animal feed – Egg animal feed	TRANSA	fraction	4, By exposure location	Value = 0.1 The selected value is based on NCRP 1984 (36) as cited in http://risk.lsd.ornl.gov/homepage/bjcor271/appf.shtml. The cited value for nonleafy vegetables is 0.1 and is applied to egg animal feed (corn grain). The GENII default average for egg animal feed = 0.1 (7).

GENII Module – Submodule	Variable Description	Variable Name	Units	Indices	Value and Discussion
Exposure – Agriculture – Animal Feed	Translocation factor for animal feed – Beef animal forage	TRANSA	fraction	5, By exposure location	Value = 1.0 The selected value is based on NCRP 1984 (36) as cited in http://risk.lsd.ornl.gov/homepage/bjcor271/appf.shtml. The cited value for pasture is 1.0 and is applied to beef animal forage (bahai grass). The GENII default average for beef animal forage = 1.0 (7).
Exposure – Agriculture – Animal Feed	Translocation factor for animal feed – Milk animal forage	TRANSA	fraction	6, By exposure location	Value = 1.0 The selected value is based on NCRP 1984 (36) as cited in http://risk.lsd.ornl.gov/homepage/bjcor271/appf.shtml. The cited value for pasture is 1.0 and is applied to milk animal forage (bahai grass). The GENII default average for milk animal forage = 1.0 (7).
Exposure – Agriculture – Food Crop	Yield – Leafy vegetables	YELD	kg/m^2	1, By exposure location	Value = 0.7 kg/m^2 According to Hamby 1991 (29) for garden productivity, the average response in a survey of county extension agents was a value of 0.2 kg/m^2. This value is one-tenth the NRC default value (32) and, therefore, would result in higher doses than the default value. Therefore, Hamby 1991 (29) recommends using a value of 0.7 kg/m^2, which corresponds to survey responses for average agricultural productivity.
Exposure – Agriculture – Food Crop	Yield – Root vegetables	YELD	kg/m^2	2, By exposure location	Value = 0.7 kg/m^2 The value is based on Hamby 1991 (29). See YELD for leafy vegetables.
Exposure – Agriculture – Food Crop	Yield – Fruits	YELD	kg/m^2	3, By exposure location	Value = 0.7 kg/m^2 The value for agricultural productivity (0.7 kg/m^2) cited by Hamby 1991 (29) was used in the Base Case for fruits. This is the same as the default value for agricultural productivity for produce or leafy vegetables ingested by man in NRC 1977 (32).
Exposure – Agriculture – Food Crop	Yield – Grains	YELD	kg/m^2	4, By exposure location	Value = 0.7 kg/m^2 The value for agricultural productivity (0.7 kg/m^2) cited by Hamby 1991 (29) was used in the Base Case for grains. This is the same as the default value for agricultural productivity for produce or leafy vegetables ingested by man in NRC 1977 (32).

GENII Module – Submodule	Variable Description	Variable Name	Units	Indices	Value and Discussion
Exposure – Agriculture – Animal Feed	Yield for animal feed – Beef animal feed	YELDA	kg/m^2	1, By exposure location	This pathway is not being modeled. The value assigned to this variable should not affect the model calculations because the amount of beef cattle feed consumed is set at Zero (see CONSUM for beef cattle feed).
Exposure – Agriculture – Animal Feed	Yield for animal feed – Poultry feed	YELDA	kg/m^2	2, By exposure location	Value = 2.4 kg/m^2 The selected value is based on the corresponding value for poultry feed standing biomass calculated from USDA 1992 data (4).
Exposure – Agriculture – Animal Feed	Yield for animal feed – Milk animal feed	YELDA	kg/m^2	3, By exposure location	Value = 2.4 kg/m^2 The selected value is based on the corresponding value for milk animal feed (corn silage) standing biomass calculated from USDA 1992 data (4).
Exposure – Agriculture – Animal Feed	Yield for animal feed – Egg animal feed	YELDA	kg/m^2	4, By exposure location	Value = 2.4 kg/m^2 The selected value is based on the corresponding value for poultry feed standing biomass calculated from USDA 1992 data (4).
Exposure – Agriculture – Animal Feed	Yield for animal feed – Beef animal forage	YELDA	kg/m^2	5, By exposure location	Value = 1.8 kg/m^2 The selected value is based on Hamby 1991 (29) which states, "Bermudagrass is the best hay plant for South Carolina and with adequate fertilization and frequent cuttings, yields of up to 8 tons per acre (1.8 kg/m^2) are common." This is based on Clemson 1988 (30).
Exposure – Agriculture – Animal Feed	Yield for animal feed – Milk animal forage	YELDA	kg/m^2	6, By exposure location	Value = 1.8 kg/m^2 The selected value is based on the corresponding yield value for beef animal forage.
Exposure – Controls	Fraction of plant roots in surface soil	RF1	fraction	0, By exposure location	Value = 1.0 The selected value is based on the GENII default average (7)
Exposure – Water	Animal feed irrigation time – Beef animal feed	IRTIMA	mon/yr	1, By exposure location	This variable is not used because the irrigation pathways are not being modeled. Several references indicate that no irrigation occurs in the exposure locations of interest downstream from the SRS, including Hamby 1991 (29) and Moore 2002 (37).

GENII Module – Submodule	Variable Description	Variable Name	Units	Indices	Value and Discussion
Exposure – Water	Animal feed irrigation time – Poultry feed	IRTIMA	mon/yr	2, By exposure location	This variable is not used because the irrigation pathways are not being modeled.
Exposure – Water	Animal feed irrigation time – Milk animal feed	IRTIMA	mon/yr	3, By exposure location	This variable is not used because the irrigation pathways are not being modeled.
Exposure – Water	Animal feed irrigation time – Egg animal feed	IRTIMA	mon/yr	4, By exposure location	This variable is not used because the irrigation pathways are not being modeled.
Exposure – Water	Animal feed irrigation time – Beef animal forage	IRTIMA	mon/yr	5, By exposure location	This variable is not used because the irrigation pathways are not being modeled.
Exposure – Water	Animal feed irrigation time – Milk animal forage	IRTIMA	mon/yr	6, By exposure location	This variable is not used because the irrigation pathways are not being modeled.
Exposure – Water	Irrigation time for residential land	IRTIMR	mon/yr	0, By exposure location	This variable is not used because the irrigation pathways are not being modeled.
Exposure – Water	Irrigation time – Leafy vegetables	IRTIMT	mon/yr	1, By exposure location	This variable is not used because the irrigation pathways are not being modeled.
Exposure – Water	Irrigation time – Root vegetables	IRTIMT	mon/yr	2, By exposure location	This variable is not used because the irrigation pathways are not being modeled.
Exposure – Water	Irrigation time – Fruits	IRTIMT	mon/yr	3, By exposure location	This variable is not used because the irrigation pathways are not being modeled.
Exposure – Water	Irrigation time – Grains	IRTIMT	mon/yr	4, By exposure location	This variable is not used because the irrigation pathways are not being modeled.
Exposure – Water	Irrigation rate – Leafy vegetables	RIRR	in/yr	1, By exposure location	This variable is not used because the irrigation pathways are not being modeled.

GENII Module – Submodule	Variable Description	Variable Name	Units	Indices	Value and Discussion
Exposure – Water	Irrigation rate – Root vegetables	RIRR	in/yr	2, By exposure location	This variable is not used because the irrigation pathways are not being modeled.
Exposure – Water	Irrigation rate – Fruits	RIRR	in/yr	3, By exposure location	This variable is not used because the irrigation pathways are not being modeled.
Exposure – Water	Irrigation rate – Grains	RIRR	in/yr	4, By exposure location	This variable is not used because the irrigation pathways are not being modeled.
Exposure – Water	Animal feed irrigation rate – Beef animal feed	RIRRA	in/yr	1, By exposure location	This variable is not used because the irrigation pathways are not being modeled.
Exposure – Water	Animal feed irrigation rate – Poultry feed	RIRRA	in/yr	2, By exposure location	This variable is not used because the irrigation pathways are not being modeled.
Exposure – Water	Animal feed irrigation rate – Milk animal feed	RIRRA	in/yr	3, By exposure location	This variable is not used because the irrigation pathways are not being modeled.
Exposure – Water	Animal feed irrigation rate – Egg animal feed	RIRRA	in/yr	4, By exposure location	This variable is not used because the irrigation pathways are not being modeled.
Exposure – Water	Animal feed irrigation rate – Beef animal forage	RIRRA	in/yr	5, By exposure location	This variable is not used because the irrigation pathways are not being modeled.
Exposure – Water	Animal feed irrigation rate – Milk animal forage	RIRRA	in/yr	6, By exposure location	This variable is not used because the irrigation pathways are not being modeled.
Exposure – Water – General	Irrigation rate for residential land	RIRRR	in/yr	0, By exposure location	This variable is not used because the irrigation pathways are not being modeled.

F.3 Additional Parameter Values

This appendix identifies the source, transport, and exposure variables used in the SRS Base Case GENII model runs, indicates the GENII module and the section and subsection of FRAMES where the variable is used (this corresponds to the dialog boxes contained in the FRAMES user interface), states the units and input value(s) of each variable, and describes how each value was determined. Supporting references are also identified.

In addition to the variables addressed herein, another set of variables—receptor factors—is discussed in Appendix E. For the Base Case analysis, the receptor factors are input into a custom post-processor unit rather than input into GENII using the FRAMES interface.

The variables discussed here are organized according to the GENII modules and FRAMES sections and subsections listed in Table F-10.

F-10 GENII Modules and FRAMES Sections and Subsections

GENII Module	FRAMES Section and Subsection
Source	Atmospheric Flux Atmospheric Flux – Flux Types
Air	Model Information – Meteorological Files Model Information – Default Parameters Model Information – Model Parameters Model Information – Radial Grid Definition
Constituent Database	Partitioning Toxicity Parameters – Exposure Factors
Exposure	Agriculture – General Controls Soil – Leaching Soil – Resuspension Soil – Surface Soil
Water	General
River	Surface Water

The following notes apply to the discussions of variables and input values in this document.

Significant Figures. Generally, for any numerical value documented, only the first two digits should be considered significant. Some values reported here are shown with more significant digits than are appropriate given the lack of precision in data and models. In these cases, the additional significant digits are included to reduce the round-off error in the subsequent computer calculations and to help readers and reviewers trace these values to the original data sources. For example, the value used for relative humidity—0.01125 kg/m^3—is a 42-year average with a standard deviation of 0.00053 kg/m^3. This clearly implies the last two digits in the cited value are in doubt, but they are included so the value may be more easily traced through the computer calculation.

Stochastic Analysis. A list of the variables selected for stochastic analysis is provided in Chapter 12.

Parameters pertaining to human radiation dosimetry. The GENII Health Impacts submodule and the FRAMES Constituent Parameter section require that the code use input values for some parameters addressing human dosimetry (e.g., lung clearance classes for determination of dose and risk from

inhalation, soil depth, and density for determination of dose and risk from external exposure to contaminated soil). Assumed values for these parameters are provided in Section D.4 of Appendix D.

References. Table F-11 summarizes the references used to support the variables addressed in this appendix. Parameter values and their bases are listed in Table F-12.

Table F-11 References Used to Support Variables Addressed in Section A.3

Citation	Reference	Variables Supported
ATL 2003a (38)	Advanced Technologies and Laboratories International, Inc. Combining sources of air releases for the SRS dose reconstruction. June 5, 2003.	Flux type, Two, ARRADVAL
ATL 2003b (39)	Source Term Analysis (under preparation)	CFLUX
ATL 2003c (40)	Distribution Coefficients for Radionuclides Considered in the Dose Reconstruction of Savannah River Site. ATL June xx, 2003.	CLKD, SOILKD
Chaki 2000 (41)	Chaki S, Parks B. CAP88-PC Version 2.1 Updated Users Guide (Beta Version), Ch.12, p.8. September 2000.	ABSHUM
DOE 2002 (42)	Savannah River Site High-Level Waste Tank Closure Final Environmental Impact Statement. U.S. Department of Energy. DOE/EIS-0303. May 2002.	SLDN, BULKD, SSLDN
EPA 2000 (43)	EPA Soil Screening Guidance for Radionuclides, Users Guide. EPA/540-R-00-007. October 2000.	MOISTC
EPA 2001 (44)	Risk Assessment Guidance for Superfund: Volume I Human Health Evaluation Manual (Part D, Standardized Planning, Reporting, and Review of Superfund Risk Assessments), Final. U.S. Environmental Protection Agency. Publication 9285.7-47. December 2001.	SHOUT
EPA 2003 (45)	Radionuclide Table: Radionuclide Carcinogenicity – Slope Factors, (Federal Guidance Report No.13, Morbidity Risk Coefficients, in Units of Picocuries). U.S. Environmental Protection Agency. http://www.epa.gov/radiation/heast/docs/heast2_table_4-d2_0401.pdf . 2003.	SOLUBIL
Cook 2002a (46)	JR Cook, MA Phifer, EL Wilhite, KE Young. Closure Plant for the E-Area Low-Level Waste Facility, Rev. 2. WSRC-RP-2000-00425. WSRC, SRS, September 2, 2002.	VLEACH
Cook 2002b (47)	JR Cook and EL Wilhite. Analysis of Disposal of Lead in the E-Area Low-Level Waste Facility. WSRC-TR-2002-00101. WSRC, SRS. February 20, 2002.	VLEACH
Hamby 1991 (29)	Hamby DM. Land and Water Use Characteristics in the Vicinity of the Savannah River Site. WSRC-RP-91-17. Westinghouse Savannah River Company, Aiken, SC. March 1, 1991.	VLEACH

Citation	Reference	Variables Supported
Hamby 1993 (48)	Hamby DM. A Probabilistic Estimation of Atmospheric Tritium Dose. Health Physics; 65(1):33-40. July 1993.	ABSHUM
Hubbard 1987 (49)	Hubbard JE and Engelhardt M. Calculation of Groundwater Recharge at the Old SRP Burial Ground Using the CREAMS Model (1961-1986). Memorandum. July 31, 1987	RAIN, VLEACH
Johnson 1962 (50)	Johnson JE. Sulfur-35 Releases from Reactor Areas. Dupont Interoffice Memorandum to CM Patterson. Savannah River Plant. RAC reference no. SKR1994020129. July 19, 1962.	SOLUBIL
Kennedy 1992 (22)	WE Kennedy and DL Strenge. Residual Radioactive Contamination from Decommissioning, Technical Basis for Translating Contamination Levels to Annual Total Effective Dose Equivalent, Final Report. NUREG/CR-5512, PNL-7994. October 1992.	LEAFRS, RESFAC
Moore 2002 (37)	Moore MS. Critical Pathway Assessment of the Savannah River Site, Aiken, South Carolina. South Carolina Department of Health and Environmental Control. May 2002.	VLEACH
Napier 2003a (51)	Personal communication. Napier BA, PNNL, to WE Joyce, ATL International. March 4, 2003.	Radius, Density
Napier 2003b (52)	Personal communication. Napier BA, PNNL, to WE Joyce, ATL International. June 9, 2003.	Density
Napier 2003c (53)	Personal communication. Napier BA, PNNL, to WE Joyce, ATL International. March 31, 2003.	DEPFR1, DEPFR2
Napier 2003d (54)	Personal communication. Napier BA, PNNL, to WE Joyce, ATL International. February 12, 2003.	ANDKR
NCDC 2003 (55)	2002 Local Climatological Data (LCD) Annual Summary with Comparative Data, Augusta, GA. ISSN 0198-1587. National Oceanic and Atmospheric Administration. National Climactic Data Center. 2003.	RAIN
NRC 1977 (32)	Regulatory Guide 1.109, Calculation of Annual Doses to Man from Routine Releases of Reactor Effluents for the Purpose of Evaluating Compliance with 10 CFR Part 50, Appendix I. Revision 1. U.S. Nuclear Regulatory Commission. October 1977.	WTIM, SLDN, SEDDN, SOILT
ORNL 2002 (56)	Food Chain Models for Risk Assessment, Appendix F. Risk Assessment Information System. Oak Ridge National Laboratory. http://risk.lsd.ornl.gov/homepage/bjcor271/appf.shtml. July 1, 2002.	DEPFR1, DPVRES
Phifer 2003 (57)	M.A Phifer and L.B. Collard. Unreviewed Disposal Question Evaluation: Backfill Soil Compaction Requirements. WSRC-TR-2003-00081. WSRC, SRS. February 6, 2003.	VLEACH
PNNL 2002 (7)	Napier, BA, Strenge DL, Ramsdell JV, Eslinger PW, and Fosmire C. GENII Version 2 Software Design Document. Pacific Northwest National Laboratory (PNNL). November 2002.	[numerous]

Citation	Reference	Variables Supported
Simpkins 2002 (6)	Ali A. Simpkins. Estimating Derived Response Levels at the Savannah River Site for Use with Emergency Response Models. WSRC-MS-2002-00596. Westinghouse Savannah River Company. 2002.	SLDN, SEDDN
Till 1983 (31)	Till JE, Meyer HR, Peterson, HT. Radiological Assessment, A Textbook on Environmental Dose Analysis. NUREG/CR-3332, ORNL-5968. September 1983.	WTIM, LEAFRS, DPVRES, RESFAC
Till 2001 (58)	Till JE. FINAL REPORT, Savannah River Site Environmental Dose Reconstruction Project, Phase II: Source Term Calculation and Ingestion Pathway Data Retrieval, Evaluation of Materials Released from the Savannah River Site. Risk Assessment Corporation, Neeses, SC. April 30, 2001.	Radius, Density
Wild 2003 (59)	Wild EW, Brigmon RL, Berry CJ, Altman DJ, Rossabi J, Looney BB, and Harris SP. D-Area Drip Irrigation-Phytoremediation Project: SRTC Final Report. WSRC-TR-2002-00080. Westinghouse Savannah River Company, Aiken, SC. January 2003.	VLEACH
WSRC 1991 (60)	Savannah River Site Environmental Report for 1990. WSRC-IM-91-28. Westinghouse Savannah River Company, Aiken, SC. 1991.	SHIN, SWFAC
WSRC 1992 (61)	Savannah River Site Environmental Report for 1991. Westinghouse Savannah River Company, Aiken, SC. 1992.	SHIN, SWFAC
WSRC 1993 (62)	Savannah River Site Environmental Report for 1992. WSRC-TR-93-075 and -077. Westinghouse Savannah River Company, Aiken, SC. 1993.	SHIN, SWFAC

Table F-12 Values for Variables and their Bases

GENII Module	Module Section-Subsection	Variable	Variable Name (Units)	Indices	Value and Basis
Source	Atmospheric Flux	Flux Type	(none)	By source	Value = Point source (for offsite exposure locations) For air releases, all sources will be defined as point sources (as opposed to area sources). The rationale is as follows: The four defined model sources are virtual sources representing several (~2 to ~5) actual sources. Most of the nuclide releases come from elevated sources (typically 61 meters). GENII can only model an elevated source if it is a point source; area sources cannot be elevated. The selection of point or area has an effect on air concentrations very close to the release location, but would not have a substantive effect on concentrations that are far (several miles) from the release location (7,38). In this study, the offsite exposure locations are far enough away from the sources that using the simpler point source flux type is not expected to substantively affect the results.
Source	Atmospheric Flux	Exit height of source (m)	Two (m)	By media type (3=Air)	Value = [see table below] This variable is established for each of four distinct "virtual sources," each of which represents several actual sources. Each virtual source represents the combined releases from several physical sources such as stacks or evaporation from basins. The exit height for each virtual source is based on the heights of the individual physical sources that it represents. The process under which these sources are defined is described in Appendix A. The source heights are specified as follows:

Virtual Source Group	Height (m)	Actual Sources Represented
1	10	A Area, M Area, SRL
2	61	F Canyon, H Canyon, H Area Tritium Stack (includes stacks and basin evaporation)
3	61	C, K, and L Reactors (includes stacks and basin evaporation)
4	61	P and R Reactors (includes stacks and basin evaporation)

GENII Module	Module Section-Subsection	Variable	Variable Name (Units)	Indices	Value and Basis
Source	Atmospheric Flux	Release Rate	CFLUX (pCi, , pCi/ml)	By Media Type and Isotope	Value = [see Appendix B]. The release rate is the Base Case source term data. For air releases, the release rate is entered in the GID file (and the FRAMES interface) in units of pCi for each nuclide over a 1-year period (corresponding to pCi/year) for each of the four virtual release points. For water releases, the release is in terms of radionuclide concentrations in Savannah River or Lower Three Runs Creek (pCi/ml). .
Source	Atmospheric Flux – Flux Types	Particle radius (um)	Radius (um)	By flux type	Value = 0.5 um Particle radius is used to characterize the source release for the air pathway. The particle radius value is used in the model to determine the rate of deposition (7). The user can specify multiple flux types, including up to three particle types (defined by their radii and density) and a gas fraction for each nuclide. For this analysis, all nuclides except the following were modeled as particles. The following nuclides were modeled as gases, based on their physical properties: H-3 (both as HT or HTO), Ar-41, I-129, I-131 (51). Part of the iodine source terms will also be modeled as a particulate release. Limited data on particle size is available (58), and an analysis of this data did not yield a meaningful single value or range of values to be used for particle diameter. The limited available data focused on stack measurements of particle size. However, as used in the model, particle size after the time of release (i.e., at the time of deposition) is more relevant. The stack measurements do not account for the particle agglomeration and other physiochemical changes that would be expected to occur after the particles are released. A radius value of 0.5 micron (i.e., 1.0 micron diameter) was selected to model particle deposition. At this size, depletion of the air concentration by gravitational deposition should be minimal, resulting in conservative (high) air concentrations at the exposure locations. In the absence of applicable data and with many factors causing variation over time, choice of a standard value is justified.

GENII Module	Module Section-Subsection	Variable	Variable Name (Units)	Indices	Value and Basis
Source	Atmospheric Flux – Flux Types	Particle density (g/cm^3)	Density (g/cm^3)	By Particle Size	Value = 2.0 g/cm^3 Particle density is used with particle radius in the model to determine the rate of dry deposition (7). Previous SRS studies identified in the RAC Phase II report (58) have assumed particle densities of 1 and 2 g/cm^3. However, there are no available data that characterize particle density for SRS air releases. Since the emissions at the SRS may be particulates as well as dehydrated solutions, a density between water (1.0) and soil (~2.5) has some appeal.
Source	Atmospheric Flux – Flux Types	Nonreactive fraction if gas	Density (fraction)	None	Value = 0.5 (Iodine isotopes) This variable is used when a nuclide source term air release is specified as a gas rather than a particle. The nonreactive fraction represents the proportion of the release quantity that is not reduced through degradation, except for iodine, which uses a special model (the reactive fraction is converted to a particle), forms of tritium, and noble gases. For forms of tritium and noble gases, GENII automatically assigns a nonreactive gas fraction of 1.0. For other gaseous nuclides, GENII allows a single nonreactive gas fraction to be specified. For iodine, a value of 0.5 is assumed, based on the assumption that the release will eventually reach equilibrium at 40% particle, 30% reactive gas, and 30% nonreactive gas (51,52).
Air	Model Information – Meteorological Files	Name of met file	ARMETFILE (met file name)	None	The name of the file containing met data to be read into GENII is determined according to the pre-processor design document (see Appendix G).
Air	Model Information – Default Parameters	Transfer resistance for Iodine	ARTRANSRESIST (s/m)	None	Value = 10 s/m Transfer resistance is used in the GENII air deposition model as a mathematical device to establish an upper limit on the deposition velocity of contaminants depositing on the soil and foliage. The deposition velocity is the factor relating the concentration of contaminants in the air and the flux rate of the contamination depositing on the ground. High transfer resistance reduces the deposition velocity and the amount of contamination deposited. As transfer resistance is decreased, deposition velocities and contaminant fluxes increase until transfer resistance becomes small in comparison to aerodynamic and surface resistances (which are calculated from near surface wind data), at which point these other resistances dominate dry deposition velocity. The GENII default for gases (iodine) is 10 s/m (7). The Base Case analysis adopted the GENII default value (10 s/m).

GENII Module	Module Section-Subsection	Variable	Variable Name (Units)	Indices	Value and Basis
Air	Model Information – Default Parameters	Transfer resistance for particulates	ARTRANSRESIST (s/m)	None	Value = 100 s/m The transfer resistance for particulates is used in the GENII air deposition model in the same manner as the transfer resistance for iodine. The Base Case analysis adopted the GENII default value of 100 s/m (7).
Air	Model Information – Model Parameters	Sigma Paramaterization Usage	ARSIGPARM (none)	None	Value = Pasquill-Gifford (NRC) This variable is used in the GENII air dispersion module chronic plume model. This variable is used to specify the approach to calculate plume diffusion coefficients which are used to describe the spread of effluents in plumes. These coefficients are related to atmospheric turbulence and the time since release. Most of the schemes used to estimate diffusion coefficients are based on atmospheric stability classes and distance from the source (see PNNL 2002, p. 59-67 [7]). The following five options available in GENII: Brigg's Open Country (Default) Pasquill-Gifford (ISC3) Pasquill-Gifford (NRC) Brigg's Urban Condition, and Turbulence Statistics. Note: For each option, it is possible to select a user-supplied calm wind distribution, which includes the fraction of time the wind blows in each given direction during calm periods. (See GENII FRAMES User Interface, air dispersion module, Model Parameters tab.) The Pasquill-Gifford (NRC) was selected because it is consistent with how SRS meteorological data is collected and stability classes determined.

<table>
<tr><th>GENII Module</th><th>Module Section-Subsection</th><th>Variable</th><th>Variable Name (Units)</th><th>Indices</th><th>Value and Basis</th></tr>
<tr><td>Air</td><td>Model Information – Radial Grid Definition</td><td>Ring Distance</td><td>ARRADVAL (m)</td><td>By Ring Index</td><td>Value = [see below].
This variable is the radii of the rings used in the sector-based air dispersion analysis. When GENII determines air concentrations at various locations, the locations are moved to the closest calculation point on a grid formed by user-defined ring distances and 16 established compass headings. The ring diameters will be set so as to minimize the distance a exposure location must be moved to get to a grid point. The radii value of each ring is set so that it coincides with the distance between the source and exposure locations.

A separate set of ring distances is calculated for each source. Since there are 4 sources and up to 10 distances can be calculated for each source, (4 x 10) 40 ring distances are calculated. The distances are listed below in units of meters (m):
<table>
<tr><th colspan="2">A-Area, M-Area, SRL</th><th colspan="2">F- and H-Area</th><th colspan="2">C-, K-, & L-Reactors, D-Area, CMX-TNX</th><th colspan="2">P- & R-Reactors</th></tr>
<tr><th>Distance</th><th>Exposure Location</th><th>Distance</th><th>Exposure Location</th><th>Distance</th><th>Exposure Location</th><th>Distance</th><th>Exposure Location</th></tr>
<tr><td>4,824</td><td>Jackson</td><td>8,666</td><td>On site</td><td>1,889</td><td>On site</td><td>8,881</td><td>On site</td></tr>
<tr><td>9,266</td><td>New Ellenton</td><td>12,392</td><td>Jackson</td><td>16,582</td><td>Jackson</td><td>20,648</td><td>Barnwell</td></tr>
<tr><td>16,226</td><td>On site</td><td>14,205</td><td>New Ellenton</td><td>21,092</td><td>New Ellenton</td><td>20,666</td><td>New Ellenton</td></tr>
<tr><td>24,196</td><td>Augusta</td><td>25,657</td><td>Williston</td><td>23,149</td><td>Girard</td><td>20,961</td><td>Jackson</td></tr>
<tr><td>30,065</td><td>Williston</td><td>28,585</td><td>Barnwell</td><td>23,629</td><td>Martin</td><td>21,880</td><td>Martin</td></tr>
<tr><td>36,789</td><td>Barnwell</td><td>29,293</td><td>Martin</td><td>27,743</td><td>Barnwell</td><td>22,354</td><td>Williston</td></tr>
<tr><td>37,477</td><td>Girard</td><td>30,033</td><td>Girard</td><td>29,256</td><td>Williston</td><td>25,800</td><td>Girard</td></tr>
<tr><td>38,309</td><td>Martin</td><td>33,397</td><td>Augusta</td><td>36,775</td><td>Waynesboro</td><td>36,775</td><td>Allendale</td></tr>
<tr><td>38,710</td><td>Waynesboro</td><td>39,858</td><td>Waynesboro</td><td>38,318</td><td>Augusta</td><td>41,940</td><td>Augusta</td></tr>
<tr><td>54,256</td><td>Allendale</td><td>45,038</td><td>Allendale</td><td>40,178</td><td>Allendale</td><td>44,286</td><td>Waynesboro</td></tr>
</table>
</td></tr>
<tr><td>Constit Database</td><td>Partitioning</td><td>Soil-water Partition Coefficient</td><td>CLKD (ml/g)</td><td>By Isotope and Daughter</td><td>This is the same as the soil adsorption coefficient (SOILKD), which is addressed in the Exposure-Soil-Leaching GENII module.</td></tr>
<tr><td>Constit Database</td><td>Toxicity Parameters – Exposure Factors</td><td>Water Purification Factor</td><td>CLWPF (none)</td><td>By isotope and daughters</td><td>Value = 0.0
This variable is used in drinking water/showering pathways. In the SRS Base Case, no families use the contaminated water for indoor uses. Usage of this variable is documented in PNNL 2002, p. 156 (7).</td></tr>
</table>

GENII Module	Module Section-Subsection	Variable	Variable Name (Units)	Indices	Value and Basis
Exposure	Agriculture – General	Weathering rate constant from plants	WTIM (days)	None	Value = 14 days This variable is the weathering half-life of nuclides that have been deposited on plant surfaces. It used in calculations of contaminant levels on foliage that is consumed by humans or by animals that are subsequently consumed by humans (7). NRC 1977, p.69 (32), recommends a value of 14 days (this is also the GENII default value). Till 1983 (31) includes a range of values (4 days to 300 days) and recognizes how the value can be affected by different seasons and different plant species. Most cited values are in the 10- to 30-day range (Till 1983, p. 5-33 to 5-38 [31]). The default value (14 days) is therefore reasonable.
Exposure	Agriculture – General	Dry deposition retention fraction to plants	DEPFR1 (fraction)	None	Value = 0.25 This variable represents the fraction of dry-deposited contamination that is retained on plant surfaces. It is also considered the interception fraction (see Napier 2003c [53]). The GENII default value is 0.20. The selected value of 0.25 is considered a reasonable value based on the following analysis cited by Oak Ridge 2002 (56) (http://risk.lsd.ornl.gov/homepage/bjcor271/appf.shtml): "...The interception fraction accounts for the proportion of aerial deposition that is intercepted by plant surfaces. The interception fraction varies with plant type and density of vegetation. NRC (1977) and NCRP (1984) use a default value of 0.25 for pasture grasses and 0.2 for vegetable crops. NCRP (1989) used 0.25 as the default for both vegetables and pasture. However, Miller (1980) reviewed a number of studies and reported a range of 0.02-0.82 for various grasses. The midpoint of this range (0.42) is suggested as the default value for use in the pasture plant models in this report. Interception fractions for vegetable crops ranged from 0.06-1.2 (Miller 1980), but 10 of 13 values were less than 0.49. The value of 0.42 used for pasture grasses is also suggested as the default for vegetable crops. Breshears et al. (1992) examined a number of values and determined that the geometric mean for the interception fraction was 0.39. The reader should note that there is considerable variability in the interception fraction values. Iodines exhibit a greater tendency to be retained on vegetation. The default iodine value of 1.0 from NRC (1977) is recommended in this white paper for both pasture and vegetable crops. The recommended value for interception of particles deposited by spray irrigation is 0.25; this is the default value used by NRC (1977) and is within the range reported by Miller (1980)."

GENII Module	Module Section-Subsection	Variable	Variable Name (Units)	Indices	Value and Basis
Exposure	Agriculture – General	Wet deposition retention fraction to plant surfaces	DEPFR2 (fraction)	None	Value = 0.25 This variable represents the fraction of wet-deposited contamination that is retained on plant surfaces. It is also considered the interception fraction. [see Napier 2003c] The GENII default value is 0.25. The rationale for selecting 0.25 is the same as described above for DEPFR1.
Exposure	Agriculture – General	Resuspension factor from soil to plant surfaces	LEAFRS (1/m)	None	Value = 10^{-5} & 10^{-7} (depending on location) The values used for this variable are the same as those used for soil resuspension for use in the soil inhalation pathway (see RESFAC, below). These values are 10^{-5} m^{-1} for the Girard (1), New Ellenton (5), and Williston (9) exposure locations, and 10^{-7} m^{-1} for all other exposure locations.
Exposure	Agriculture – General	Deposition velocity from soil to plant surfaces	DPVRES (m/s)	None	Value = 0.001 m/s. The selected value of 0.001 m/s is based on a review of Till 1983, p.5-16 through 5-21 [31]. Limited data are available, most of it for iodine deposition. Values tend to cover a range between 0.01 and 0.00001 m/s. The GENII Default = 0.001 m/s, and NCRP 1989 (as cited in ORNL 2002 [56]) recommends a value of 1000 m/d (roughly equal to 0.01 m/s). GENII requires a single value be used for all nuclides.
Exposure	Agriculture – General	Radionuclide removal due to harvesting	HARVST (on/off)	None	Value = FALSE (OFF) This variable is an on/off switch used to account for reductions in soil contamination levels resulting when contaminated plants are harvested and removed from the area (7). To be conservative, the switch will be OFF in the Base Case scenario. OFF means that the soil contamination levels will not be automatically reduced to account for contamination removed from the field when crops are harvested.

GENII Module	Module Section-Subsection	Variable	Variable Name (Units)	Indices	Value and Basis
Exposure	Controls	Absolute humidity, used only for tritium model	ABSHUM (kg/m^3)	None	Value = 0.01125 kg/m^3 The absolute humidity parameter is used only in the tritium model of the GENII exposure module (7). Only a single value is needed to model the Base Case scenario. The following two candidate values were identified: The value selected for the Base Case scenario is a site-specific value (0.01125 kg/m^3). According to Hamby 1993 [48], weekly averages at the SRS over a two-year period ranged from 0.0032 to 0.0244 kg/m^3 (Hamby and Jumper 1990, cited in Hamby 1993, p. 34 [48]). Annual averages, however, are less variable. A database of average daily temperature and average daily wet-bulb temperature from the Columbia, SC, National Weather Service station were analyzed to generate a distribution of annual average absolute humidity values for the SRS. The database includes the 42-year period from 1949 to 1990 and provides the basis for the selected value of the absolute humidity parameter. The mean value of the distribution of the 42 data points is 0.01125 kg/m^3, with a standard deviation of 0.00053 kg/m^3 (48). An alternative, non-site-specific default value (not used) of 0.008 kg/m^3 is proposed in the documentation for EPA's CAP88-PC computer model for estimating dose and risk for radionuclide emissions to air. The 0.008 kg/m^3 value is proposed for use with the CAP-88 tritium module (Chaki 2000 [41]). The GENII default value = 0.008.

GENII Module	Module Section-Subsection	Variable	Variable Name (Units)	Indices	Value and Basis
Exposure	Controls	Average daily rain rate	RAIN (mm/d)	None	Value = 11.4mm/d This is the average daily rain rate, when it is raining. It is used in the calculation of wet deposition (7). A value of 11.4 mm/d was calculated using data from two references (55,49). Hubbard 1987 [49] presents annual rainfall data for F-Area at the SRS for the 1961-1986 period and calculates an average value of 48.51 inches. This value is slightly higher than the "normal" annual rainfall reported for Augusta on NCDC 2003, p. 3 (55) (44.66 inches/year). NCDC 2003, p. 3, (55) also reports 108.2 days/year with precipitation of at least 0.01 inches (normal long-term average). Using this data, the average daily rain rate is calculated as follows: (48.51 in/yr) * (25.4 mm/in) / (108.2 d/yr) = 11.4 mm/d

GENII Module	Module Section-Subsection	Variable	Variable Name (Units)	Indices	Value and Basis
Exposure	Soil – Leaching	Surface soil moisture content	MOISTC (fraction)	None	Value = 0.22 This variable is used in the GENII leach rate calculations. GENII offers 3 options for leach rates: Use GENII Default leach rates (Not Used) Use leach rates calculated from user input. For this option, the user must specify the following variables: Surface Soil Thickness Surf. Soil Moisture Content (fraction) Surf. Soil Bulk Density Total Infiltration Rate Soil Adsorption Coefficient (Kd), which is specific for each nuclide Use User-provided leach rate constants. (Not Used) In this study, leach rates are determined using option (2), above. See formulas in PNNL 2002, p.101, 104, and 143 (7). Using the formulas and values in EPA 2000, pp. A-5 and A-6 (43), the following soil moisture values can be calculated using the local 40 cm/year infiltration rate and the following formula: Soil Moisture (unitless fraction) = $n * (I / K_s)^e$, where: n = total soil porosity (unitless fraction) [value = 0.4 (see below)] I = infiltration rate (m/yr) [local value =0.373 m/yr] K_s = saturated hydraulic conductivity (m/yr) e = soil-specific exponential parameter (unitless) Values for K_s and e are provided by EPA 2000 (43) for different soil types (below). For total soil porosity (n), n = (1 – (dry soil bulk density / soil particle density)) Using EPA's recommended soil particle density value of 2.65 g/cm^3 and the local soil bulk density of 1.59 g/cm^3, n = 0.4:

Soil Type	I (m/yr)	K_s (m/yr)	E	(I/Ks)e	BulkSoil Porosity	Soil Moist
Sand	0.373	1830	0.09	0.47	0.4	0.19
Loamy Sand	0.373	540	0.085	0.54	0.4	0.22
Sandy Loam	0.373	230	0.08	0.60	0.4	0.24
Silt Loam	0.373	120	0.074	0.66	0.4	0.26
Loam	0.373	60	0.073	0.69	0.4	0.28
Sandy Clay Loam	0.373	40	0.058	0.77	0.4	0.30
Silt Clay Loam	0.373	13	0.054	0.83	0.4	0.33
Clay Loam	0.373	20	0.05	0.82	0.4	0.33
Sandy Clay	0.373	10	0.042	0.87	0.4	0.35
Silt Clay	0.373	8	0.042	0.88	0.4	0.35
Clay	0.373	5	0.039	0.90	0.4	0.36

GENII Module	Module Section-Subsection	Variable	Variable Name (Units)	Indices	Value and Basis
Exposure	Soil - Leaching	Surface soil thickness	THICK (cm)	None	GENII Default = 15 cm. Used in direct exposure and leach rate calculations - See PNNL 2002, p. 186 (7). (same as SURCM). This is a standard value widely used.
Exposure	Soil – Leaching	Total infiltration rate	VLEACH (cm/yr)	None	Value = 37.3 cm/yr This value is based on a study conducted at the SRS (49) which calculated ground-water recharge rates at the SRS in the vicinity of the Old SRP Burial Ground from 1961 to 1986. Several other SRS and local studies have cited a local value of about 40 cm/yr. Phifer 2003, p. 5 (57), cites an infiltration rate of 40 cm/year based on "past infiltration studies conducted at SRS." Other references citing a 40 cm/yr infiltration rate (46,47). Wild 2003, p.17 (59), cites an infiltration rate of "1/6th to 1/3 of rainfall" which, when combined with the 1961-86 average precipitation rate at F-Area (48.51 inches/year [49]) yields an infiltration rate of 20 to 41 cm/year. These studies use values that do not consider additional infiltration resulting from irrigation. In this analysis, irrigation is assumed to be zero (see Moore 2002, pp. 17-18 [37], and Hamby 1991 [29]).

GENII Module	Module Section-Subsection	Variable	Variable Name (Units)	Indices	Value and Basis
Exposure	Soil – Leaching	Soil adsorption coefficient	SOILKD (ml/g)	By Isotope Index	This variable is also known the Kd or distribution coefficient. The Kd is used in the soil model to calculate leaching of contaminants from the surface soil to deeper soil (PNNL 2002, pp. 105 & 143 [7]). Higher Kds result in the contaminant remaining in the surface soil longer and resulting in higher availability of the contaminant to transfer to the air (resuspension) or to plants (for ingestion). An analysis of available Kd data from several sources for the purpose of this model is presented in ATL 2003c (40). The Kd values resulting from the analysis are as follows:

Nuc.	Value		Nuc.	Value
Am	2000		Pu	4100
Ar	Not Applic		Ru	55
C	Not Applic		S	7.5
Ce	490		Sr	3041
Co	60		Tc	2.49
Cs	59		Th	3000
H3	0		U	1000
I	1.55		Y	510
Nb	160		Zn	200
P	173		Zr	600

GENII Module	Module Section-Subsection	Variable	Variable Name (Units)	Indices	Value and Basis
Exposure	Soil – Resuspension	Resuspension factor	RESFAC (1/m)	None	Value = 10^{-5} m^{-1} and 10^{-7} m^{-1}, depending on location GENII offers 3 different ways to calculate a soil resuspension factor (1/m), which is multiplied by the areal soil concentration (Bq/m^2) to calculate an air concentration (Bq/m^3) (PNNL 2002, p. 159 [7]): Mass loading model. This method requires a Mass Loading Factor [GENII Default = 5.00×10^{-5} g/m3] to calculate a resuspension factor (1/m). [Not Used] Anspaugh model. This is a time-dependent approach that is independent of soil characteristics. It calculates a resuspension factor that is exponential with time. It requires a top soil depth [GENII Default = 1 cm]. [Not Used] User input of resuspension factor, GENII default = 1.0×10^{-9} m^{-1}. The third option, which allows the user to input a resuspension factor, was selected for this analysis. Two values are selected for this variable. A higher value (10^{-5}/m) is assigned to exposure locations around agricultural areas where there is a relatively higher level of soil disturbance. A lower value (10^{-7}/m) is assigned to exposure locations in areas where there is comparatively less soil disturbance. In each case, the available literature does not identify a single preferred value for this variable. However, recommended values occur over a range (see Kennedy 1992, Table 6-4 [22], and Till 1983, Sect 5.2.2.6 (p.5-30) and Table 5.8 [31]). Exposure Locations, CDC Scenarios, (Location Index Numbers), and Assigned Values for Resuspension Factor

1×10^{-5} m^{-1} (More Disturbed Exposure Locations)	10×10^{-7} m^{-1} (Less Disturbed Exposure Locations)
Girard – Rural Family One (1) New Ellenton – Migrant Family (5) Williston – Rural Family Two (9)	Waynesboro – Rural Family One (2) Augusta – Urban Family (3) Jackson – Outdoors Family(4) Barnwell – Delivery Person (6) Martin/LTRC – Near River Family, Delivery Family (7 and 21) Allendale – Delivery Family (8) Onsite Location – Urban Family, Delivery Family, Outdoors Family (10)

GENII Module	Module Section-Subsection	Variable	Variable Name (Units)	Indices	Value and Basis
Exposure	Soil – Surface Soil	Surface soil areal density	SLDN (kg/m^2)	None	Value = 240 kg/m^2 This variable is used in calculating soil concentrations for use in food chain pathways. It represents the bulk mass of soil into which air-deposited contamination is mixed. The selected value of is consistent with a soil thickness of 15 cm and the site-specific soil density of 1,600 kg/m^3. This value is also equal to the default value (240 kg/m^3) recommended by the NRC (32). The SRS adopted the same NRC default value in a dose modeling study (6). The 240 kg/m^2 value is also the GENII default value (7). The basis for the soil thickness and density values cited above is explained below.
Exposure	Soil – Surface Soil	GENII soil layer thickness used for density	SURCM (cm)	None	Value = 15 cm This variable is used in calculating direct exposure from contaminated soil (PNNL 2002, p. 186 [7]). GENII Default = 15 cm (7).
Exposure	Soil – Surface Soil	Surface soil bulk density	BULKD (g/cm^3)	None	Value 1.60 g/cm^3 This variable is used in connection with SURCM in the calculation of the direct exposure pathway (7). The selected value of 1.60 g/cm^3 is based on the bulk density of soil of the vadose zone at H and F areas used in DOE 2002, p.C-22 (42) (the value was rounded from 1.59 g/cm^3).
Exposure	Water - General	Delay time in water distribution system	HOLDDW (days)	None	Value = 0 days This variable is the drinking water and shower inhalation pathways. For the base case, because no member of any exposure scenario is assumed to use contaminated water for drinking or showering, the assumption of a value has no effect on the base case assessment. It would be otherwise reasonable to assume that any river water used by a scenario family would have minimal holdup time between when it is removed from the river and used in the household. Therefore, a value of zero (0) is assumed for input to GENII.
Exposure	Water – General	Shoreline sediment density	SEDDN (kg/m^2)	None	Value = 240 kg/m^2 This variable is used in determining the direct exposure rate resulting from contaminant deposition along the shoreline. Neither default nor site-specific data for sediment density was found. The selected value is based on the value selected for the surface soil areal density (SLDN).

GENII Module	Module Section-Subsection	Variable	Variable Name (Units)	Indices	Value and Basis
Exposure	Water - General	Indoor volatilization factor for radionuclides	ANDKR (l/m^3)	None	Value = 0.0 This variable is used in determining the amount of nuclides in water that volatilize into indoor breathing air. This exposure pathway is not considered in the base case assessment. Nonetheless, because the variable is not contaminant specific, and because most radionuclides that were discharged to surface water from SRS are nonvolatile, this variable should always be set to 0 (54).
Receptor	External Ground Exposure	Indoor shielding factor	SHIN (none)	None	Value = 0.7 A value of 0.7 is assumed. Values of 0.5, 0.7 and 0.8 were found in the literature. EPA recommends a value of 0.8 for Reasonable Maximum Exposure in an example screening scenario (EPA 2001, Example Scenario 11, Table 4.3 [44]). Values 0.7 and 0.5 are used by the SRS in population dose modeling (WSRC 1991, p. A-48 [60]; WSRC 1992, p. 115 [61]; WSRC 1993, p. 133 [62]).
Receptor	External Ground Exposure	Outdoor shielding factor	SHOUT (none)	None	Value = 1.0 A value of 1.0 is assumed. The GENII default value = 1.0 (PNNL 2002, p. 300 [7]). No shielding would be expected in outdoor situations. A value of 1.0 is specified by EPA for Reasonable Maximum Exposure (44).
Receptor	External Exposure to Shoreline	Shoreline width factor	SWFAC (none)	None	Value = 0.2 The shore width factor is a factor for reduction of the external dose rate factor for exposure to the shoreline. The external dose rate factors are based on exposure to an infinite flat plane of contamination. Because most shorelines do not represent an infinite plane, a reduction is allowed to address this difference in geometry. A value of 0.2 was selected based on its use in SRS analyses and use as a GENII default value (PNNL 2002, p.300 [7], WSRC 1991, p.A-56 [60], WSRC 1992, p. 123 [61], WSRC 1992, p. 138 [61]). A value of 0.2 accounts for the shoreline being a narrow strip rather than an infinite plane.
River	Surface Water	Concentration	CVAL	pCi/ml	This variable represents the concentration of each contaminant at a specified exposure location. The values for this variable differ based on the year of release, the nuclide of interest, and the specified exposure location. Values for this variable are determined through a separate analysis of releases, water flowrates, and holdup/loss between the release and exposure locations.

F.4 References

1. Napier BA. [personal communication with Joyce WE, ATL] 2003 Mar 6.

2. International Atomic Energy Agency. Handbook of parameter values for the prediction of radionuclide transfer in temperate environments. Technical Reports Series No. 364. Vienna, Austria. 1994.

3. Friday GP, Cummins CL, Schwartzman AL. Radiological bioconcentration factors for aquatic, terrestrial, and wetland ecosystems at the Savannah River Site (U). WSRC-TR-96-0231. Westinghouse Savannah River Company. Aiken, South Carolina. 1996.

4. U.S. Department of Agriculture, National Agricultural Statistics Service. 1992 census of agriculture volume 1: Part 40, Chapter 2, South Carolina state and county data. 1993.

5. Westinghouse Savannah River Company. Savannah River Site environmental report for 2001. WSRC-TR-2001-00474. Aiken, South Carolina. 2001.

6. Simpkins A. Estimating derived response levels at the Savannah River Site for use with emergency response models. WSRC-MS-2002-00596. Westinghouse Savannah River Company. Aiken, South Carolina. 2002.

7. Napier BA, Strenge DL, Ramsdell JV, Eslinger PW, and Fosmire C. GENII version 2 software design document. Pacific Northwest National Laboratory. Richland, Washington. November 2002.

8. Baes CF, Sharp RD, Sjoreen AL, Shor RW. A review and analysis of parameters for assessing transport of environmentally released radionuclides through agriculture, Rep ORNL-5786. Oak Ridge National Laboratory, Tennessee. 1984.

9. Bishop GP, Beetham CJ, Cuff YS. Review of literature for chlorine, technetium, iodine and neptunium. Nirex Radioactive Waste Disposal Safety Studies, Rep. NSS/R193. UK Nirex Ltd, Harwell. 1989.

10. Commission of the European Communities. Radionuclide transfer factors for animal feedingstuffs and animal products. Doc. 7682/87. Luxembourg. 1987.

11. Coughtrey PJ, Thorne MC. Radionuclide distribution and transport in terrestrial and aquatic ecosystems, a critical review of data. Vols. 1–6. A.A. Balkema, Rotterdam. 1983.

12. Coughtrey PJ. Radioactivity transfer to animal products. Rep EUR 12608 EN. Commission of the European Communities. Luxembourg. 1990.

13. Cramp TJ, Cuff YS, Davis A, Morgan JE. Review of data for uranium, nickel, and cobalt. Rep 2150-RI. Associated Nuclear Services Ltd, Epsom. 1990.

14. Ennis ME Jr, Ward GM, Johnson JE, Boamah, KN. Transfer coefficients of selected radionuclides to animal products. II Hen Eggs and Meat, Health Physics 54, 167-170. 1988

15. Ennis ME Jr, Johnson JE, Ward GM, Voigt GM. A specific activity effect in the metabolism of technetium. Health Physics 54, 157-160. 1988.

16. Frissel MJ, van Bergeijk, KE. Mean transfer values derived by simple statistical regression analysis. Sixth Report of IUR Working Group on Soil-to-Plant Transfer Factors. RIVM Bilthoven. 1989.

17. Frissel MJ, van Bergeijk, KE. Mean transfer values derived by simple statistical regression analysis. Sixth Report of IUR Working Group on Soil-to-Plant Transfer Factors. RIVM Bilthoven. 1992.

18. Gerzabek MH, Horak O, Mohamad S, Muck K. Gefabversuche zum Radionuclidtransfer Boden-Pfanze, Fusionsreaktor – Erste Wand, Rep. OEFZS A-2531, Osterreichisches Forschungszentrum Seibersdorf, 22-31. 1993

19. Handl J, Pfau A. Long-term transfer of I-129 into the food chain. Sci. Total Environ 85, 245-252. 1989.

20. Hoffman FO, Amaral E, Mohrbacher DA, Deming E. The comparison of generic model predictions with Chernobyl fallout data on the transfer of radioiodine over the air-pasture-cow-milk pathway. J. Environmental Radioactivity 8, 53-71. 1988.

21. Johnson JE, Ward GM, Ennis ME Jr, Boamah KN. Transfer coefficients of selected radionuclides to animal products. 1. Comparison of Milk and Meat from Dairy Cows and Goats, Health Physics 54, 161-166. 1988.

22. Kennedy WE, Strenge DL. Residual radioactive contamination from decommissioning, technical basis for translating contamination levels to annual total effective dose equivalent. Final Report. NUREG/CR-5512, PNL-7994. October 1992.

23. Morgan JE, Beetham, CJ. Review of literature for radium, protactinium, tin, and carbon. Nirex Radioactive Waste Disposal Studies. UK Nirex Ltd, Harwell. 1990.

24. Napier BA, Peloquin RA, Strenge DL, Ramsdell JV. GENII – the Hanford environmental radiation dosimetry software system. Pacific Northwest Laboratory. PNL-6584. Richland, Washington. 1988.

25. Ng YC, Colsher CS, Quinn DJ, Tompson SE. Transfer coefficients for the prediction of the dose to man via the forage-cow-milk pathway from radionuclides released to the biosphere. UCRL-51939. Lawrence Livermore National Laboratory, California. 1977.

26. Ng YC, Colsher CS, Tompson SE. Soil-to-plant concentration factors for radiological assessments. Rep. NUREG/CR-2975 UCID-19463. Lawrence Livermore National Laboratory, California. 1982.

27. Ng YC. A review of transfer factors for assessing the dose from radionuclides in agricultural products. Nucl. Saf. 23, 57-71. 1982

28. Ng YC, Colsher CS, Thompson, SE. Transfer coefficients for assessing the dose from radionuclides in meat and eggs. Final Rep. to USNRC NUREG/CR-2976 UCID-19464. Lawrence Livermore National Laboratory, California. 1982.

29. Hamby DM. Land and water use characteristics in the vicinity of the Savannah River Site. WSRC-RP-91-17. Westinghouse Savannah River Company. Aiken, South Carolina. March 1, 1991.

30. Clemson University Cooperative Extension Service. Utilization of bermudagrass. Forage Leaflet 3. May 1988.

31. Till JE, Meyer HR, Peterson, HT. Radiological assessment, a textbook on environmental dose analysis. NUREG/CR-3332, ORNL-5968. September 1983.

32. U.S. Nuclear Regulatory Commission. Calculation of annual doses to man from routine releases of reactor effluents for the purpose of evaluating compliance with 10 CFR part 50, appendix I. Regulatory Guide 1.109, Revision 1. October 1977.

33. Ng YC, Colsher CS, Thompson SE. Transfer coefficients for assessing the dose from radionuclides in meat and eggs. Final Rep. to USNRC NUREG/CR-2976 UCID-19464. Lawrence Livermore National Laboratory, California. 1982.

34. U.S. Department of Agriculture. Home vegetable gardening, circular 570. USDA Cooperative Extension Service, Clemson University, South Carolina. January 1990.

35. U.S. Department of Agriculture. Usual planting and harvesting dates for U.S. field crops. National Agricultural Statistics Service. Agricultural Handbook No. 628. December 1997.

36. National Council of Radiation Protection and Measurements. Radiological assessment: predicting the transport, bioaccumulation, and uptake by man of radionuclides released to the environment. NCRP Report No. 76. Bethesda, MD. 1984.

37. Moore MS. Critical pathway assessment of the Savannah River Site, Aiken, South Carolina. South Carolina Department of Health and Environmental Control. May 2002.

38. Advanced Technologies and Laboratories International, Inc. Combining sources of air releases for the SRS dose reconstruction. June 5, 2003.

39. Advanced Technologies and Laboratories International, Inc. Source term analysis (under preparation).

40. Advanced Technologies and Laboratories International, Inc. Distribution coefficients for radionuclides considered in the dose reconstruction of Savannah River Site. June xx, 2003.

41. Chaki S, Parks B. CAP88-PC version 2.1 updated users guide (beta version). Ch.12, p.8. September 2000.

42. U.S. Department of Energy. Savannah River Site high-level waste tank closure final environmental impact statement. DOE/EIS-0303. May 2002.

43. U.S. Environmental Protection Agency. EPA soil screening guidance for radionuclides. Users guide. EPA/540-R-00-007. October 2000.

44. U.S. Environmental Protection Agency. Risk assessment guidance for superfund: volume I human health evaluation manual (part D, standardized planning, reporting, and review of superfund risk assessments). Final. Publication 9285.7-47. December 2001.

45. U.S. Environmental Protection Agency. Radionuclide table: radionuclide carcinogenicity – slope factors. Federal Guidance Report No.13, Morbidity Risk Coefficients, in Units of Picocuries. 2003. *http://www.epa.gov/radiation/heast/docs/heast2_table_4-d2_0401.pdf*.

46. Cook JR, Phifer MA, Wilhite EL, Young KE. Closure plant for the E-area low-level waste facility. Rev. 2. WSRC-RP-2000-00425. Westinghouse Savannah River Company, Aiken, South Carolina. September 2, 2002.

47. Cook JR, Wilhite EL. Analysis of disposal of lead in the E-area low-level waste facility. WSRC-TR-2002-00101. Westinghouse Savannah River Company, Aiken, South Carolina. February 20, 2002.

48. Hamby DM. A probabilistic estimation of atmospheric tritium dose. Health Physics 65(1):33-40. July 1993.

49. Hubbard JE, Engelhardt M. Calculation of groundwater recharge at the old SRP burial ground using the CREAMS model (1961-1986). Memorandum. July 31, 1987

50. Johnson JE. Sulfur-35 releases from reactor areas. Dupont Interoffice Memorandum to CM Patterson. Savannah River Plant. RAC reference no. SKR1994020129. July 19, 1962.

51. Napier BA. [personal communication with Joyce WE, ATL] 2003 Mar 4.

52. Napier BA. [personal communication with Joyce WE, ATL] 2003 June 9.

53. Napier BA. [personal communication with Joyce WE, ATL] 2003 Mar 31.

54. Napier BA. [personal communication with Joyce WE, ATL] 2003 Feb 12.

55. National Oceanic and Atmospheric Administration, National Climactic Data Center. 2002 local climatological data (LCD) annual summary with comparative data, Augusta, Georgia. ISSN 0198-1587. 2003.

56. Oak Ridge National Laboratory. Food chain models for risk assessment, Appendix F. Risk Assessment Information System. 2002 Jul 1. *http://risk.lsd.ornl.gov/homepage/bjcor271/appf.shtml*.

57. Phifer MA, Collard LB. Unreviewed disposal question evaluation: backfill soil compaction requirements. WSRC-TR-2003-00081. Westinghouse Savannah River Company, Aiken, South Carolina. February 6, 2003.

58. Till JE. Final report, Savannah River Site environmental dose reconstruction project, phase II: source term calculation and ingestion pathway data retrieval, evaluation of materials released from the Savannah River Site. Risk Assessment Corporation. Neeses, South Carolina. April 30, 2001.

59. Wild EW, Brigmon RL, Berry CJ, Altman DJ, Rossabi J, Looney BB, Harris SP. D-area drip irrigation-phytoremediation project: SRTC final report. WSRC-TR-2002-00080. Westinghouse Savannah River Company, Aiken, South Carolina. January 2003.

60. Westinghouse Savannah River Company. Savannah River Site environmental report for 1990. WSRC-IM-91-28. Aiken, South Carolina. 1991.

61. Westinghouse Savannah River Company. Savannah River Site environmental report for 1991. Aiken, South Carolina. 1992.

62. Westinghouse Savannah River Company. Savannah River Site environmental report for 1992. WSRC-TR-93-075 and -077. Aiken, South Carolina. 1993.

APPENDIX G SYSTEM IMPLEMENTATION

G.1 Introduction

This appendix describes how the GENII-V2 computer was implemented to create an integrated system for the Dose Reconstruction Project at the Savannah River Site. The first step in the implementation was the understanding how GENII-V2 could be used to implement the requirements for this project. An analysis of the scope of the problem identified the following: 1) upwards of 40 unique locations for exposure, 2) approximately 17 releases points, 3) 39 years of release data, 4) approximately 25 isotopes released, 5) both atmospheric and liquid releases, 6) six different age groups for most exposure locations, and 7) each receptor's dose output was needed by isotope and pathway. In addition there could be up to 100 uncertainty/sensitivity runs for each of the above runs.

Several tasks were identified to reduce the scope of the calculations. These included reducing the number of locations to 10 and combining the release point to 4. There understanding the GENII-V2 methodology, it was concluded that based on assuming that GENII-V3 calculated doses for a receptor was of known age and know usage rates/ exposure times, additional doses/risks could be produced for a receptor of any age and any usage rate/ exposure times. It was also found that doses could be generated for receptors at 10 different exposure locations within a given GENII-V2 computer run. At this point a single GENII-V2 input file (GID file) consisted of over 8,000 lines of data in a text format. Manually setting up and verifying the input for these runs, and ensuring that the input is successfully activating GENII-V2 would require a significant labor commitment and risk creating input errors. A single output file consisted of over 2 megabytes of data in a comma delimited text format. Reading and analyzing the output would also require a significant labor commitment and also incur potential errors.

It was concluded that the process of generating, running and analyzing a GENII-V2 analysis would require automation. It was decided that two separate programs would be generated: a preprocessor to generate input files and a postprocessor to "read" the output and prepare output suitable for further analysis. Automating the input activities using a customized pre-processor interface to GENII-V2 would result in faster and less labor-intensive modeling efforts, and reduce the likelihood of data input errors. In addition, a post-processor would read and extract GENII-V2 output (HIF) files based on the user's requirements.

The System Architecture is discussed in Chapter G.2, Details of the computer programs are presented and Chapter G.3, Pre-Processor, and Chapter G.4, Post-Processor. Testing of the computer programs discussed in Chapter G.5.

G.2 System Architecture

The pre-processor and post-processor modules were both written in Microsoft Visual Basic and use Microsoft Access database table structure and calculations. Due to the limitation and no thread capability of the Access database, any database file stored in Access can not be larger than 2GB of data. Thus, the SRSDR system was designed by using dual database files, one was for application and parameter tables, and the other was for temporary and processing data tables. This method provides the capability to compact and optimize the temporary database files without interrupting the processing of data. Also, since the program requires a large amount of disk space and time to run, the data for each facility will be run independently. Both the pre- and post-processor run on distributed client systems, with the required input files for both modules located on each client system. The output for the post-processor is written to the Access database for the appropriate receptor family located on a shared network drive.

The overall scheme for generating a series of GID files consists of a series of loops. All process operations are table driven within the database. Once the user specifies the facility, the type of release, the years desired, whether uncertainty is to be run, and file names, the pre-processor will loop over the isotopes within the release file and loop over the number of runs to be created, generating a GID file for each completion of a loop over the number of runs. These output files are stored in the local hard drive to be used by GENII-V2 for calculation. At the same time when generating the GID files, each file name and its location path is written to a batch file to be execuate by the integrated GENII-V2 system, and a list of the file information is written to the QC file for quality assurance purpose.

The post-processor takes in a set of GENII-V2 output (HIF) files for a given facility and prepares a set of dose/risk results for the receptors designated in the scenario requirements for that facility. It will then combine the facility based results to form results for the entire site once all the facility results are available. The post-processor has the capability of providing various levels of results depending on the user input. The post-processor output is written to the Access database for the appropriate receptor family located on a shared network drive.

Figure G-1 illustrates these system modules, and briefly describes the input flow for each module.

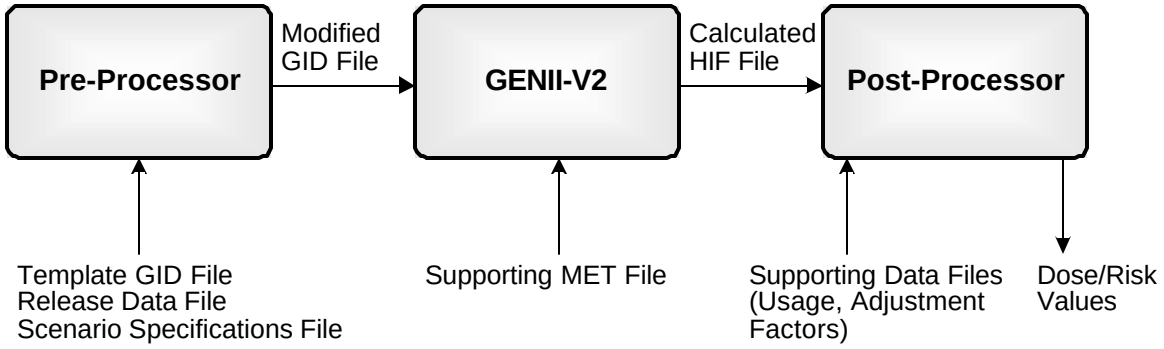

Figure G-1 System Module Input Flow

G.3 The Pre-Processor

The pre-processor will take a standardized GENII-V2 input file (GID file) and make changes in the standardized GID to account for varying facilities releases by isotope, year of operation and receptor combination. In addition, for each facility, year, and receptor combination, there could be up to 101 GID files generated as required by the uncertainty analysis (one for the point estimate data and 100 for the uncertainty data).

The overall processing was designed to proceed in the following fashion.

- Read user-specified input.
- Read template (standardized) GID file(s) as required.
- For a user specified facility and release type (atmospheric or liquid).
- Read the isotope description data file.
- Read the uncertainty data files (both the source term and parameters) to determine the point estimate and the set of uncertainty values for each parameter in the file.
- Cycle over the available standardized GID files.

- Modify the standardized GID data for changes required only once.
- Cycle over the years of operation.
- Cycle over the number of uncertainty runs (There will always be one run to evaluate the point estimate data.).
- Prepare the release data by isotope.
- Prepare the values for the parameters in the uncertainty file.
- Generate an input file for execution by GENII-V2.

G.3.1 The Pre-Processor User Interface

The user selects the pre-processor module from the SRS Dose Reconstruction System (SRSDRS) main menu screen, as shown in Figure G-2.

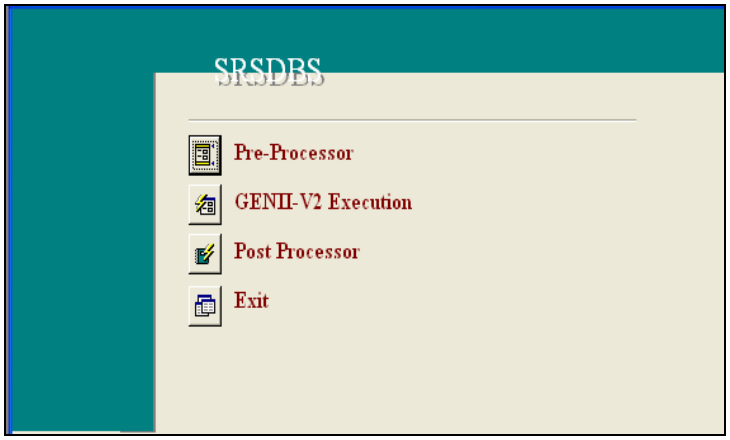

Figure G-2 SRSDRS Menu Screen

The user then enters the following information:

- Facility name and ID,
- The type of release (atmospheric and liquid), and
- The year or range of years for processing the source terms,

The Pre-Processor user interface screen is shown in Figure G-3. Table G-1 describes the type of information that should be entered into the screen.

Based on the information entered into this screen, the user is presented with a list of facility release data files that comply with the above requirements. The list of files is composed of files with names having the format of ABCDEFX.XLS where

- A is the type of release (A for atmospheric, and L for liquid),
- B is the facility ID,
- CD is the last two digits of the first year of releases,
- EF is the last two digits of the last year of releases, and
- X is the version.

NOTE: *The year or range of years required by the user must be contained between the years specified by CD and EF. The user will be asked to select the file name containing the appropriate release data.*

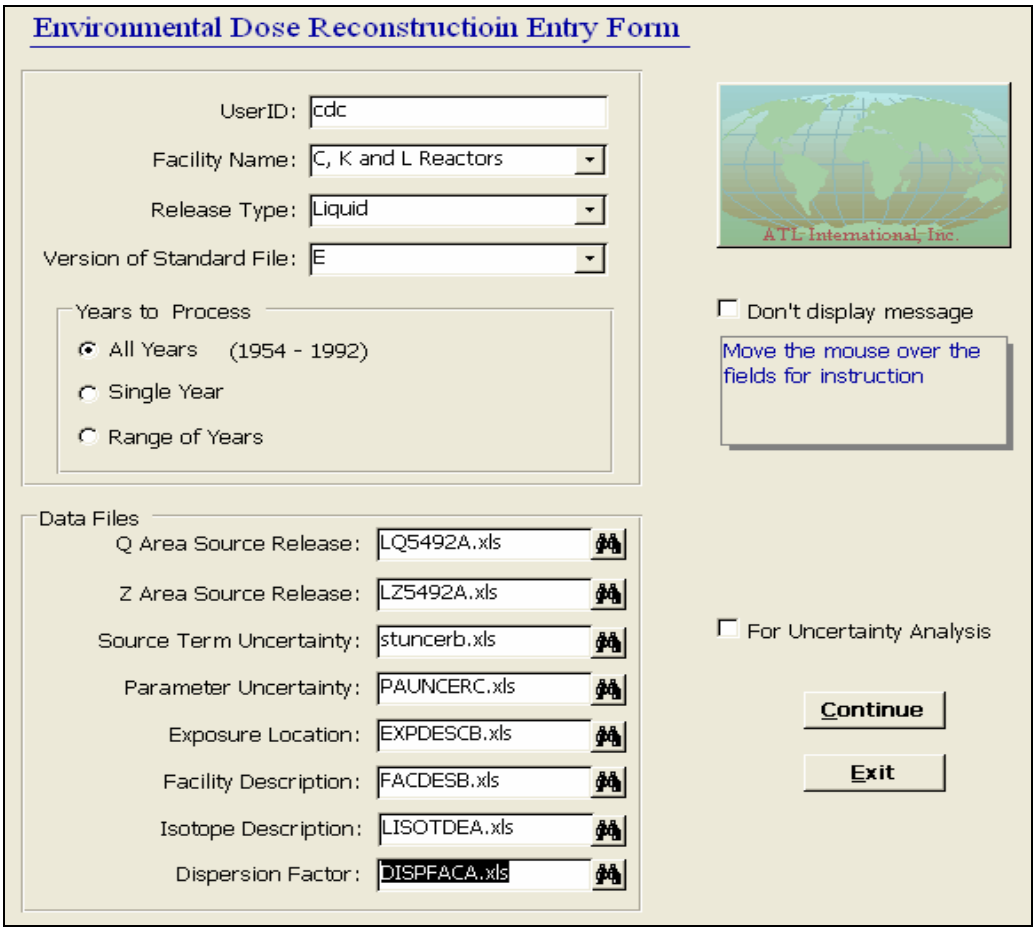

Figure G-3 Pre-processor User Interface Screen

Table G-1 Data Entry for the Pre-processor User Interface Screen

Field Name	Description
User ID	Enter the user ID to identify the person who runs the program.
Facility Name	Select the facility name from the dropdown menu. Available facility names include A M & SRL, H&F Area, C K & L Reactors, P&R Reactors, and All Site Liquid Release
Release Type	Select the release type from the dropdown menu. Available release types include Atmospheric and Liquid.
Version of Standard File	The identification code to the modified version of the standard template file.
Years to Process	Select the radio button corresponding to the appropriate year or range of years. Valid selections include 1954 - 1992, Single Year (enter the single year of your choice), and Range of Years (enter the year range of your choice).

Field Name	Description
Data Files	For each Data File type, select a data file from the dropdown menus. The dropdown menus that will be visible and the files that will be available for selection will depend upon the facility selected. These data files are described in more detail in the following paragraphs.

There are nine additional data files that the preprocessor needs to read. All of these files are EXCEL files and are located in the C:\CDC\Preprocessor\Input directory.

The user is prompted to select a file for the source term uncertainty file from a list of available files. The list is composed of files having names with a format of STUNCERx.XLS.

The user is then prompted to select a file for the parameter uncertainty file from a list of available files. The list is composed of files having names with a format of PAUNCERx.XLS.

The user is then presented with a list of exposure location description files available. The list is composed of files having names with a format of EXPDESx.XLS. The user is asked to select a file name.

The user is then presented with a list of facility description files available. The list is composed of files having names with a format of FACDESx.XLS. The user is asked to select a file name.

The user is then presented with a list of isotope description files available. The list is composed of files having names with a format of ISOTDESx.XLS. The user is asked to select a file name.

The user is then presented with a list of dispersion parameter files available. The list is composed of files having names with a format of DISPDECx.XLS. The user is asked to select a file name.

The user is then prompted to determine whether an uncertainty analysis is needed. If the user replies by checking the Uncertainty Run option, then the number of runs is needed to be selected, and that number of GID files will be prepared for each standardized GID file read. Otherwise, only the point estimate file will be prepared for each standardized GID file read.

NOTE: *If the user specifies an input that results in an incorrect value, such as a facility not contained in the facility description file, a facility without a release file, or year not within the range of years in existing release files, a message will be written to the message file and the pre-processor will abort.*

When data entry is complete, the *Continue* button will take the user to the pre-processor confirmation screen shown in Figure G-4.

Click the *Create GID* button on the Pre-processor Confirmation screen to generate the GID input file for GENII-V2. A message will be displayed that the GID has been successfully created.

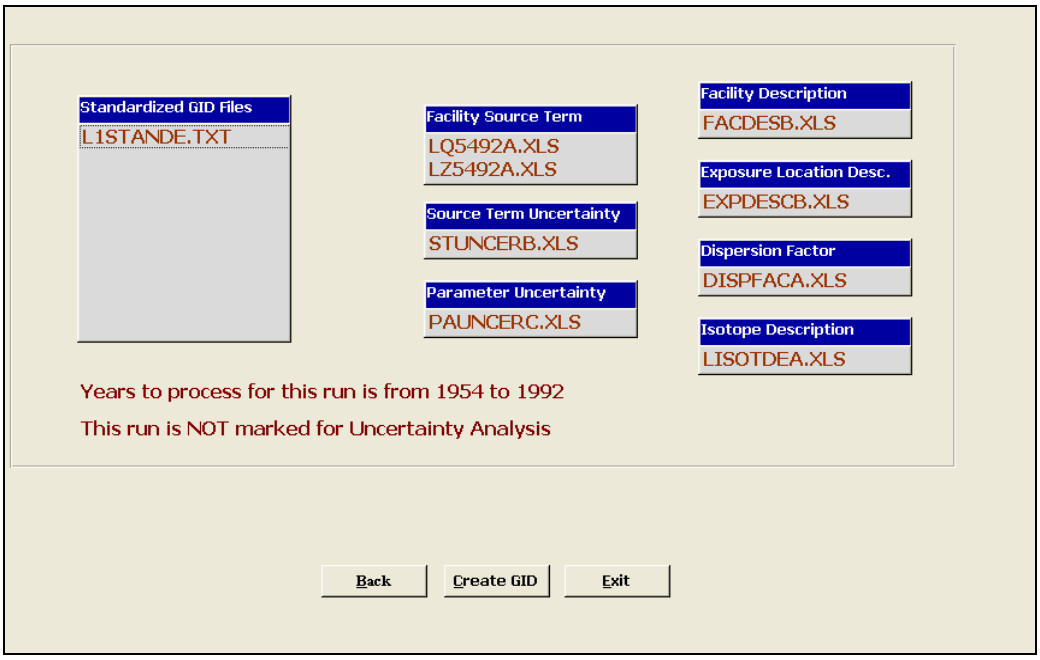

Figure G-4 Pre-processor Confirmation Screen

G.3.2 Standardized GID Files (Template Files)

The template files are located in the C:\CDC\Preprocessor\Input directory, they must have the TXT file extension. Their names have the following format: xySTANDz.TXT where

- x = A, L or S (A – Atmospheric, L – liquid)
- y = 1,2,3, or 4 is the number of depending on the total number of exposure locations, each template GID file can have up to 10 exposure locations
- z = A, B, C, etc depending on the total number of revisions that have been made to the template files

When the user has responded, the pre-processor must cycle through the appropriate number of template files with the release type and revision number specified by the user. For example, if the user has specified an atmospheric release and there are three atmospheric template files (that means more than 30 exposure locations in this scenario) , the file names will be A1STANDA.TXT, A2STANDA.TXT and A3STANDA.TXT assuming version "A" of the template file was specified. Therefore the pre-processor needs to read these three files.

The template GID files are ASCII files containing prepared input files suitable for execution by GENII-V2. These files contain data which will be modified by processing; however, the format (the number of lines, format of each line, etc) will not be changed. In general, each line within the GID file has the following format:

Variable Name
Seven index values
Two string values
A value in either an integer or string format.

There are many sections within a GID file, each section has a module ID, and the number of lines of data that follow for that module.

If there is an error in reading any of the template files, a message will be written to the message file and the pre-processor will abort. The message should contain the file name and the contents of the last line of data read. If possible, the line causing the error should also be written if possible.

G.3.3 Generating GID Files -- Processing Overview

The overall scheme for generating a series of GID files consists of a series of loops. Once the users has specified the facility, the type of release, the years desired, whether or not uncertainty is to be run, and file names, the pre-processor will loop over the number of years, loop over the isotopes within the release file and loop over the number of runs to be created, generating a GID file for each completion of the loop over the number of runs.

Some processing will need to be done only once and it will apply to all runs for a given facility, type of release and receptor combination (for a given template file). For atmospheric releases, one variable may have to be changed based on the release year. Some processing will need to be done for all runs. The processing requirements will be divided into atmospheric releases, and liquid releases. Presently, only the atmospheric processing requirements will be addressed. Some processing will refer to a section within the GID file such as “src” or “exp.” It should be noted that the label for a section is three characters followed by a number (such as src5 or exp21.) For some sections (exp, rcp and hei), the number is the exposure location index; for other sections (src, air, con), the number is just a number generated when the template file was created.

G.3.3.1 Atmospheric Release Processing -- Required only Once

G.3.3.1.1 Source Term Data

Two changes in the “src” section will need to apply for all runs (for all years and for both the point estimate and the uncertainty runs.) These include the variables “two” and “three.”

"two",3,0,0,0,0,0,0,"m","m",0
"three",3,0,0,0,0,0,0,"m","m",0

The value for two is the release height obtained from the facility description file. The value for three is the height of adjacent building obtained from the facility description file.

G.3.3.1.2 Air Dispersion Data

The ten “ARRADVAL” variables need to be read and adjusted to reflect the distances between the release facility and each exposure location. The ten values need to be put into increasing order. For some template files, there may not be 10 exposure locations or 10 different distances. In this case, the unused values can be filled with the smaller distances from the file.

In the “air” section the 10 values in the following variables need to be changed. These variables and values represent the standardized spacing between the 10 annular distances used by GENII-V2. The following presents a fragment from a GID containing these variables and values.

"ARRADVAL",1,1,1,0,0,0,0,"m","m", 805
"ARRADVAL",1,1,2,0,0,0,0,"m","m", 2414

```
"ARRADVAL",1,1,3,0,0,0,0,"m","m", 4023
"ARRADVAL",1,1,4,0,0,0,0,"m","m", 5632
"ARRADVAL",1,1,5,0,0,0,0,"m","m", 7241
"ARRADVAL",1,1,6,0,0,0,0,"m","m", 12069
"ARRADVAL",1,1,7,0,0,0,0,"m","m", 24135
"ARRADVAL",1,1,8,0,0,0,0,"m","m", 40255
"ARRADVAL",1,1,9,0,0,0,0,"m","m", 56315
"ARRADVAL",1,1,10,0,0,0,0,"m","m", 72405
```

As can be seen from the fragment, the first two indices are always 1. The third index is the ring number varying from 1 to 10 (the number of rings allowed by GENII-V2.) The values need to be changed to reflect more closely the distances from the release facility to each exposure location within the standardized GID file.

The 10 values are stored in a temporary matrix. The distances from the releasing facility to the each receptor are calculated within the template file. The data for each receptor is contained in the exposure location description file. The exposure location index from this file is the same as contained in the "expx" line of each "exp" section of the GID file. The facility X-UTM (Universal Transverse Mercator) and Y-UTM measurements are obtained from the Facility Description File associated with the facility ID requested by the user. The distance is calculated by the following formula:

Distance = square root $[(\text{Delta X-UTM})^2 + (\text{Delta Y-UTM})^2]$
Where Delta X-UTM = Facility X-UTM – Receptor X-UTM and
Delta Y-UTM = Facility Y-UTM – Receptor Y-UTM

The distances are inserted into the temporary matrix. The distances are then ordered from the smallest to largest distance.

If there are less than 10 exposure locations in the template file, the remaining unused values are not changed in the temporary matrix.

G.3.3.1.3 Exposure Location Data

The next item to be performed is the identification of the correct section of the GID file in which the exposure location name and easting and northing values are placed. The exposure location index (for example 1) will be combined with the string "exp" to form a new string of the form "exp1". This string will be used to search the GID file for the variable expName with that value (see the following fragment from a GID file.) The second index will be collected. The value for the expLabel (with the correct second index) will be changed if different than that contained in the exposure description file. The expX and expY (with the correct second index) for the location will be changed to the easting and northing values.

```
"expName",1,1,0,0,0,0,0,"N/A","N/A","exp1"
"expLabel",1,1,0,0,0,0,0,"N/A","N/A","Rural Family-Gaird,GA"
"expModel",1,1,0,0,0,0,0,"N/A","N/A","GENII V.2 Chronic Exposure Module"
"expDesPath",1,1,0,0,0,0,0,"N/A","N/A","\FRAMES\Gen_Exp.des"
"expX",1,1,0,0,0,0,0,"N/A","N/A",10
"expY",1,1,0,0,0,0,0,"N/A","N/A",10
```

To calculate the easting and northing, the following steps are performed:

The offset from the exposure location file is converted into radians by multiplying the offset in degrees by PI/180.

The angle "alpha" which is an angle in the UTM coordinate system is calculated by:

Alpha = inverse tan (DeltaY-UTM/DeltaX-UTM)

The magnitude of the distance easting in kilometers = Distance * cos(Alpha – offset) / 1000
The magnitude of the distance northing in kilometer = Distance * sin(Alpha – offset)/ 1000

If Delta Y-UTM is negative then the distance northing is negative. Similarly if Delta X-UTM is negative then the distance easting is negative.

G.3.3.2 Miscellaneous Processing

The site name is read from the template file. The year of the release and facility is added to the SiteName and a new site name is written.

For each "xxxModelStat" variable (such as "rcpModelStat") the value is 1 except for the "conModelStat" which should be set to 2.

For each "ModState" variable, the value is 1.

G.3.3.3 Processing Over Release Years

The meteorological file name, obtained from the Dispersion File, is inserted into the value for the variable ARMETFILE.

"ARMETFILE",1,1,0,0,0,0,0,"N/A","N/A","C:\FRAMES\SRS7579.5YR"

G.3.3.4 Processing Over Uncertainty Runs

Once the above changes have been made, the pre-processor cycles over the number of required years processing the release data, the uncertainty data for the source term, and the parameters for each year desired. The description of the processing is divided into processing the source term data and processing the parameters in the parameter uncertainty file. Once the processing over a given uncertainty run, a GID file is created.

G.3.3.5 Source Term Processing

For each isotope, the lines in Example G-1 need to be read from the template file, processed, and modified as necessary and written. There are always at least these lines for every isotope with the initial release quantities. A "casid" line will be followed by two sets of "ctime" lines. Within each set of "ctime" lines there will be one or more "cflux" lines. The number of "cflux" lines per "ctime" line pairs will be dependent on the number of flux types for each type of release (at least two flux types for atmospheric releases and one flux type for liquid release).

The following is a partial example of an atmospheric release with two flux types (CO60 was the first isotope in this example).

Example G-1

```
"casid",3,1,0,0,0,0,0,"yr","pCi/yr","CO60"
"ctime",3,1,0,1,0,0,0,"yr","yr",0
"cflux",3,1,0,1,1,0,0,"pCi/yr","pCi/yr",0
"cflux",3,1,0,1,2,0,0,"pCi/yr","pCi/yr",10
"ctime",3,1,0,2,0,0,0,"yr","yr",100
"cflux",3,1,0,2,1,0,0,"pCi/yr","pCi/yr",0
"cflux",3,1,0,2,2,0,0,"pCi/yr","pCi/yr",10
```

Table G-2 contains the meaning of each of the seven indices used within the source term data section.

Table G-2 Index Values for Source Term Data

Index Position	Value	Meaning
	Cflux	
1	0	Not Used
	1	Not Used
	2	Liquid Release
	3	Atmospheric Release
	4	Not Used
2		Isotope Index
3		Daughter Index
4	1	First Time Period
	2	Second Time Period
5		Flux Type
6 and 7		Not Used

For some isotopes, there may be a “casid” line with the third index as 1. These lines are not changes. These are daughters of the isotope. The amounts of these daughters will have initial releases of zero (no cflux lines).

The processing of the isotope data begins with a “casid” line containing the isotope name and isotope index. There will be two “ctime” lines each followed two or more “cflux” lines. Each “ctime” line starts the release data for a given time. Each “cflux” line contains the release data. The pre-processor will read the facility release file for the quantity of isotopes released by year. From the Atmospheric Isotope Description file, the pre-processor will obtain the isotope index and flux type associated with the isotope name. From the Source Term Uncertainty file, the preprocessor will obtain a set of scaling factors for the point estimate and uncertainty runs. The preprocessor will cycle over the required years. For each year, the pre-processor will cycle over the point estimate values and the 100 uncertainty files (if desired), by isotope, changing the values contained in the GID file as necessary. For a given isotope, the released value is the quantity released, from the Source Term File, multiplied by the quantity of $1x10^{12}$, multiplied by the appropriate factor in the Source Term Uncertainty File. The resulting value is entered in both “ctime” groups. Only one “cflux” line within each “ctime” group will be changed (the “cflux” line with the correct isotope index and the flux type.) The remaining “cflux” lines will remain with a zero release.

In summary, only the values in two lines for each isotope are changed. These are the "cflux" values for the correct "cflux" type, one in each "ctime" group.

If there are isotopes contained in the template file for which the release is not changed, the values should be changed to zero. A message will be written to the message file.

G.3.3.6 Parameter Uncertainty Data

The processing for the parameter uncertainty data is driven by the data within the Parameter Uncertainty File. This file contains a list of parameters for which a point estimate and 100 uncertainty data values are provided. Each parameter is identified by a variable name, isotope name (if applicable) and a series of three indices. An additional index is also provided to allow a parameter to be changed from exposure location to exposure location. Since the list of parameters is provided by tabular input, specific sections within a GID file cannot be identified. The pre-processor will search the template file for a match with a variable name and its three indices. If the exposure location index is zero, then all occurrences of the variable name and its three indices are changed. If the exposure location index is not zero, the variable for the specified exposure location is changed.

If any parameter contained in the Parameter Uncertainty file is not used, a message will be written in the message file.

G.3.3.7 Creating a GID File

Once the processing is completed for a given point estimate or uncertainty run, a GID file can be generated. The GID file will be comprised of all the lines in the template file with the appropriate values changed as describe above. The output GID file will be written to a folder in C:\CDC\GENIIV2\Input with a name as specified as follows:

ABCDEFGH.GID

where:

- A is for atmospheric release,
- B is the second character of the standardized GID file,
- C is the facility ID,
- DE is the last two digits of the year of the release, and
- FGH is a number that varies from 000 (the point estimate) to 100 (the number of the uncertainty runs).

G.3.4 Generating Other Output Files

There are three output files other than the GID files used for input into the GENII-V2 calculation. These are: a QCQA file, a batch file and a message file.

Each file name will have the following format:

ABCDEFG.xxx

Where

- A is the type of releases,
- B is the facility,

- CD is the last two digits of the first year of releases processed,
- EF is the last two digits of the last year releases processed,
- G is the version of the standardized GID file processed, and
- xxx is QA for the QCQA file, BAT for the batch file and MES for the message file.

The contents of each file are described below.

G.3.4.1 QC/QA File

This file contains information related to the documentation of the creation of the GID files. Included in this file are:

- The date of the pre-processor run,
- The version of the pre-processor run,
- The list of all the user inputs (user name, facility selected, type of release, the year or range of years chosen, files selected and date of the run),
- The list of GID files generated,
- The name of the batch file generated, and
- The name of the message file generated.

G.3.4.2 Batch File

This file contains the command line information for the execution of GENII-V2 of the GID files created. The file should also contain commands to delete all files created by GENII-V2 except for the GID file used as input and the "HIF" file once GENII-V2 has completed processing a GID file. The commands move each processed "GID" file and "HIF" file to a folder of completed runs..

G.3.4.3 Message File

This file contains all messages generated by the pre-processor. Messages could consist of two types. The first type are messages generated to document such items as parameter variables that are not processed, such as a parameter variable in the Parameter Uncertainty File. These are merely information messages and not errors. This situation could arise during the pre-processing when a parameter included in the file is not appropriate for the type of release calculated (such as a parameter which relates to a liquid release and the type of release being processed is an atmospheric release.) The second type of message results from an error having occurred during the processing. Error messages could be generated from any of a number of reasons. These include:

- An isotope contained in the facility release data that is not found in the Isotope Description file,
- An isotope release quantity set to zero when its data is not included in the Facility Release File,
- A facility ID contained in the facility release data that is not found in the Facility Description file
- A receptor found in the standardized GID that is not contained in the Exposure Location Description file.
- A Mismatch in the number of uncertainty values in the source term and parameter uncertainty files, and
- A file missing or misread.

If an error message is generated, the pre-processor will immediately write the message to both the message file and to the screen. Then the pre-processor will abort.

G.4 The Post-Processor

Briefly, the post-processor will read a calculated GENII-V2 output file (HIF file) for a given facility, and will also read user-defined report parameters (Pathway file), and prepare a set of dose/risk results for the receptors designated in the scenario requirements for the facility. It will then combine the facility-based results to generate results for the entire site once all the facility results are available. The post-processor has the capability of providing various levels of detail depending on the user input. The primary level of detail will be the Total Effective Dose Estimate (TEDE) and the effective cancer incidence and cancer fatalities by scenario receptor. The most detail will consist of the dose and risk numbers by organ, year, exposure pathway, isotope, and facility.

For the first stage, the post-processor "reads" a set of HIF file(s). The set of HIF files could consist of up to 3939 output files for a given facility (39 years of releases times up to 101 runs per year.) The post-processor also reads two files containing the scenario receptor description and behavior. One file contains the year of birth of each receptor. The second file contains data where each receptor is located and what they consume, the consumption rates, and duration that they are at the location. The post-processor also reads a file of dose conversion and risk conversion factors. The post-processor uses this data to adjust the GENII-V2 output results to account for each receptor's behavior and age. As an intermediate result, the post-processor will produce a table of results for each scenario receptor that includes the dose/risk results specified by the user for up to 101 runs by release year. Once all facilities have been processed, a final table of results is produced combining all of the intermediate results by facility into the doses/risks on a site basis.

For the second stage, the post-processor reads each facility's results and combines them into the results for the site.

The following briefly describes the flow of information processing, as shown in Figure G-5:

- The user-specified input data is read: Facility ID, Release Type (Air or Liquid), Pathway File, and Year(s)
  - The Facility IDs available for selection depend upon the Release Type.
    If *Atmospheric* is selected for Release Type, then:
    Facility IDs will include the following:
    A, M and SRL; C, K, and L Reactors; H and F Area; and P and R Reactors
    If Liquid is selected for release type, then:
    Facility IDs include the following: AllSiteLiquidRelease
  - The years desired (from 1954 to 1992).
  - Number of uncertainty runs (from 0 to 100).
  - The level of detail:
    Total Effective Dose/Risk of cancer incidents and cancer fatalities.
    Dose/Risk values by organ, exposure pathway, isotope and years.
  - The Receptor names.
- The specified Pathway file is loaded to the database table.
  - The pathway file contains the usage factors for each exposure location corresponding to the receptor(s) under study.

- The Risk and Dose factor file is loaded to the database table.
  - The Risk Factor file contains the risk factor value for each body organ by isotope by pathway by age.
  - The Dose Factor file contains the dose factor value for each body organ by isotope by pathway by age.
- The GENII-V2 generated HIF file is read. Each HIF file contains sets of dose and risk value for each body organ by exposure location.
  - Exposure location (for example, hei1) is read.
  - Under each exposure location, the data for each isotope is read.
  - For each isotope, the data for every possible pathway is read.
  - For each pathway, read the dose and risk data for each organ is read.
    The Risk and dose factors based on age of the user-specified receptor(s) are applied.
    The Usage or Exposure Factor based on the age of the user-specified receptor(s) are applied.
- Is this the last exposure location?
- If yes, then report is generated.
- If no, then the next exposure location is read.
- Cycle through all exposure locations, isotopes, and associated pathways and organ dose data, as described above.
- A report is generated.

The calculations performed by the post-processor involve the following:

- Determination of the age of the receptor (the difference between the year of birth and current year processed).
- Based on the receptor's age, the correct dose factors, risk factors are obtained and usage/exposure factors by pathway, isotope and organ.
- Multiply the values for the doses/risks in the HIF File by the dose and risk factor for the correct age of the selected recipient(s).
- Divide the adjusted doses by the dose factor for the adult receptor (used in GENII-V2) year period.
- Divide the adjusted risks by the risk factor for the 0-110 age receptor.
- Multiply the results of the above calculation by the receptors usage/exposure factor.
- Perform summations as indicated by the user input choices, such as summation over isotopes for a given pathway/route, summation over isotopes and pathway/routes, etc.

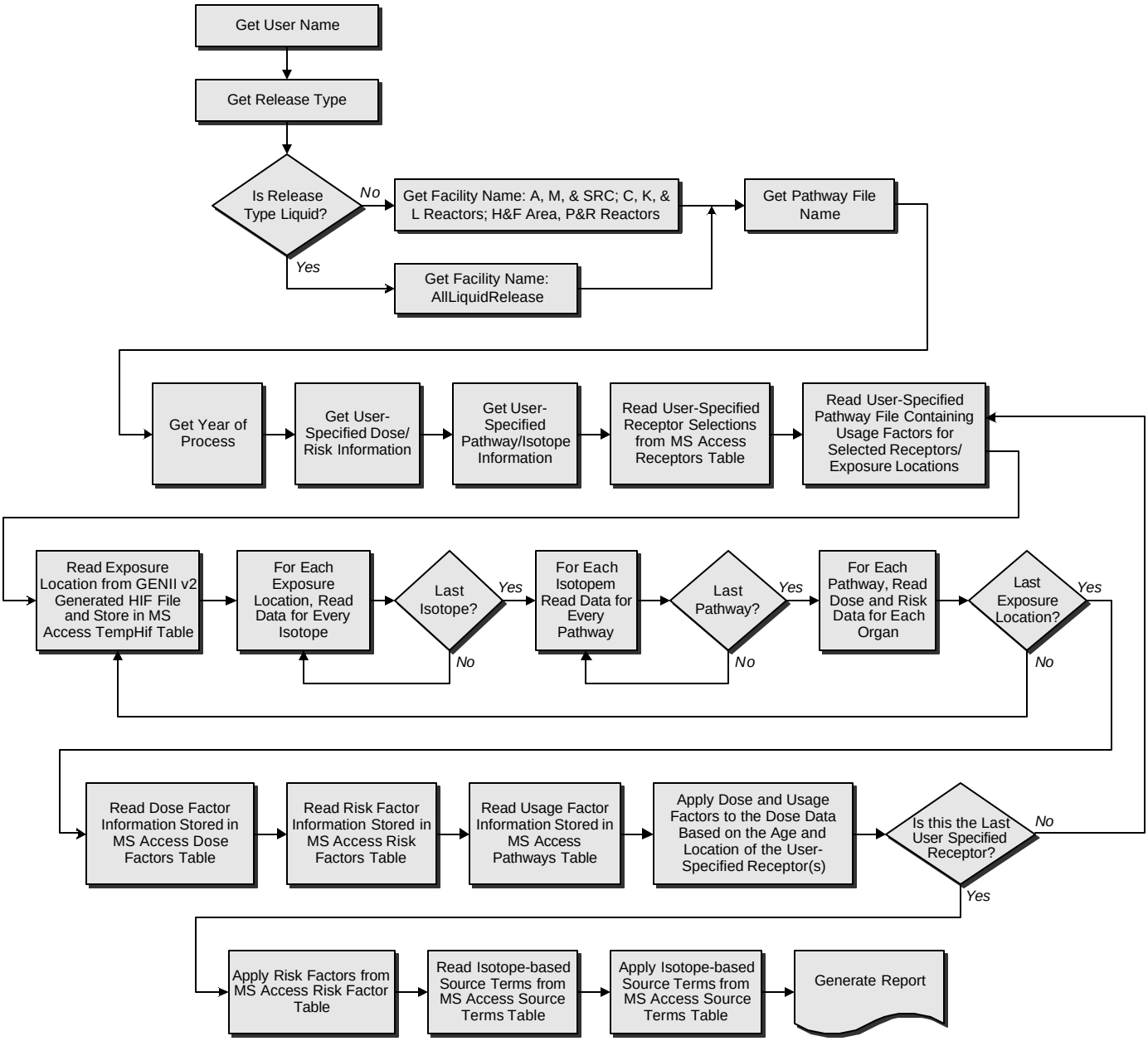

Figure G-5 High-level Post-Processor Process Flow

G.4.1 The Post-Processor User Interface

The post-processor user interface is composed of the following tabs. Information entered into each of these tabs determines the content of the post-processor output report.

G.4.1.1 The General Information Tab

In the General Information tab, as shown in Figure G-6, the user inputs the *User Name*, and selects the *Release Type* and *Facility Name* from dropdown menus. *Release Type* includes *Atmospheric* and *Liquid*, and *Facility Names*. Facility Names will be provided based on the selected release type. For atmospheric the available facility types are "A, M and SRL", "F and H Area", "C, K and L Reactors", and "P and R Reactors". For liquid releases, only one facility name will be provided: "All Site Liquid Release". The user specifies the *Pathway Data File*, which is an Excel spreadsheet containing data about the selected pathway type. This value may either be keyed directly, or the user must browse to locate a file. *Years to Process* may include *All Years (1954 – 1992)*, *Single Year*, or *Range of Years*. The user enters the desired range if this option is selected. All values of dropdown menus are stored in Access lookup tables. The post-processor uses the information entered by the user on this screen to determine the exposure location, release type, and which pathway table to read. The dose and risk factors that will be applied during the calculation of the effective dose over time will be determined by these values. Table G-3 provides descriptions of the General Information fields.

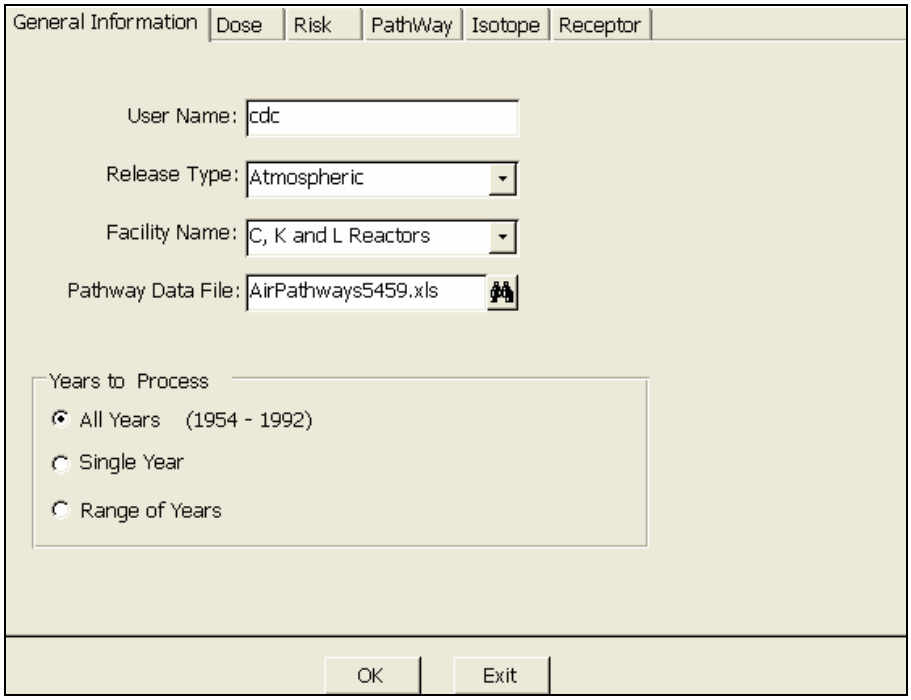

Figure G-6 General Information Tab

Table G-3 Field Descriptions for the General Information Tab

Field Name	Description
User Name	Enter a user name to identify the person who creates the reports.
Release Type	Atmospheric or Liquid.
Facility Name	Based on the release type a list of available facilities is displayed in a drop down box. The user can then choose any one facility from the list.
Pathway Data File	Brows to select a data file. The files that will be visible to you will depend upon the selections made for Facility Name and Release Type.
Years to Process	Select the radio button corresponding to the appropriate year or range of years. Valid selections are based on the range of years determined in the source term files available for use based on the above user selections.

G.4.1.2 The Dose Tab

The user selects *Total Effective Dose Estimate (TEDE)* or *By Organs* to control the amount of dose information presented in the results report. If *By Organs* is selected, the user must select which organs are to be included in the report. Selected organs are then stored in an Access temporary table to be referenced during Post-processor calculations.

Figure G-7 shows the Dose Tab, with "By Organs" selected. Figure G-8 shows the Dose Tab with TEDE selected.

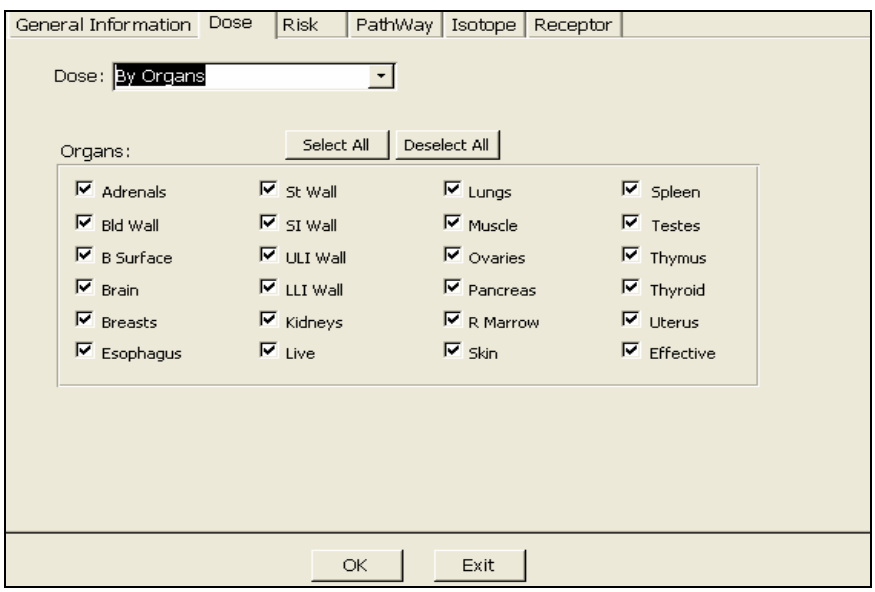

Figure G-7 The Dose Tab, "By Organs" Selected

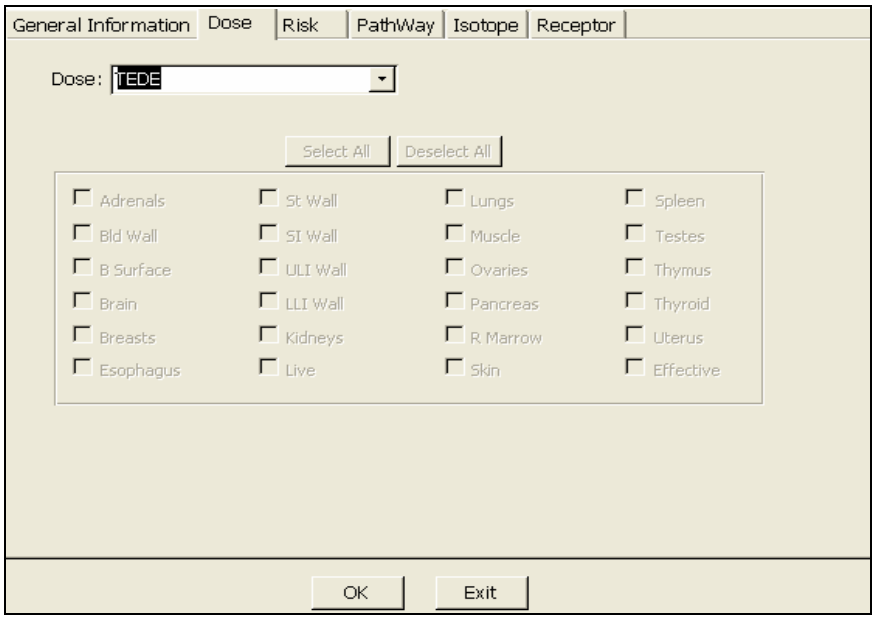

Figure G-8 The Dose Tab, "TEDE" Selected

G.4.1.3 The Risk Tab

This tab is used to calculate the cancer risks. The user elects whether to create the results report with or without cancer results. If the user chooses *With Cancer Results,* two selections become available, *Cancer Incidents,* and *Cancer Fatalities.* When the user selects one or both of these options, a list of organs becomes available. The user may select all, or select specific organs to be included in the report.

Figure G-9 shows the Risk Tab with "No Cancer Results" selected. Figure G-10 shows the Risk Tab with cancer results.

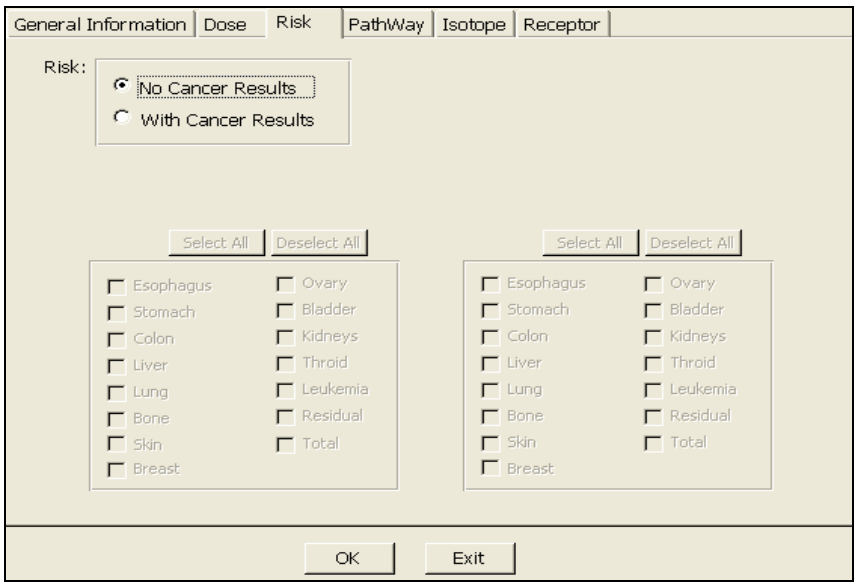

Figure G-9 The Risk Tab, "No Cancer Results" Selected

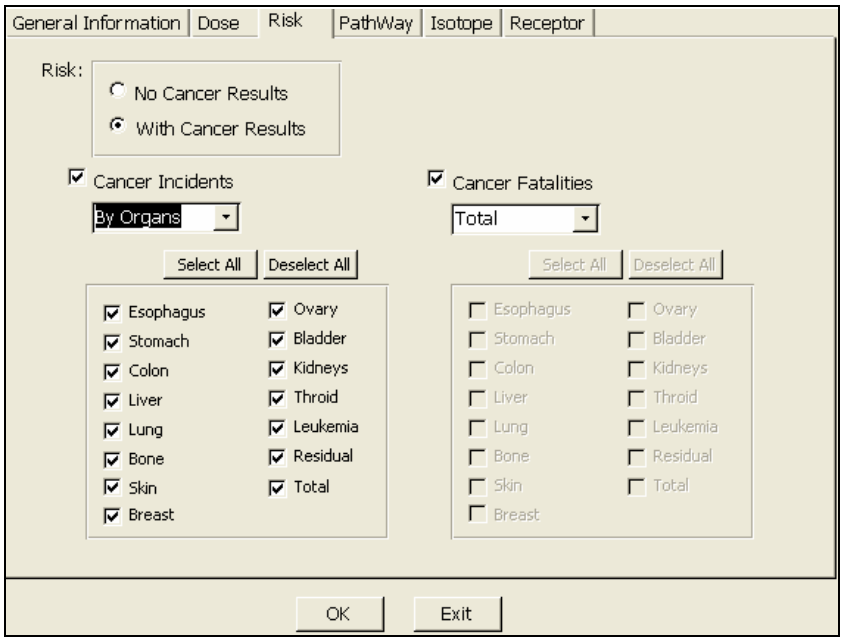

Figure G-10 The Risk Tab, "Cancer Results" Selected

G.4.1.4 The Pathway Tab

This tab controls how the results are displayed for the various pathways (*Summed Over All Pathways,* or *By Pathway)*. If *By Pathway* is selected, a listing of pathways becomes available. The user may select all, or select specific pathways. Doses and/or risks will be presented for the selected pathways. Depending upon the selections the user makes on this tab, information on this tab is used to build the query for the results report. If pathways are selected that are not included in the GENII-V2 HIF file, they will not be included in the report file. Figure G-11 shows the Pathway tab, with *By Exposure Pathways* selected.

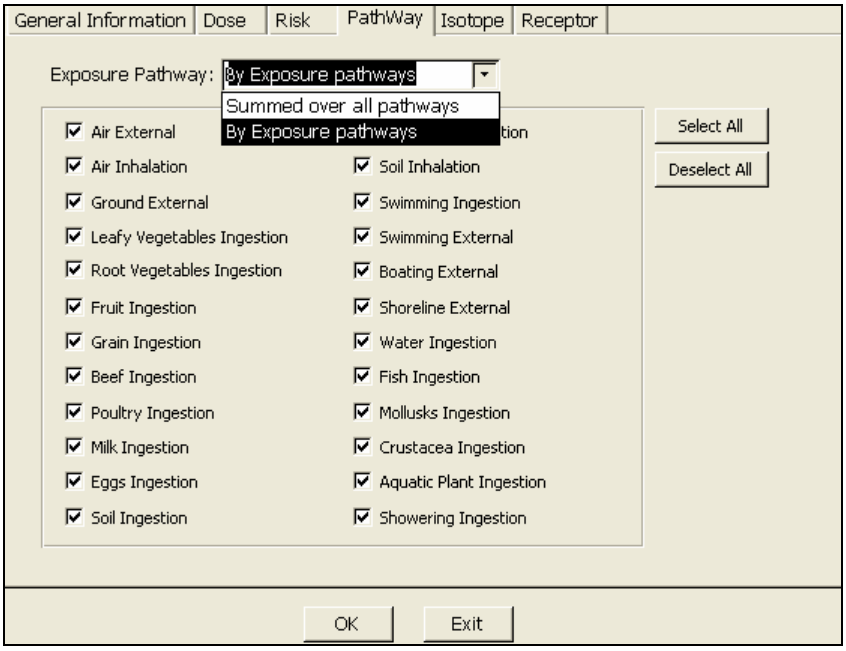

Figure G-11 The Pathway Tab, "By Exposure Pathways" Selected

G.4.1.5 The Isotope Tab

This tab is used to control the display of results as a function of isotopes (*Summed Over All Isotopes*, or *By Isotope.)* If *By Isotope* is selected, a listing of isotopes becomes available. The user may select all, or select specific isotopes. Results will be displayed for the selected isotopes only. Isotope names are stored in an Access lookup table. Information selected on this tab is used to build the query for the results report. If isotopes are selected that are not included in the GENII-V2 HIF file, they will not be included in the report file.

Figure G-12 shows the Isotope Tab with "Summed Over All Isotopes" selected. Figure G-13 shows the Isotope Tab with "By Isotope" selected.

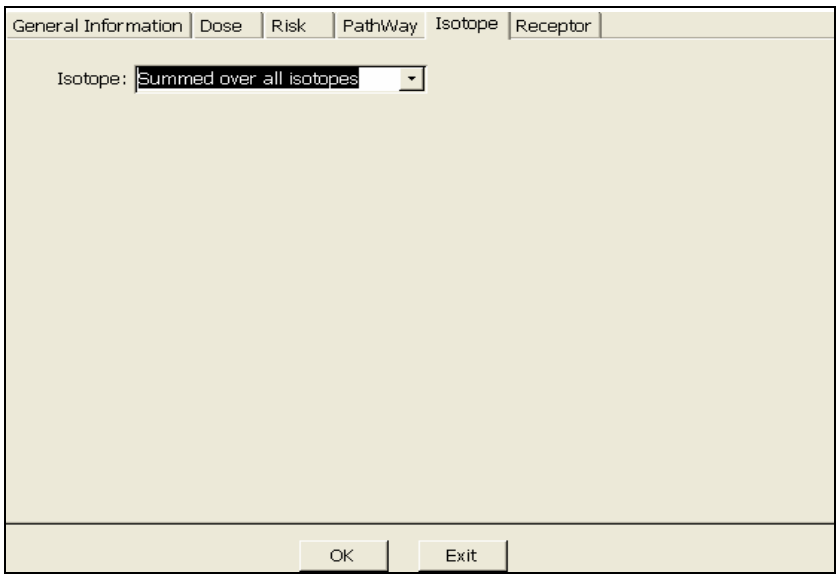

Figure G-12 Isotope Tab, "Summed Over All Isotopes" Selected

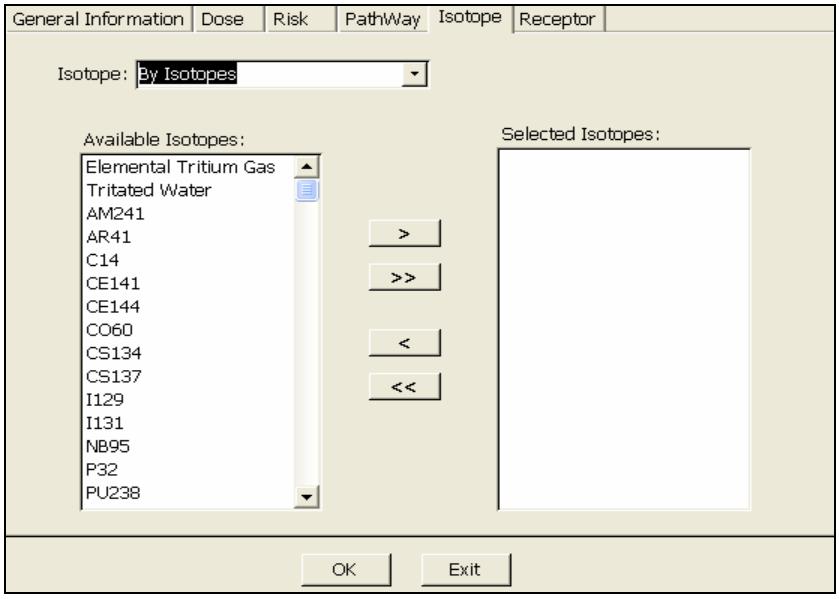

Figure G-13 Isotope Tab, "By Isotope" Selected

G.4.1.6 The Year Tab

The user selects *Summed over all years* or *By year* to control the detail of dose information presented in the results report. If *Summed over all years* is selected, the output result will be the total of the range of years. If *By year* is selected, the output result will be grouped by each year.

Figure G-14 shows the Year Tab with the "Summed over all years" or "By year" selections visible in the dropdown menu.

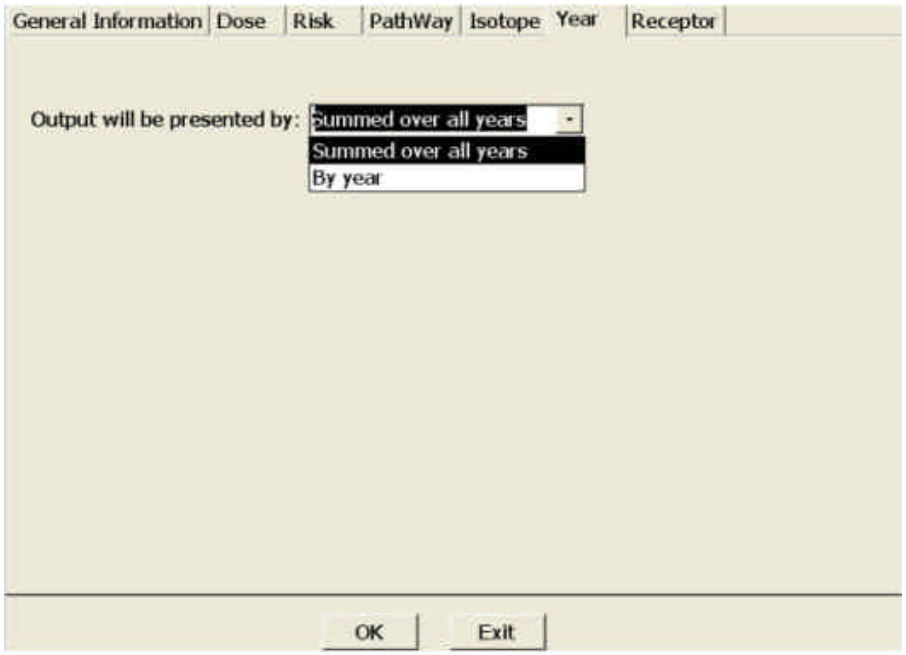

Figure G-14 Year Tab with "Summed over all Years" or "By Year" Selections Visible

G.4.1.7 The Receptor Tab

The user selects one or more possible recipients for which doses/risks will be calculated. User choices include: *All Family, Rural Family #1, Rural Family #2, Urban Family, Delivery Family, etc*. Information selected on this tab is read from the Access Receptor table, which contains fixed values.

At least one receptor must be selected to generate a report.

The post-processor will generated a dose/risk report for each selected receptor from the list based on the above user input information. Figure G-15 shows the Receptor Tab.

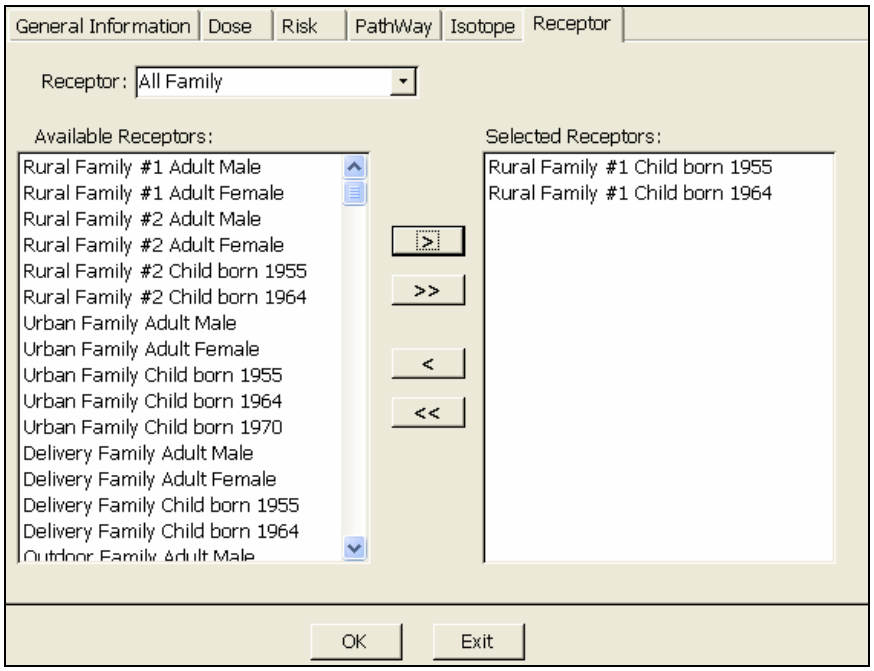

Figure G-15 The Receptor Tab

G.4.2 The Post-Processor Input File Requirements

There are three file types required for any given post-processor run. These include: 1) GENII-V2 output data contained in the GENII-V2 files with the HIF extension, 2) pathways behavior file (Usage factor), isotope description file, Dose adjustment file (Dose factor), and Risk adjustment file (Risk factor), and 3) data selected by the user from the post-processor user interface by facility, which will be used as input for developing site doses and risk numbers.

There are a total of seven input files required by the Post-processor:

- One HIF file, which will be determined by the system based on the user-input information
- One user-specified input file (Pathways)
- Five other supporting tables which are already loaded to the database during the system development cycle:
  - DoseFactor – contains adjustment values from the Federal Guidance Report 13 (1) for all isotopes, all pathways, all routes, all lung-classes, and all organs at all ages.
  - RiskFactor – contains adjustment values from the Federal Guidance Report 13 (1) for all isotopes, all pathways, all routes, all lung-classes, and all organs at all ages.
  - IsotopeNames – contain names of all radionuclides for both atmospheric and liquid releases.
  - IsotopeList – contains descriptions of isotopes such as isotope index number, daughter index if any, and its lung-class value.
  - Receptors – information of receptor's name, family name, and the birth year.

G.4.2.1 The GENII-V2 HIF File

GENII-V2 produces several output files during the execution of a given computer run. These files contain doses, cancer incidents, and cancer fatalities by exposure location, by isotope, by pathway, and organ. Due to the strict naming convention established in the pre-processor requirements, the post-processor can identify GENII-V2 results by type of release, facility, year of release, and uncertainty run ID. The filename has the standard format for GENIIV2 output, for example, ABCDE000.HIF:

Where

- A = A (atmospheric) or L (Liquid),
- B is the second character of the template file,
- C is the facility ID,
- DE is the last two digits of the year of the release, and
- FGH is a number that varies from 000 (the point estimate) to 100 (the number of the uncertainty runs).

The HIF files are ASCII files containing the generic values which were calculated by GENII-V2. These values are for each organ by all pathways by all isotopes. In general, each HIF file has ten sections, each section has a section header following by the number of lines in that section. A section header is three characters, “hei”, plus the exposure location number.

Within each “hei” section, there will two lines with organ names, one is the header for risk organs, and the other one is the header for dose organs, followed by a section for each isotope. Within each isotope section, there will be three lines for each pathway, the first two lines list the generic values for each risk organ, and the third line contains the values for the dose organs. Figure G-16 shows the contents of an HIF file:

```
"hei1",2069
  4,
 This GLYPH has data for  1 RECEPTOR sources.
 GENII VER 2.0 B1
Run on: 02-21-2004  at 11:57:17
  1,"chronic",
  1,
"chronic","exp1","Air",  1, 1, 18, 15, 24,
"Esophagus","Stomach","Colon","Liver",…….,"Thyroid","Leukemia","Residual","Total",
"Adrenals","Bld Wall","B Surface",…….,"Testes","Thymus","Thyroid","Uterus","Effective",
     11.1,"km",    -35.8,"km",
   0.,  70.,"yr",
"AM241","AM241", 0,   1,
     0.00,"yr",     1.000,"yr", 42,
       1.,"Air","external","risk","cancer incidence",
 3.20E-10, 3.10E-10, 2.40E-10, 0.00E+00, ......, 0.00E+00, 0.00E+00, 0.00E+00, 5.20E-08,
       1.,"Air","external","risk","cancer fatalities",
 3.10E-10, 3.40E-10, 2.40E-10, 0.00E+00, ......, 0.00E+00, 0.00E+00, 0.00E+00, 6.20E-08,
       1.,"Air","external","Sv","radiation dose",
 3.20E-10, 3.10E-10, 2.40E-10, 0.00E+00, ......, 0.00E+00, 0.00E+00, 0.00E+00, 7.20E-08,
…
…
"AR41","AR41", 0,   1,
     0.00,"yr",     1.000,"yr", 42,
       1.,"Air","external","risk","cancer incidence",
 0.00E+00, 0.00E+00, 0.00E+00, 0.00E+00, ......, 0.00E+00, 0.00E+00, 0.00E+00, 0.00E+00,
       1.,"Air","external","risk","cancer fatalities",
 0.00E+00, 0.00E+00, 0.00E+00, 0.00E+00, ......, 0.00E+00, 0.00E+00, 0.00E+00, 0.00E+00,
       1.,"Air","external","Sv","radiation dose",
 0.00E+00, 0.00E+00, 0.00E+00, 0.00E+00, ......, 0.00E+00, 0.00E+00, 0.00E+00, 0.00E+00,
…
...
"hei2",2069
"Esophagus","Stomach","Colon","Liver",…….,"Thyroid","Leukemia","Residual","Total",
"Adrenals","Bld Wall","B Surface",…….,"Testes","Thymus","Thyroid","Uterus","Effective",
     11.1,"km",    -35.8,"km",
   0.,  70.,"yr",
"AM241","AM241", 0,   1,
     0.00,"yr",     1.000,"yr", 42,
       1.,"Air","external","risk","cancer incidence",
 0.00E+00, 0.00E+00, 0.00E+00, 0.00E+00, ......, 0.00E+00, 0.00E+00, 0.00E+00, 0.00E+00,
       1.,"Air","external","risk","cancer fatalities",
 0.00E+00, 0.00E+00, 0.00E+00, 0.00E+00, ......, 0.00E+00, 0.00E+00, 0.00E+00, 0.00E+00,
       1.,"Air","external","Sv","radiation dose",
 0.00E+00, 0.00E+00, 0.00E+00, 0.00E+00, ......, 0.00E+00, 0.00E+00, 0.00E+00, 0.00E+00,
…
"AR41","AR41", 0,   1,
     0.00,"yr",     1.000,"yr", 42,
       1.,"Air","external","risk","cancer incidence",
 0.00E+00, 0.00E+00, 0.00E+00, 0.00E+00, ......, 0.00E+00, 0.00E+00, 0.00E+00, 0.00E+00,
       1.,"Air","external","risk","cancer fatalities",
 0.00E+00, 0.00E+00, 0.00E+00, 0.00E+00, ......, 0.00E+00, 0.00E+00, 0.00E+00, 0.00E+00,
       1.,"Air","external","Sv","radiation dose",
 0.00E+00, 0.00E+00, 0.00E+00, 0.00E+00, ......, 0.00E+00, 0.00E+00, 0.00E+00, 0.00E+00,
…
```

Figure G-16 HIF File

G.4.2.2 The User-Specified Excel Pathways File (User Supplied)

The user-specified Pathways matrices contain information about the means by which the radioactivity was transmitted (Air, Liquid). These matrices are in Excel spreadsheet format. The post-processor reads the information in this file and loads it into the Access Pathways table for use by the system. The columns of this matrix are shown in Table G-4.

Table G-4 Pathways Matrix Column Heading Descriptions

Matrix Column Heading	Definition
Receptor Location	The location of the recipient at the time of exposure
Receptor Age	The age of the recipient at the time of exposure
Medium	The medium or substance by which the radiation was transmitted
Route	The means by which the radiation traveled. Values include *external*, *inhalation*, and *ingestion*.
Exposure Location 1	A code indicating the location of the recipient at the time of exposure.
Usage Factor 1	A value indicating the extent of usage of the medium that transmitted the radiation. For example, if the medium is air, then this value would be the number of hours the air was breathed by the recipient.
Adjustment Factor 1	A factor by which the dose calculation will be adjusted to allow for the fact that the recipient may not have been exposed 100% of the time. For example, if the recipient was estimated to have eaten 100 kg of vegetables per year, but half of these vegetables were purchased at a location that carried non-local food, then the adjustment factor would be 0.5.
Exposure Location 2	A code indicating a second location of the recipient at the time of exposure.
Usage Factor 2	The usage factor applied to exposure location 2.
Adjustment factor 2	The adjustment factor applied to exposure location 2
Exposure Location 3	A code indicating a third location of the recipient at the time of exposure.
Usage Factor 3	The usage factor applied to exposure location 3.
Adjustment factor 3	The adjustment factor applied to exposure location 3
Exposure Location 4	A code indicating a fourth location of the recipient at the time of exposure.
Usage Factor 4	The usage factor applied to exposure location 4.
Adjustment factor 4	The adjustment factor applied to exposure location 4

G.4.2.3 Other Supporting Files (pre-loaded)

This section will describe the contents of additional files that need to be read by the post-processor, and the relationship that exists between various files. There are seven additional Excel files that the post-

processor needs to read. These Excel files are pre-loaded to the database during the system development cycle.

G.4.2.3.1 The DoseFactor Table

The Dose Factors Table contains a set of dose factors for various age groups, lung classes, selected pathways, routes, and isotopes by organ. The entries for this file are extracted out of the Federal Guidance Report 13 (1).

The columns of the Dose Factors table are shown in Table G-5.

Table G-5 Dose Factors Table Column Heading Descriptions

Table Field	Definition
Isotope	Abbreviations of all isotopes relevant to the exposure
Pathway	The pathway by which the exposure was received by the recipient (Air, Liquid)
Route	The route by which the dose was received (inhalation, ingestion, external)
Lung_class	Values include F, M, S, V, and G. The lung class determine the solubility from Federal Guide Report 13
Age	Age group for the dose factor (Infant, 1 yr old, 5 yr old, 10 yr old, 15 yr old and adult)
Twenty two columns of dose factor by organ	Dose factor for a given organ by pathway, route, lung class and age.
Adrenals	Dose factor for the adrenal glands by pathway, route, lung class, and age.
UB Wall	Dose factor for the UB wall by pathway, route, lung class, and age
B_Surface	Dose factor for the B Surface by pathway, route, lung class, and age
Brain	Dose factor for the brain by pathway, route, lung class, and age
Breast	Dose factor for the breast by pathway, route, lung class, and age
ET_Region	Dose factor for the esophagus-trachea Region by pathway, route, lung class, and age
St_Wall	Dose factor for the stomach wall by pathway, route, lung class, and age
SI_Wall	Dose factor for the small intestine wall by pathway, route, lung class, and age
ULI Wall	Dose factor for the upper large intestine wall by pathway, route, lung class, and age
LLI Wall	Dose factor for the lower large Intestine wall by pathway, route, lung class, and age
Kidneys	Dose factor for the Kidneys by pathway, route, lung class, and age
Liver	Dose factor for the Liver by pathway, route, lung class, and age
Lung	Dose factor for the Lung by pathway, route, lung class, and age
Muscle	Dose factor for the muscle tissue by pathway, route, lung class, and age
Ovaries	Dose factor for the ovaries by pathway, route, lung class, and age
Pancreas	Dose factor for the pancreas by pathway, route, lung class, and age
R_Marrow	Dose factor for the red marrow by pathway, route, lung class, and age

Table Field	Definition
Skin	Dose factor for the skin by pathway, route, lung class, and age
Spleen	Dose factor for the spleen by pathway, route, lung class, and age
Testes	Dose factor for the testes by pathway, route, lung class, and age
Thymus	Dose factor for the thymus by pathway, route, lung class, and age
Thyroid	Dose factor for the thyroid by pathway, route, lung class, and age
Uterus	Dose factor for the uterus by pathway, route, lung class, and age
E_50	Equivalent dose factor by pathway, route, lung class and age

G.4.2.3.2 The RiskFactor Table

The Risk Factors Table contains information about the calculated cancer risks factors. The entries for this file are extracted out of the Federal Guidance Report 13 (1).

Table G-6 describes the columns of the Risk Factors Table.

Table G-6 Risk Factors Table Column Heading Descriptions

Table Fields	Definition
Isotope	The Abbreviations of all isotopes relevant to SRS exposures.
Pathway	The pathway by which the exposure was transmitted. Values include Air, D Water (drinking water), Dietary, Ground, or Swimming
Route	External, Inhalation, or Ingestion.
Lung_Class	Values include F, M, S, V, and G. The lung class determines the solubility from Federal Guide Report 13
Age	Age group for the risk factors (0-5 yr, 5-15yr, 15-25yr, 25- 70yr and 0-110 yr)
Thirty columns of risk factors by organ	The risk factors are grouped first by risk of cancer incidence and by risk of cancer fatalities...
Esophagus	Cancer Fatality Risk Factor for the esophagus by pathway, route, lung class, and age.
CFStomach	Cancer Fatality Risk Factor for the stomach by pathway, route, lung class, and age
CFColon	Cancer Fatality Risk Factor for the colon by pathway, route, lung class, and age
CFLiver	Cancer Fatality Risk Factor for the liver by pathway, route, lung class, and age
CFLung	Cancer Fatality Risk Factor for the lung by pathway, route, lung class, and age
CFBone	Cancer Fatality Risk Factor for the bone by pathway, route, lung class, and age
CFSkin	Cancer Fatality Risk Factor for the skin by pathway, route, lung class, and age
CFBreast	Cancer Fatality Risk Factor for the breast by pathway, route, lung class, and age
CFOvary	Cancer Fatality Risk Factor for the ovary by pathway, route, lung class, and age

Table Fields	Definition
CFBladder	Cancer Fatality Risk Factor for the bladder by pathway, route, lung class, and age
CFKidney	Cancer Fatality Risk Factor for the kidney by pathway, route, lung class, and age
CFThyroid	Cancer Fatality Risk Factor for the thyroid by pathway, route, lung class, and age
CFLeukemia	Cancer Fatality Risk Factor for Leukemia by pathway, route, lung class, and age
CFResidual	Cancer Fatality Risk Factor for the residual organs by pathway, route, lung class, and age
CFTotal	Total Cancer Fatality Risk Factor by pathway, route, lung class, and age
CIEsophagus	Cancer Incidence Risk Factor for the esophagus by pathway, route, lung class, and age.
CIStomach	Cancer Incidence Risk Factor for the stomach by pathway, route, lung class, and age
CIColon	Cancer Incidence Risk Factor for the colon by pathway, route, lung class, and age
CILiver	Cancer Incidence Risk Factor for the liver by pathway, route, lung class, and age
CILung	Cancer Incidence Risk Factor for the lung by pathway, route, lung class, and age
CIBone	Cancer Incidence Risk Factor for the bone by pathway, route, lung class, and age
CISkin	Cancer Incidence Risk Factor for the skin by pathway, route, lung class, and age
CIBreast	Cancer Incidence Risk Factor for the breast by pathway, route, lung class, and age
CIOvary	Cancer Incidence Risk Factor for the ovary by pathway, route, lung class, and age
CIBladder	Cancer Incidence Risk Factor for the bladder by pathway, route, lung class, and age
CIKidney	Cancer Incidence Risk Factor for the kidney by pathway, route, lung class, and age
CIThyroid	Cancer Incidence Risk Factor for the thyroid by pathway, route, lung class, and age
CILeukemia	Cancer Incidence Risk Factor for the Leukemia by pathway, route, lung class, and age
CIResidual	Cancer Incidence Risk Factor for the residual organs by pathway, route, lung class, and age
CITotal	Total Cancer Incidence Risk Factor by pathway, route, lung class, and age

G.4.2.3.3 The Isotope Names Table

The Isotope Names Table lists the name of each isotope to be displayed in the isotope list box for atmospheric or liquid pathways. Column headings of the Isotope Names Table are described in Table G-7.

Table G-7 Isotope Names Table Column Heading Descriptions

Table Fields	Definition
Isotope	The names of all relevant isotopes involved in the exposure.
Selected (true or false)	Specifies whether or not the user selected the isotope for use in the dose calculations.
AtmosphericRelease	Specifies whether or not the dose was received by atmospheric release.
LiquidReleases	Specifies whether or not the dose was received by liquid release.

G.4.2.3.4 Isotope List Table

The IsotopeList table lists the correct isotope number, the isotope abbreviations, the index of any daughter isotope, and the lung-class, which determines the solubility of the contaminant according to Federal Guide Report 13 (1). The column headings of the IsotopeList table are described in Table G-8.

Table G-8 Isotope List Table Column Heading Descriptions

Table Fields	Definition
Isotope	The abbreviations of all relevant isotopes involved in the exposure.
IsotopeNum	The index of an isotope.
DaugIndex	The index of any daughter isotopes that the parent isotopes yield due to radioactive decay.
Lung_Class	The lung class determines the solubility from Federal Guide Report 13. Values include F, M, S, G, and V.

G.4.2.3.5 The Receptors Table (User Supplied)

The Receptors Table contains the location, age at the time of exposure, age range over the duration of the exposure, and birth year of all receptors. Users select specific receptors through the post-processor user interface, and their selections are recorded in the *Selected* field. The column headings of the Receptors table are described in Table G-9.

Table G-9 The Receptors Table Column Heading Descriptions

Table Fields	Definitions
Name	Type of receptor, for example, Rural Family #1 Adult Male.
Location	The location of the receptor, for example, Rural Family #2.
Receptor	The age range of the receptor, for example, Adult Male.
YearBorn	The birth year of a given receptor type.
Selected	A yes/no field indicating that the user has selected an option.

G.4.3 Detailed Processing Required to Generate the Final Post-processor Report

The post-processor will read the files described in G.4.2.3. The post-processor will then obtain the user's choices. Then, based on the user's choices, the post-processor will read the appropriate GENII-V2 HIF files. As the post-processor reads each HIF file, the computer code will adjust the results according to the information in the behavior file and by the dose conversion/risk factors. The results will then be accumulated into the correct cells of the DoseRisk Table depending on the user's choices.

This section describes the logic that the post-processor will use during the calculations. The logic flow begins after the post-processor has obtained the user choices and read the supplemental files. Briefly, for a given exposure location, the post-processor will read doses/risk results by isotope and pathway. The post-processor will adjust the dose/risk numbers for a given receptor to account for that receptor's behavior contained in the behavior file and birth year files. The adjustments will include an adjustment of the

dose/risk to change the results from age independent to age dependent dose/risk factors and age dependent location behavior.

For example, look at the Rural Family #1 Child born in 1955 with the external air pathway and a release year of 1969. The receptor is now a teenager who resides at his house for 7500 hours per year (exposure location 1) and goes to school for 1260 hours per year (exposure location 2.) The post-processor will adjust GENII-V2 dose/risk results for each isotope and organ. For exposure location 1, the dose/risk results would be multiplied by a factor of 6760 and multiplied by the teenager air external dose conversion factor by isotope and organ divided by the adult air external dose factor by isotope and organ. The resulting dose/risk will be stored and summed as required by the user.

G.4.3.1 The Dose Reconstruction Report

The logic flow begins after the post-processor has obtained the user choices and read the supplemental files. For a given exposure location, the post-processor will read the doses/risk results by isotope and pathway. The post-processor will adjust the dose/risk numbers for a given receptor to account for that receptor's behavior, as described in the behavior file and birth year files. The adjustments will include an adjustment of the dose/risk to change the results from age independent to age dependent dose/risk factors and age dependent location behavior.

For example, look at a child born in 1954 with the external air pathway and a release year of 1969. The receptor is now a teenager who resides at his house for 7375 hours per year (exposure location 1) and goes to school for 1295 hours per year (exposure location 2.) The post-processor will adjust GENII-V2 dose/risk results for each isotope and organ. For exposure location 1, the dose/risk results would be multiplied by a factor of 6760 and multiplied by the teenager air external dose conversion factor by isotope and organ divided by the adult air external dose factor by isotope and organ. The resulting dose/risk will be stored and summed as required by the user.

The post-processor collects information from the user input window, based on the release type, facility ID, and the year of process, then loops through the GENII-V2 output files and checks to see if this run is valid for Uncertainty or just for Point-Estimate. For a given release type, facility ID and year of processing, if there are 101 GID files, the system will assign 100 to the MaxRun variable. Otherwise, it will set MaxRun equals 0). Once this process has completed, the post-processor will load the user-specified Pathway file into the Pathways table in the database.

For each receptor in the selected list, the receptor’s name is assigned to the RecpName variable. Based on the RecpName value, the Location, Receptor, and YearBorn are obtained from the Receptor table.

For each year of the specified processing years (the user specifies the starting year and the ending year of the process), the current processing year is assigned to the intYear variable (intYear is used to determine which HIF file should be loaded and the current age of the receptor).

As the processing year goes up, the receptor’s age is also changing. All age group variables must be reassigned with a proper value based on the receptor’s current age at that processing year. (See Age Group Assignment Table for detail)

There are four varying age group variables:

RecepAge = 1900 + intYear – YearBorn

RiskAge = Risk factor age based on the RecepAge

DoseAge = Dose factor age based on the RecepAge

USFAge = Usage factor age based on the RecepAge

For RunNum from 0 to MaxRun

Clean up the HIFData and TempHIF tables

Load HIF file based on RunNum to HIFData table

Read each record from the HIFData table, arrange require fields and write to TempHIF table

Select all records from the Pathways table based on the known Location and USFAge values

For each record read above

Assign the first set of values from the Pathways table to the variables of ExpLoc, Pathway, Route, UsageFactor, and AdjFactor

Read all records from TempHIF table based on the known ExpLoc, UsageFactor, and AdjFactor

For each record read from the TempHIF table, assign the Isotope value to the Isotope variable

Read the Isotope Table based on the Isotope value to get the lung-class

Get DoseFactor for each organ and store in a 1 by 24 temporary array called DoseFactor(24)

The DoseFactor for each organ is equal to the current age Dose AdjFactor divides by the adult age Dose AdjFactor

The current age Dose AdjFactor is read from the DoseFactor table based on the Isoto, Route, Pathway, Lung-class, and DoseAge

The adult age Dose AdjFactor is read from the DoseFactor table based on the Isoto, Route, Pathway, Lung-class, and DoseGroup, which equals “Adult”

Certain rules may apply to the DoseFactor:

The DoseFactor table does not have values for a Route equals “Inhalation” and the Pathway equals “Indoor Air”. In this case, the Pathway will be assumed to “Air”.

If Route equals “External” the DoseFactor value will 1.

Get RiskFactor for each organ and store in a 1 by 30 temporary array Call RiskFactor (30)

The RiskFactor for each organ is equal to the current age Risk AdjFactor divides by the adult age Risk AdjFactor

The current age Risk AdjFactor is read from the RiskFactor table based on the Isoto, Route, Pathway, Lung-class, and RiskAge

The adult age Risk AdjFactor is read from the RiskFactor table based on the Isoto, Route, Pathway, Lung-class, and RiskGroup which equals “0-110 y”

Certain rules may apply to the RiskFactor:

The DoseFactor table does not have values for a Route equals “Inhalation” and the Pathway equals or “Indoor Air”. In this case, the Pathway will be assumed to “Air”.

If Route equals “Ingestion” and Pathway equals “Swimming”, or “Showering”, or “Water” then the Pathway will be set to “D Water” when reading the RiskFactor table.

If the Pathway equals “Fish” then the Pathway will be set to “Dietary” when reading the RiskFactor table.

Apply the UsageFactor and each of the RiskFactor (30) to the first 30 organs from the TempHIF record.

Apply the UsageFactor and each of the DoseFactor (24) to the last 24 organs from the TempHIF record.

Write TempHIF record to DoseRisk table.

Read next TempHIF record

Read next Pathway record

Process next RunNum through

Process next intYear through the end

Export DoseRisk table to C:\CDC\Postprocessor\Completed for the current receptor in an Excel format.

Process next Receptor from selection list.

G.4.3.2 Other Output Files

Two Post-processor output files are generated in addition to the calculated Excel Dose/Risk Report. These are a QA file and a message (MES) file.

Each file name will have the following format:

ABCDEFG.xxx

Where

- A is the type of releases (A, S, L)
- B is the facility
- CD is the last two digits of the first year of releases processed
- EF is the last two digits of the last year releases processed
- G is the version of the standardized GID file processed. and
- xxx is QA for the QA file and MES for the message file

G.4.3.3 QA File

This file contains referencing information related to the processing of the post-processor during the creation of the report files. Included in this file are:

- The post-processor start date and time.
- The user who created the post-processor run
- The Facility Name
- Pathway Usage Factors excel file used
- The list of output files generated
- A message describing if the post-processor run completed successfully and the date and time of completion.

G.4.3.4 MES File

The Message (EMS) file documents any errors that occurred during the post-processor run. The program generates an error message for the EMS file and displays it to the user if any unexpected condition arises. Several conditions that could arise are:

- Missing of GENII-V2 output file
- An exposure location that is not in an output file.
- An isotope name is not found.
- An error occurred when reading input file.

G.5 Testing

The Quality Assurance Application Test Plan for the Pre- and Post-Processors to GENII-V2, contains the detailed test plan. The following sections briefly describe testing approaches for the pre- and post-processor.

G.5.1 Pre-Processor

G.5.1.1 Input Data Creation

The test data for the Pre-Processor is set up to address specific test scenarios and is contained in a combination of standard GID templates for given exposure location sets and facility specific source term data files. Reference data is contained in pre-defined isotope description files, dispersion factor files, exposure description files, facility description files, parameter uncertainty files and source term uncertainty files. The appropriate combination of input files is set up for each execution run as they pertain to the test scenarios within that particular run. Many input reference files remain constant across test scenarios and will be re-used by multiple test runs as necessary. Any variation of input files is documented and kept for reference.

G.5.1.2 Expected Results Calculation

Expected results for each test scenario are determined through both manual calculations and other tool-assisted methods. In the most basic scenario, the application obtains data directly from a source term file for a given media and facility, then multiplies by a unit conversion factor and places the data in a specific row within the GID output file based on corresponding variable names and row indices for a given isotope or exposure location. These calculations are relatively simple, self-explanatory and do not require additional explanation beyond referencing the detailed design requirement. Distance calculations are slightly more complex and a separate tool was developed using Excel to determine values for expected results. Since user interface requirements typically affect all test runs and only occur during execution setup, they have no particular test scenarios and no specific expected results to compare. Visual verification will suffice to confirm application functionality for most user interface requirements.

G.5.1.3 Error Messages Confirmation

Error message functionality is confirmed by setting up various error scenarios within the input files and capturing output text within message files. Since the same message output filename may be used for several error scenarios, the message output files will be re-named after each error run to include the corresponding scenario for easy traceability.

G.5.1.4 Output Data Comparison Analysis

Once each test execution run has completed successfully, the output files for each run will be captured and analyzed using a text editor or Excel to assist in the analysis.

For each test scenario within the corresponding GID output file, the specific field name and index values are matched to find the actual quantity, distance or setup values. The row number is noted and the entire row of data is captured and the actual values are placed in the traceability matrix for comparison with the expected values.

If the actual value matches expected results within acceptable tolerances, the scenario is marked as passed in the verification column. If the value does not match the expected results, the scenario is marked as failed in the verification column and placed in the failed history. Failed scenarios must be retested as fixes are made available.

G.5.2 Post-Processor

G.5.2.1 Input Data Creation

The test data for the post-processor needs to be generated by the GEN-II V2 dose calculation software and will be contained in a combination of HIF files based on selected media, facility, year range and uncertainty criteria. Reference data is contained in pre-defined receptor description files, isotope description files, risk factor files, dose factor files and behavior pathway usage files. The appropriate combination of input files will be set up for each execution run as they pertain to the test scenarios within that particular run.

G.5.2.2 Expected Results Calculation

Expected results for each test scenario are determined through both manual calculations and other tool-assisted methods. In the most basic scenario, the application obtains data directly from an HIF file for a given media, exposure set, facility, year and uncertainty, then multiplies by a series of risk, dose and usage factors and places the data by organ and total in a specific row within the XLS output file based on corresponding row indices for a given location, receptor, year, uncertainty, pathway and isotope. These calculations are relatively simple, self-explanatory and do not require additional explanation beyond referencing the detailed design requirement. A tool was be developed using Excel to determine risk and dose values for expected results.

G.5.2.3 Output Data Comparison Analysis

Once each test execution run has completed successfully, the output files for each run are captured and analyzed using a text editor or Excel to assist in the analysis.

For each test scenario within the corresponding XLS output file, the index values are matched to find the actual risk and dose values for specific organ name or total. The row number is noted and the index portion of the row of data is captured including the organ name or total and the actual risk or dose values are placed in the traceability matrix for comparison with the expected values.

If the actual value matches expected results within acceptable tolerances, the scenario is marked as passed in the verification column. If the value does not match the expected results, the scenario is marked as failed in the verification column and placed in the failed history. Failed scenarios must be retested as fixes are made available.

G.6 References

1. U.S. Environmental Protection Agency. Federal guidance report 13. "Cancer Risk Coefficients for Environmental Exposure to Radionuclides": CD supplement. EPA 402-C-99-001, Rev. 1. Oak Ridge National Laboratory and United States Environmental Protection Agency. April 2002.

APPENDIX H SELECTION OF GENII, VERSION II, FOR ASSESSMENT OF DOSES AND RISKS FOR THE SRS DOSE RECONSTRUCTION PROJECT

H.1 Introduction

As part of its work to complete the revised Phase III effort for the Dose Reconstruction Project for the Savannah River Site (SRS), a project overseen by the U.S. Department of Health and Human Services, Centers for Disease Control and Prevention (CDC), Advanced Technologies and Laboratories International, Inc. (ATL) had to select a software program to estimate human doses and risks caused by past SRS operations. ATL's selection of Version 2 of GENII, a product of the Pacific Northwest National Laboratory (PNNL) is documented in ATL's *Software Selection Decision for the Savannah River Site Dose Reconstruction Software Program* (ATL, 2003). The software decision document was based on the requirements for the software that ATL documented in its *Software Requirements Document for the Savannah River Site Dose Reconstruction Software Program* (ATL, 2002).

This appendix summarizes ATL's selection of GENII Version 2, drawing information from (ATL, 2003) and (ATL, 2002).

H.2 Identification of Computational Requirements

When initiating the revised Phase III effort, ATL recognized a critical need to develop a software program to perform the detailed mathematical modeling computations that would be required. ATL envisioned a dose assessment program that could be represented conceptually as having three components: a pre-processor, a dose calculation component, and a post-processor (Figure H-1). The preprocessor would compile input data and prepare it for use by the modeling program. The dose calculation component would perform the transport and exposure pathway computations that estimate the movement, dilution, buildup, and concentration of radionuclide contaminants in the environment and the human intake of and exposure to the contaminants, and the resulting human health risks. The postprocessor would extract results from output files and compile them in a readily useable format.

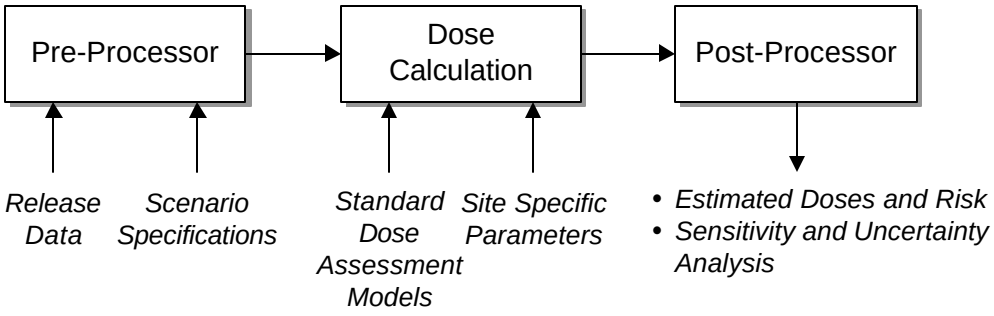

Figure H-1 Conceptual Configuration of SRS Dose Assessment Program

For the dose calculation component of the program, ATL considered two potential approaches: (1) use an existing code, or (2) custom-develop a code. Under either approach, the dose calculation component performing the modeling computations would be mated to the pre-processor and post-processor components.

Although a custom-developed modeling code could have been produced that met all applicable project requirements, it would have required an extensive effort. Therefore, ATL determined that an existing modeling program would be preferable if one could be found that met the minimum requirements.

ATL reviewed the modeling requirements for the dose reconstruction efforts against the environmental transfer and exposure pathways that needed to be considered (ATL, 2002). ATL then organized the requirements into three high-level groupings:

1. **Mandatory.** Requirements that had to be incorporated in the modeling code to meet project objectives. Although in some cases, the pre- or post-processor could have been used to meet a mandatory requirement, it was preferable that the modeling code meet these requirements.
2. **Highly Desirable.** Requirements that were not mandatory, but would greatly facilitate use of the software and enhance its ability to meet project objectives.
3. **Discretionary.** Requirements that would help the project, but were not necessary. However, if multiple modeling programs were found that met higher level requirements, these requirements could be used to differentiate between the programs.

The requirements were categorized as follows:

- Transport
  General
  Surface Water
  Air
  Food Chain
- Exposure
- Dose and Risk
- Data Input and Output
- Other

Altogether, ATL identified 18 mandatory requirements and 15 non-mandatory (i.e., highly desirable or discretionary) requirements. The requirements are summarized below.

H.2.1 Mandatory Requirements

H.2.1.1 Transport–General

Annual Releases. Must be able to model annual releases of contaminants.

Site-Specific Transport Parameters. Must be able to use site-specific transport parameters in place of default values.

Chronic Releases. Must be able to model long-term contaminant releases.

Linked Compartments. For the various transport and exposure pathways, the code must be able to link and sequence the computations so that the calculated concentration values produced as output from each module (compartment) is automatically fed as data input to all appropriate downstream modules.

H.2.1.2 Transport-Surface Water

Simple Dilution Model. Must use a simple dilution model to simulate surface water contaminant transport.

Annual Flow. Must be able to use variable annual flow data.

Sediment Transfer. Must include a module to simulate the transfer of contam-ination from water to sediment, the subsequent transfer of this contamination to other media, and the external exposure of individuals from sediment.

H.2.1.3 Transport-Air

Sector Averaging Model. Must use a sector-averaging model to simulation the transport and dilution of contamination in air.

Deposition. Must include a module to calculate the transfer of contamination from air to soil by dry and wet deposition.

H.2.1.4 Transport-Food Chain

Established Models. Must use established formulations to model the transfer and accumulation of contamination in the food chain.

Site-Specific Transfer Factors. Must allow for use of site-specific values (rather than default values) in calculating the transfer (uptake and usage) and accumulation of contamination in the food chain.

H.2.1.5 Exposure

Food Categories Specified. For the modeling of contamination transfer and accumulation within the food chain, the code must allow for the multiple different food categories (e.g., grain, meat, milk, leafy vegetables, fish), each with different uptake and usage factors, to be modeled simultaneously.

Five Exposure Pathways. The code must include modules to account for the five different exposure pathways represented in the CDC exposure scenarios (inhalation, ingestion, submersion, ground plane, sediment).

H.2.1.6 Dose/Risk

There were no mandatory requirements in this category/subcategory.

H.2.1.7 Data Input/Output

Disaggregate Doses. Must allow the computation of results in a disaggregate form according to radionuclide, transport pathway, exposure pathway, and year.

QA Transparency. Must produce output that is easy to review and verify/validate.

H.2.1.8 Other

Special Models for C-14 and H-3. Must include special models for carbon-14 and tritium since the behavior of these contaminants in the environment is different that of other contaminants.

RN Chains. Must include calculations to account for decay of radionuclides, including ingrowth, that occurs during contaminant transport.

Availability. Must be available to ATL for use on this project.

H.2.2 Highly Desirable Requirements

H.2.2.1 Transport-General

There were no requirements in this subcategory.

H.2.2.2 Transport-Surface Water

Additional Compartments. Within the surface water transport model, the code should include additional compartments to simulate different contaminant transport behaviors that could affect surface water. For example, an additional compartment may be needed to simulate operation of the seepage basins.

H.2.2.3 Transport-Air

Annual Meteorological Data. Within the air transport model, the code should include the capability to use annual meteorological data.

H.2.2.4 Transport-Food Chain

Resuspension Factor. Within the food chain transport model, the code should include a soil resuspension compartment to address resuspension of contaminated soil that subsequently deposits on food chain crops.

Soil Build-up. Within the food chain transport model, the code should include the capability to model the build-up over time of contamination in the soil resulting from long-term (>1 year) deposition.

H.2.2.5 Exposure

Variable Exposure Parameters. The code should have the capability to accommodate user-assigned values for exposure parameters.

H.2.2.6 Dose/Risk

FGR-13. The code should use the values for dose conversion factors (DCFs) set forth in U.S. Environmental Protection Agency Federal Guidance Report No. 13 (EPA 402-R-99-001, September 1999).

Age Dependent DCFs. The code should be able to calculate doses using age-specific dose conversion factors.

H.2.2.7 Data Input/Output

Easy to Automate. The code should easily accommodate approaches to automate modeling runs. This project will probably require hundreds or thousands of individual modeling runs. Therefore, it is desirable to avoid manual data entry and processing.

Intermediate Results. The code should produce intermediate results between modules so that intermediate results can be reviewed. For example, intermediate results would include the number of curies passing through a specific transport pathway.

H.2.2.8 Other

Chemicals. The code should accommodate the modeling of nonradioactive chemicals, including noncarcinogenic health effects and biodegredation.

Multiple years with Varying Releases. The code should allow for modeling multi-year releases with rates that vary by year.

Cost. The cost of the code should be reasonable and not have a significant effect on the task budget.

QA Status. The code should be verified and validated and in a final product form.

Stochastic Capability. The code should accommodate sensitivity and uncertainty analyses using stochastic variable distributions.

H.2.3 Discretionary Requirements.

Only one discretionary requirement was identified.

H.2.3.1 Transport-General

Acute Releases. The code should be capable of modeling the environmental transport and subsequent human exposure and health consequences resulting short duration pulse releases of a few hours or days.

H.3 Assessment of Candidate Codes

ATL conducted the software assessment in phases. In the first phase, ATL identified available modeling codes. The codes were then screened. In the second phase, the screened codes were evaluated against identified software requirements to identify the most suitable (ATL, 2002).

In its survey, ATL identified 66 codes based on their general classification as tools for environmental transport, exposure, dose and risk modeling. (These codes perform various combinations of contaminant transport and exposure computations to determine exposure levels, doses, and risks to humans.) The criteria used in the screening included the following:

- Compatible and consistent with transport and exposure formulations in IAEA Safety Reports Series No. 19.
- Capable of calculating dose and risk for individuals (as identified in CDC exposure scenarios).
- Capable of modeling long-term non-constant release levels from industrial facilities such as the sources identified for SRS.
- Available in a personal computer (Windows or DOS) version.
- Not obsolete by a more recent version.

From this screening process, ATL further evaluated 17 candidate codes to determine their suitability for the SRS Dose Reconstruction Project. This evaluation eliminated codes that only addressed a limited number of pathways and exposure scenarios

ATL identified two suitable codes: Hanford Environmental Dosimetry System, Generation II, Version 2 (GENII-V2), and Multimedia Environmental Pollutant Assessment System (MEPAS).

The GENII computer code was developed at PNNL to support radiological exposure and risk assessment for the U.S. Environmental Protection Agency's (EPA's) Office of Indoor Air and Radiation. The GENII code was developed to provide a state-of-the-art, technically peer-reviewed, documented set of programs for calculating radiation doses from radionuclides released to the environment. It was designed with the flexibility to accommodate input parameters for a variety of generic sites, and includes capabilities for calculating radiation doses following chronic and acute releases. Radionuclide transport via air, water, or biological activity may be considered.

The MEPAS code was also developed by PNNL and is a risk analysis software tool to estimate environmental concentrations and chronic public health impacts from radioactive and hazardous materials. It uses standard EPA mathematical models to predict the potential for release and transport of contaminants into the environment as well as the impact to the surrounding environment, individuals, and populations. MEPAS addresses major exposure routes resulting in either carcinogenic and noncarcinogenic impacts.

ATL subjected GENII-V2 and MEPAS to one final evaluation against the specific software requirements (ATL, 2002). To assist this evaluation, ATL collected additional relevant information about the two codes by obtaining and reviewing available literature and copies of these codes and discussing various code characteristics with PNNL representatives who were responsible for developing and validating the codes. ATL then critically compared these codes for each of the mandatory, desirable, and discretionary requirements (ATL, 2003). This evaluation resulted in the selection of GENII-V2.

H.4 Selection of GENII, Version 2

Mandatory Requirements. GENII-V2 met all mandatory requirements. MEPAS met all but one of the mandatory requirements. MEPAS did not meet requirement for special models for C-14 and H-3. By itself, this distinction was enough to determine GENII-V2 as the preferable software code for this project. However, for completeness, a discussion of the desirable and discretionary requirements follows.

Desirable Requirements. GENII-V2 met all except three desirable requirements:

- Soil Buildup,
- Chemicals, and
- Multiple Years with Varying Releases.

In addition, ATL determined that GENII-V2 would be easy to automate, with only limited certainty (a more precise understanding of the automated functions was needed to address this requirement with greater certainty). In comparison, MEPAS met all but three desirable requirements, and had limited certainty in meeting a fourth. The three desirable requirements that MEPAS did not meet were:

- Soil Buildup (same as for GENII-V2)
- FGR-13, and
- Multiple Years with Varying Releases (same as for GENII-V2).

In addition, ATL determined that MEPAS would be easy to automate, with only limited certainty (same as for GENII-V2).

Discretionary Requirements. GENII-V2 met the only discretionary requirement. MEPAS did not.

Conclusion. ATL determined that GENII-V2 would be the best choice among those available to perform pathway and exposure calculations for the Phase III effort.

H.5 References for Appendix H

ATL, 2003. ATL International, Inc. Software Selection Decision for the Savannah River Site Dose Reconstruction Program. (Internal ATL document.) January 13, 2003.

ATL, 2002. ATL International, Inc. Software Requirements Document for the Savannah River Site Dose Reconstruction Project. (Internal unpublished draft document.) December 9, 2002.

APPENDIX I TABLES OF DOSES AND RISKS BY YEAR FOR EACH SCENARIO

This appendix presents the calculated Effective Dose, Total Cancer Incident Risk, and Total Cancer Fatality Risk by year for each hypothetical individual in each scenario. Reports for Effective Dose, Total Cancer Incident Risk, and Total Cancer Fatality Risk are listed in separate tables grouped by different release pathways when applicable.

Tables are presented electronically via the following links for each scenario.

Delivery Family Scenario

Urban Family Scenario

Migrant Family Scenario

Near Water Family Scenario

Outdoor Family Scenario

Rural Family One Scenario

Rural Family Two Scenario

APPENDIX J TABLES OF DOSES AND RISKS BY EXPOSURE ROUTE

This appendix presents the calculated 39-year Total Effective Dose, Total Cancer Incident Risk, and Total Cancer Fatality Risk for the hypothetical individual in each scenario. The 39-year Total Effective Dose, Total Cancer Incident Risk, and Total Cancer Fatality Risk are listed by exposure route and in separate tables grouped by different release pathways when applicable.

Tables are presented electronically via the following links for each scenario.

Delivery Family Scenario

Urban Family Scenario

Migrant Family Scenario

Outdoor Family Scenario

Near Water Family Scenario

Rural Family One Scenario

Rural Family Two Scenario

APPENDIX K TABLES OF DOSES AND RISKS BY PATHWAY AND RADIONUCLIDE

This appendix presents the calculated 39-year Total Effective Dose, Total Cancer Incident Risk, and Total Cancer Fatality Risk for the hypothetical individual in each scenario. The 39-year Total Effective Dose, Total Cancer Incident Risk, and Total Cancer Fatality Risk are listed by exposure route and isotope for each hypothetical individual in separate tables grouped by different release pathways when applicable.

Tables are presented electronically via the following links for each scenario.

Delivery Family Scenario

Urban Family Scenario

Migrant Family Scenario

Outdoor Family Scenario

Near Water Family Scenario

Rural Family One Scenario

Rural Family Two Scenario

APPENDIX L VARIANCE CALCULATION SIMPLIFICATION

L.1 Calculation Simplification

The Savannah River Site (SRS) dose for releases in a particular medium (air or water) may be represented by the following sum:

$$D = \sum_{1954}^{1992} \sum_{1}^{N} \sum_{1}^{M} D_{ijk} \qquad \text{(L.1)}$$

Where,

D	=	the dose to a particular receptor
D_{ijk}	=	the incremental dose (by year, nuclide, and pathway)
i	=	the index by year, from 1954-1992
j	=	the index by radionuclide, with upper limit N equal to 16 for air and 22 for water
k	=	the index by exposure pathway, with upper limit M equal to 13 for air and 5 for water

(Note there are no pathways in common for both air and water).

The point estimate for D is calculated by substituting in the point estimates for a number of input variables. This also generates the point estimates for the component doses from each radionuclide and pathway, D_{ijk}. Denote these point estimates of dose by D and D_{ijk}, respectively. Based on these values the fraction of the total dose due to various factors is computed. For example:

$$E_{ijk} = D_{ijk}/D$$

Using shorthand notation, if an index is omitted from a fraction or a dose, then summation over the omitted indexes is assumed. For example,

$$\breve{E}_j = \frac{\sum_{1954}^{1992} \sum_{1}^{M} \breve{D}_{ijk}}{\breve{D}} = \frac{\breve{D}_j}{\breve{D}} \qquad \text{(L.2)}$$

When the Monte Carlo analysis is performed, an assumption is made that the doses are random variables. A set of realizations is computed leading to a sample of doses; each of these randomly generated doses can be partitioned and indexed as with the point estimate dose (i.e., as indexed in Equation (L.1)). However, an additional index, l, representing the realization is needed to completely characterize the set of numbers; the index l has a range of 1 to L, where L is the total number of realizations. What is being sought is the population mean and variance. As usual, the population mean and variance is estimated by using the sample mean and variance.

Because the input variable distributions will be chosen to be centered on the point estimate values, it is expected that the sample mean, μ, will be close to the point estimate of dose, D. A similar relationship is expected to hold for any subset of doses or even the D_{ijk}. Then by extending the notation used before:

$$\mu_{ijk} = \frac{\sum_{1}^{L} D_{ijkl}}{L} \qquad \text{(L.3)}$$

That is, μ_{ijk} is the mean value of the dose realizations for a particular year, radionuclide, and pathway.

$$E_{ijk} = \mu_{ijk}/D = [D_{ijk}/D][\mu_{ijk}/ D_{ijk}] = E_{ijk} \cdot [\mu_{ijk}/ D_{ijk}] \qquad \text{(L.4)}$$

That is, E_{ijk} is μ_{ijk} divided by the total point-estimate dose, D.

However, for a well-behaved problem in which the point-estimate dose is close to the mean dose, the second factor ~ 1. If both sides of (L.4) are summed with respect to all indices, then:

$$E = 1 \cong \sum_{1954}^{1992} \sum_{1}^{N} \sum_{1}^{M} E_{ijk} \cdot 1 \qquad \text{(L.5)}$$

In other words, the result is that the estimate of mean dose can be obtained if elements of the sum are omitted, but only if the <u>aggregate</u> sum of the E_{ijk} for those elements is a suitable small percentage of unity. However, if the interest is in characterizing the variability, more elements of the sum may be omitted, provided the missing dose is added back in at the end. That is:

$$\mu = \mu_v + \mu_f \qquad \text{(L.6)}$$

Where μ_v is a partial mean calculated based on Monte Carlo sampling and μ_f is a partial mean calculated based on the point estimate calculation, where the partition is on any basis that is convenient.

To estimate the variance, rather than the mean, the situation is quite different. Although it is expected that the point-estimate total dose will be close to the mean of the total dose from the Monte Carlo sampling, the point estimate provides no information on the variance of the dose distribution. This information must come from the Monte Carlo simulation. To simplify the analysis, consider the sum over time indicated in Equation (L.1). Because the adults and child born in 1955 experience large releases early in the history of the site, the doses for these receptors are dominated by the first 20 years of releases. However, the child born in 1964 misses most of these large doses, so the cumulative releases over a 20 year period are important. If both time ranges are to be studied, then, because of the calculation approach adopted for the project, the doses for the entire 39 year period of the study might as well be calculated. Because simplification by eliminating certain years does not seem feasible, the index related to summing over years will be dropped and the summation will be assumed. Then Equation (L.1) becomes:

$$D = \sum_{1}^{N} \sum_{1}^{M} D_{jk} \qquad \text{(L.7)}$$

where the summation over time is understood, but will not be used to simplify the variance calculation. In other words, D_{jk} should be read as the dose for a particular radionuclide and pathway summed over 39 years. Furthermore, it should now be understood that D is a random variable; in practice a sample of this random variable of size L will be created.

To facilitate the analysis, transform both the doses and the independent variables by their point estimate values; i.e.,

$$Z = X / \breve{X} \qquad \text{(L.8)}$$

where,

Z = the normalized input variable or dose;

X = the lth realization of the input variable or dose;
$\breve{X}$ = the point estimate value of the input variable or dose.

Then Equation (L.7) becomes:

$$F = \frac{D}{\breve{D}} = \sum_{1}^{N}\sum_{1}^{M}\frac{D_{jk}}{\breve{D}} \qquad \text{(L.9)}$$

where D_{jk}, D, and F are all random variables.

This can be rearranged into a slightly more convenient form (similar to what was done in Equation (L.4)):

$$F = \sum_{1}^{N}\sum_{1}^{M}\frac{D_{jk}}{\breve{D}_{jk}}\cdot\frac{\breve{D}_{jk}}{\breve{D}} \qquad \text{(L.10)}$$

Note the variance of a random variable, X, by $s^2\{X\}$. Then some useful relationships are:

$$s^2\{cX\} = c^2 s^2\{X\} \qquad \text{(L.11a)}$$

and

$$s^2\{X + Y\} = s^2\{X\} + s^2\{Y\} \qquad \text{(L.11b)}$$

where,
c = a constant
X and Y = independent random variables.

Note that the term D_{jk}/D in Equation (L.9) is the fractional contribution to total dose by pathway and radionuclide based on the point estimate calculation, i.e., E_{jk}. This quantity is a constant for each choice of j and k. The variance of the normalized total dose can be found by determining the variance of each of the contributing terms in Equation (L.10) and then using the rules in Equations (L.11) to combine them. This procedure yields:

$$\sigma^2\{F\} = \sum_{1}^{N}\sum_{1}^{M}\sigma^2\left\{\frac{D_{jk}}{\breve{D}_{jk}}\cdot\frac{\breve{D}_{jk}}{\breve{D}}\right\} = \sum_{1}^{N}\sum_{1}^{M}\sigma^2\left\{\frac{D_{jk}}{\breve{D}_{jk}}\right\}E_{jk}^2 \qquad \text{(L.12)}$$

In other words, the variance of the dose is equal to the variance of the normalized dose contributors by radionuclide and exposure pathway, multiplied by the square of the contribution of that radionuclide and exposure pathway to the point estimate dose. If the variance of each normalized contributor to dose, $s^2\{D_{ij}/D_{ij}\}$, is bounded by some quantity, say Q^2, then the sum can be approximated by eliminating any terms for which:

$$E_{ij}^2 / \max\{E_{ij}^2\} << 1 \qquad \text{(L.13)}$$

and where max $\{x_{ij}\}$ is the maximum value of the indexed variable. In other words, if the variances of the normalized contributors to dose are bounded, only the terms with a large fractional contribution to the point estimate dose (E^2_{ij}) will be important. Based on the results of the point estimate runs, the ratios indicated by Equation (L.13) can be calculated. For example, the results for the adult female in Rural Family 2 are given in Table L-1. Table L-2 shows the reduced renormalized set after some nuclides and pathways were eliminated because they had only a minor contribution to dose. Table L-3 shows the

values indicated in Equation (L.12) and demonstrates that only four values account for over 98% of the total. This clearly highlights four nuclide/pathway pairs that are candidates to account for most of the variance in the dose. Table L-4 shows the equivalent of Table L-3, but for the child born in 1964. This shows more and different pathways and nuclides, primarily those involving tritium.

To reach this point, however, it was assumed the variance of each normalized contributor to dose is bounded. Consider the variance of each normalized contributor to dose, denoted in Equation (L.12) by the term:

$$\sigma^2\left\{\frac{D_{jk}}{\breve{D}_{jk}}\right\}.$$

To simplify the notation for the upcoming derivation, denote D_{jk} by u. Then the normalized contributor to dose is u/u. Suppose this contributor to dose is expanded in a Taylor series of the variables involved in calculating this aspect of dose; note that this set of variables may include variables unique to this nuclide and pathway, such as the uptake of iodine by milk from animal feed, but it may also include variables common to many pathways and radionuclides, such as the particle diameter used to determine deposition velocity. We can then write:

$$u(z_1,z_2,...,z_n) = a_0 + a_1z_1 + a_2z_2 + \ldots + a_nz_n \qquad \text{(L.14)}$$

If the variance of both sides of (L.14) are taken and the relationships in equations (L.11a) and (L.11b) are applied, then:

$$s^2\{u\} = ?\ a_m^2 s^2\{z_m\} \qquad \text{(L.15)}$$

where m is the index for the n independent variables. Note also that the variance of a constant (a_0) is zero.

Similar to Equation (L.5) an expression for the variance of u/u can be written as:

$$\sigma^2\{u/\breve{u}\} = \sigma^2\{u\}/\breve{u}^2 = \sum_1^n \frac{a_m^2\sigma^2\{z_m\}}{\breve{u}^2} = \sum_1^n \frac{a_m^2\breve{z}_m^2}{\breve{u}^2}\frac{\sigma^2\{z_m\}}{\breve{z}_m^2} \qquad \text{(L.16)}$$

But, from the definition of the Taylor series,

$$a_m = \left(\frac{\partial u}{\partial z_m}\right)_{z_m=\breve{z}_m} \qquad \text{(L.17)}$$

Furthermore, the definition of the dimensionless sensitivity coefficient, S_m, is given by:

$$S_m = \left(\frac{\breve{z}_m}{\breve{u}}\frac{\partial u}{\partial z_m}\right)_{z_m=\breve{z}_m} \qquad \text{(L.18)}$$

Then combining (L.16), (L.17), and (L.18) yields:

$$\frac{\sigma^2\{u\}}{\breve{u}^2} = \sum_1^n S_l^2 \cdot \frac{\sigma^2\{z_m\}}{\breve{z}_m^2} = \sum_l S_m^2 \cdot V_m^2 \qquad \text{(L.19)}$$

Where the term, V_m, denotes the coefficient of variation for variable z_m; i.e., the standard deviation of z_m divided by its mean. However, this requires that the mean value of the random variable is approximately equal to the point-estimate value of the same variable. This can be achieved by "anchoring" the distribution of the random variable, by making its mean (or possibly its median for a log-normal distribution) to the point estimate value for that variable. If the means of the independent random variables are equal to their point estimate values, it would be expected that the mean of the dose to be approximately equal to its point estimate value.

Although this may seem to be a lot of mathematical manipulation, the result summarized by Equation (L.19) is quite useful. Essentially the square of the coefficient of variation of u, (recall that u is another name for D_{jk}, the contribution to dose from a particular radionuclide and pathway) is equal to the sum over all variables of the square of the product of the sensitivity coefficient for the variable z_m and the coefficient of variation for that same variable. This is an approximate relationship, because it was assumed that the mean of the random variables is approximately equal to the point estimate value of the variable (including the dose). Although this is an approximate relationship, depending on the degree of fit of the Taylor series expansion, it provides a means to determine which variables contribute substantially to the variance of the incremental dose.

Equation (L.18) can be simplified further, by noting the following. Many of the equations used to estimate dose are of the form:

$$u = Az_1z_2z_3 \qquad \text{(L.20)}$$

Where A is a constant and the z_m's are variables. Then,

$$\frac{\partial u}{\partial z_1} = Az_2z_3 \qquad \text{(L.21)}$$

and

$$S_1 = \frac{\breve{z}_1}{\breve{u}}\frac{\partial u}{\partial z_1}_{z_m=\breve{z}_m} = \frac{\breve{z}_1}{A\breve{z}_1\breve{z}_2\breve{z}_3}A\breve{z}_2\breve{z}_3 = 1 \qquad \text{(L.22)}$$

If the equation is of the form:

$$u = Az_2z_3/z_1 \qquad \text{(L.23)}$$

then,

$$\frac{\partial u}{\partial z_1} = -Az_2z_3/z_1^2 \qquad \text{(L.24)}$$

and

$$S_1 = \frac{\breve{z}_1}{\breve{u}} \frac{\partial u}{\partial z_1}_{z_m = \breve{z}_{m1}} = \frac{\breve{z}_1}{(A\breve{z}_2\breve{z}_3 / \breve{z}_1^2)}(-A\breve{z}_2\breve{z}_3 / \breve{z}_1^2) = -1 \qquad \text{(L.25)}$$

Since many of the dose equations are of the form in Equation (L.20) or (L.23) the value to be used for S_m becomes either +1 or -1 in these cases. Since S_m is squared in Equation (L.19), the squared value, in many cases, will be unity. On this basis Equations (L.18) and (L.11) can be combined to yield:

$$\frac{\sigma^2\{D\}}{\breve{D}^2} = \sum_1^N \sum_1^M E_{jk}^2 \sigma^2 \left\{ \frac{D_{jk}}{\breve{D}_{jk}} \right\} = \sum_1^N \sum_1^M E_{jk}^2 \sum_1^n S_{jkm}^2 V_m^2 \qquad \text{(L.26)}$$

Note that now the sensitivity coefficient depends on the independent variable, m, as well as the Taylor series representation for the particular contributor to dose, jk. If the m ranges over all variables, then S_{jkm} will be approximately unity if the variable enters into the dose equation for that nuclide and pathway, otherwise it will be zero.

In evaluating this expression to determine which variables to include in the variance estimation, there are two distinct cases: (1) a variable enters into only one increment of dose, E_{jk}, and (2) a variable enters into two or more increments of dose. An example of case 1 is the uptake factor for ruthenium-106 from animal feed to milk. This variable enters only into the dose from the milk pathway for the isotope ruthenium-106. An example of case 2 is the absolute humidity variable that affects all food-chain pathways involving tritium. For case 1 the contribution to the normalized variance by variable l is given simply by:

$$V_m^2 E_{jk}^2 \qquad \text{(L.27)}$$

where the E_{jk} is defined as before as the value associated with the pathway and nuclide in which the variable l plays a role. For case 2 the contribution to the normalized variance by variable l is given by:

$$\sum_{j'} \sum_{k'} V_m^2 E_{jk}^2 \qquad \text{(L.28)}$$

where the summation is over all nuclides, j', and pathways, k', involving variable m. However, because V_m is frequently unity, then V_m^2 will be unity, and a good approximation to Equation (L.28) will usually be:

$$\sum_{j'} \sum_{k'} E_{jk}^2 \qquad \text{(L.29)}$$

where again the summation is over all nuclides, j', and pathways, k', involving variable m. The types of functional dependence that will make the sensitivity coefficient substantially different from unity are exponential, logarithmic, and power functions of the variables. This type of functional dependence in dose assessment does occur, but infrequently.

L.2 Summary of Implementation Approach

1. Take the entire set of about 350 input variables and eliminate from consideration any variables solely associated with the following pathways and radionuclides:

   a. Air Release:
      i. Radionuclides: Am-241, Cs-137, I-129, Sr-89, Sr-90, all isotopes of U
      ii. Pathways: ground contamination, grain, and soil ingestion

   b. Water Release:
      i. Radionuclides: I-129, Nb-95, Sr-89, all isotopes of U.
      ii. Pathways: Boating, swimming immersion, swimming inadvertent ingestion.

These radionuclides and pathways were eliminated from the dose assessment model used for the uncertainty analysis, because their cumulative contribution to the dose of all receptors was less than 5%.

2. Eliminate categories of variables not considered suitable for inclusion in the uncertainty analysis. For example, dose and risk coefficients, although uncertain, were considered to be certain variables. These variables, whose nominal values are established by national and international standards organizations, have less uncertainty than many other variables in the study; furthermore, incorporating their variability would confound the results from other variables. Variables specified by scenarios, e.g. consumption values such as breathing rate and quantities of food ingested, were considered to be certain. The variability in these variables was considered to be addressed by the creation and use of the scenarios; incorporating variability for these variables would confound the effects of the various scenarios and blur their differences.

3. Develop Tables of the E^2jk based on a couple of representative receptors for air and water (e.g., Rural Family 2, the adult female and child born in 1964).

4. Use the results of Step 3 to focus on a few key pathways and radionuclides. Identify the variables involved in those pathways and radionuclides. Then develop the distributions describing the uncertainty in those variables. Form the products indicated in Equation (L.27). If any product is noticeably small, eliminate that variable from further consideration. In the case that a variable is used for all pathways, but a single radionuclide, an appropriate sum based on Equation (L.29) can be used instead of Equation (L.27);

5. Look at the entire list (singleton variables) and the approximate contribution to variance computed for each. Order according to expected importance and draw an appropriate line for inclusion/elimination.

6. Evaluate the eliminated variables to make sure consideration of multiple radionuclides or pathways would not cause it to be included; include if appropriate.

L.3 Tables

Table L-1 presents the contribution to total dose by pathway and radionuclide. The contribution of some radionuclides has been eliminated (Am-241, Cs-137, I-129, Sr-89, Sr-90, all isotopes of U), as has the contribution of some pathways (ground contamination, grain, and soil ingestion). These numbers are the D_{jk} in the notation of this Appendix. Note that the maximum value is 3.48E-04 for I-131 and beef ingestion.

Table L-2 identifies the reduced renormalized matrix. For this matrix, we have eliminated the noncontributing pathways and radionuclides and renormalized by the total dose based on those pathways and nuclides included. The highlighted cell indicates the maximum contributor to dose (I-131 through beef ingestion). The entries in this table are approximately equal to E_{jk}/E_{total}.

Table L-3 matrix is the square of the normalized contribution to dose (E^2jk in my notation) divided by the maximum value of these numbers. The highlighted terms contribute at least 1% of the maximum value. The sum of these four terms constitutes over 98% of the sum over all terms.

The matrix presented in Table L-4 is the square of the normalized contribution to dose (E^2jk in my notation) divided by the maximum value of these numbers. The highlighted terms contribute at least 1% of the maximum value. The sum of these four terms constitutes over 98% of the sum over all terms.

Table L-1 Contribution to Total Dose by Pathway and Radionuclide

	Am-241	Ar-41	C-14	Cs-137	H-3	I-129	I-131	Pu-238	Pu-239	Ru-106	Sr-89	Sr-90	U-234	U-235	U-236	U-238	Sum Over
Air Immers	0.00E+00	5.39E-05	2.55E-12	0.00E+00	0.00E+00	0.00E+00	2.30E-07	1.58E-15	1.00E-14	3.63E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.41E-05
Ground Cc	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Beef	0.00E+00	0.00E+00	1.74E-06	0.00E+00	1.14E-05	0.00E+00	3.48E-04	1.56E-10	1.31E-09	1.83E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.63E-04
Eggs	0.00E+00	0.00E+00	7.13E-08	0.00E+00	2.60E-06	0.00E+00	2.44E-14	4.69E-14	3.30E-13	7.44E-13	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.67E-06
Fruit	0.00E+00	0.00E+00	3.72E-07	0.00E+00	9.70E-06	0.00E+00	1.28E-05	2.20E-08	1.84E-07	5.12E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.31E-05
Grain	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Leafy Vege	0.00E+00	0.00E+00	1.10E-07	0.00E+00	3.10E-06	0.00E+00	3.77E-05	6.50E-08	5.42E-07	1.51E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.17E-05
Milk	0.00E+00	0.00E+00	8.80E-07	0.00E+00	1.63E-05	0.00E+00	9.45E-05	2.06E-11	1.45E-10	1.37E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.12E-04
Poultry	0.00E+00	0.00E+00	6.66E-08	0.00E+00	1.85E-06	0.00E+00	4.26E-17	1.92E-13	1.60E-12	8.42E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.91E-06
Root Vege	0.00E+00	0.00E+00	3.76E-07	0.00E+00	9.81E-06	0.00E+00	4.21E-06	2.22E-08	1.86E-07	5.05E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.47E-05
Soil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Air Inhalati	0.00E+00	0.00E+00	8.04E-10	0.00E+00	1.30E-05	0.00E+00	2.75E-05	2.72E-06	1.89E-05	1.25E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.23E-05
Resuspen	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.98E-07	1.17E-06	8.13E-06	4.30E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.74E-06
Total Over	0.00E+00	5.39E-05	3.62E-06	0.00E+00	6.78E-05	0.00E+00	5.26E-04	4.00E-06	2.79E-05	2.25E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.85E-04
Total Dose	6.96E-04																

Table L-2 Reduced Renormalized Matrix

REDUCED RENORMALIZED MATRIX
Rural Family #2
Adult Female

	Ar-41	C-14	H-3	I-131	Pu-238	Pu-239	Ru-106	Sum Over I
Air Immers	7.86E-02	3.73E-09	0.00E+00	3.36E-04	2.31E-12	1.46E-11	5.30E-07	7.90E-02
Beef	0.00E+00	2.54E-03	1.66E-02	5.08E-01	2.27E-07	1.91E-06	2.67E-03	5.30E-01
Eggs	0.00E+00	1.04E-04	3.79E-03	3.56E-11	6.85E-11	4.82E-10	1.09E-09	3.89E-03
Fruit	0.00E+00	5.44E-04	1.42E-02	1.87E-02	3.21E-05	2.68E-04	7.47E-05	3.37E-02
Leafy Vege	0.00E+00	1.60E-04	4.52E-03	5.51E-02	9.48E-05	7.91E-04	2.20E-04	6.09E-02
Milk	0.00E+00	1.28E-03	2.38E-02	1.38E-01	3.00E-08	2.11E-07	2.01E-07	1.63E-01
Poultry	0.00E+00	9.71E-05	2.70E-03	6.22E-14	2.80E-10	2.34E-09	1.23E-06	2.79E-03
Root Vege	0.00E+00	5.49E-04	1.43E-02	6.14E-03	3.23E-05	2.71E-04	7.36E-05	2.14E-02
Air Inhalati	0.00E+00	1.17E-06	1.90E-02	4.02E-02	3.98E-03	2.76E-02	1.83E-04	9.09E-02
Resuspen	0.00E+00	0.00E+00	0.00E+00	5.81E-04	1.70E-03	1.19E-02	6.27E-05	1.42E-02
Total Over	7.86E-02	5.28E-03	9.89E-02	7.67E-01	5.84E-03	4.08E-02	3.28E-03	1.00E+00

Table L-3 Eij^2/max Eij^2

Eij^2 / max Eij^2
Rural Family #2
Adult Female

	Ar-41	C-14	H-3	I-131	Pu-238	Pu-239	Ru-106	Sum Over I
Air Immers	2.39E-02	5.38E-17	0.00E+00	4.38E-07	2.06E-23	8.29E-22	1.09E-12	2.39E-02
Beef	0.00E+00	2.50E-05	1.06E-03	1.00E+00	2.00E-13	1.41E-11	2.75E-05	1.00E+00
Eggs	0.00E+00	4.19E-08	5.56E-05	4.92E-21	1.82E-20	8.99E-19	4.56E-18	5.56E-05
Fruit	0.00E+00	1.14E-06	7.75E-04	1.35E-03	3.99E-09	2.78E-07	2.16E-08	2.12E-03
Leafy Vege	0.00E+00	9.96E-08	7.91E-05	1.17E-02	3.48E-08	2.42E-06	1.87E-07	1.18E-02
Milk	0.00E+00	6.38E-06	2.20E-03	7.36E-02	3.49E-15	1.73E-13	1.56E-13	7.58E-02
Poultry	0.00E+00	3.65E-08	2.81E-05	1.49E-26	3.03E-19	2.11E-17	5.85E-12	2.82E-05
Root Veget	0.00E+00	1.17E-06	7.94E-04	1.46E-04	4.04E-09	2.84E-07	2.10E-08	9.41E-04
Air Inhalati	0.00E+00	5.33E-12	1.40E-03	6.24E-03	6.11E-05	2.94E-03	1.29E-07	1.06E-02
Resuspenc	0.00E+00	0.00E+00	0.00E+00	1.30E-06	1.12E-05	5.45E-04	1.52E-08	5.57E-04
Total Over	2.39E-02	3.38E-05	6.39E-03	1.09E+00	7.24E-05	3.49E-03	2.79E-05	1.13E+00

Table L-4 Child Born in 1964

Eij^2 / max Eij^2
Rural Family #2
Child born 1964

	Ar-41	C-14	H-3	I-131	Pu-238	Pu-239	Ru-106	Sum Over I
Air Immers	4.62E-01	1.88E-15	0.00E+00	1.17E-09	1.69E-21	6.85E-23	3.25E-11	4.62E-01
Beef	0.00E+00	1.74E-03	7.68E-02	2.83E-02	3.03E-11	1.46E-12	4.58E-03	1.11E-01
Eggs	0.00E+00	3.21E-06	4.24E-03	2.42E-22	2.40E-18	1.37E-19	8.93E-16	4.24E-03
Fruit	0.00E+00	6.71E-05	5.76E-02	5.70E-05	4.79E-07	3.91E-08	3.95E-06	5.77E-02
Leafy Vege	0.00E+00	1.53E-06	1.25E-03	5.72E-05	1.19E-06	4.41E-08	5.27E-06	1.31E-03
Milk	0.00E+00	2.57E-03	1.00E+00	3.03E-02	3.46E-12	2.36E-13	2.42E-10	1.03E+00
Poultry	0.00E+00	1.89E-06	1.38E-03	3.67E-28	3.41E-17	1.66E-18	7.94E-10	1.38E-03
Root Veget	0.00E+00	4.41E-05	3.46E-02	1.91E-06	1.39E-07	1.22E-08	1.62E-06	3.46E-02
Air Inhalati	0.00E+00	4.02E-10	9.47E-02	2.63E-04	8.29E-03	3.15E-04	1.16E-05	1.04E-01
Resuspenc	0.00E+00	0.00E+00	0.00E+00	5.66E-08	1.52E-03	5.80E-05	1.36E-06	1.58E-03
Total Over	4.62E-01	4.43E-03	1.27E+00	5.90E-02	9.81E-03	3.73E-04	4.61E-03	1.81E+00

APPENDIX M PROBABILITY DISTRIBUTIONS FOR UNCERTAIN VARIABLES

This appendix provides a brief discussion on how a probability distribution for each of the 21 uncertain variables was determined. The type of distribution and its parameters, e.g., mean and standard deviation, are briefly discussed.

Lognormal distribution was assumed for all, except two, of the 21 uncertain variables. Normal distribution was assumed for ABSHUM and CONSUM, 5. Assumptions regarding probability distributions were based on literature survey, including studies similar to the ones provided in the main report.

While the spreadsheets provided in this appendix may have long names for detailed identification purposes, they are also identified as Spreadsheet M1, M2, through M11…to make the task of referencing easier.

It should be noted that for each lognormal distribution assumed, the log mean value is the natural logarithm of the point estimate value of the variable under consideration. In other words, the point estimate value is the geometric mean (or the arithmetic median) of the distribution.

M.1 Probability Distribution and its Parameters for the Release Factor F (Variable 21)

M.1.1 F, Release Factor (Variable 21)

Spreadsheet M1 provides the following information on the isotopes of interest in air and water:

- Isotopes in air (H-3, I-131, Pu, U).
- Isotopes in water (Cs-137, Sr-90, H-3).
- Sources involved in releasing the isotopes.
- Sigma Y bar (log standard deviations averaged over all years) for each isotope.
- The total release for each isotope.
- Weighted average of Sigma Y bars (weighting done with respect to the total releases).
- Overall weighted average of Sigma Y bars.

The overall weighted averages for air and water isotopes were determined as 0.2310, and 0.2034, respectively.

The steps and formulas that were followed to compute values reflected in Spreadsheet M1 ("Sigmas and Totals") are provided below.

Sigma Y (Log standard deviation) for each year, and the average (over all years) Sigma Y, referred to as Sigma Y bar, were calculated in the right most block (or at the bottom) of Spreadsheets M2 through M7 with the following titles respectively (the string "ASM122903" has been added to each file name for identification purposes only):

- Annual_reactor_releasesASM122903.
- Annual_Tritium_Facility_releasesASM122903.
- Est_I-131_Releases_(Reactors)ASM122903.
- Revised_I-131_Releases_(F,H)ASM122903.

- Estimated_Source_TermASM122903.
- Water_ReleasesASM122903.

Within each spreadsheet, for each isotope of interest, and for each release year, the value of Sigma Y has been calculated in three steps (columns). In some cases, geometric standard deviation (GSD) has been computed too (Step 4). The averages (arithmetic means) of the computed values over all years are provided at the bottom of the columns within the spreadsheet. The total release (over all years) was also calculated (to the left of the spreadsheet). The steps and formulas used are as follows:

1. Find the ratio of the 95th percentile (95%) over the 5th percentile (5%).
2. Take the natural log of the ratio obtained in step 1.
3. Divide the result of step 2 by 3.29.
4. GSD = EXP(Sigma Y).

It should be noted that in the spreadsheet "Revised_I-131_Releases_(F,H)ASM122903," M5, a weighted average (considering the weights in columns O and P) has been calculated for Sigma Y in each row. And, within "Water_ReleasesASM122903," M7, it should be noted that the sheets/tabs named "Cs annual," "Sr-annual," and "Tritium-annual" have been considered.

The following three spreadsheets (M8 through M10) provided the total releases used in computing the weighted averages (the string "ASM122903-Totals" has been added to each name for identification purposes only):

- Air Master Templete_Revised_Uncertainty4ASM 122903-Total
- SR Liquid Release Cat 13 Master_Revised_Total_110703_Uncertainty2ASM 122903-Totals
- Sr-89_Sr-90_Sr-8990_UN BetaGamma_Cat 13_Revised_Uncertainty1ASM 122903-Totals

The Sigma Y bar values and the total releases obtained from Spreadsheets M2 through M10 have been reflected in Spreadsheet M1, where the overall weighted averages of Sigma Y bars (with respect to total releases) have been computed.

It should be noted that for H-3 from facility releases, the total releases have been obtained from the same spreadsheet that the Sigma Y bar values come from ("Annual_Tritium_Facility_releasesASM122903," M3), and the total value of 17820415 has not been used.

Each weighted average has been obtained by considering the following steps:

1. Adding up the product of each Sigma Y bar and its associated total release
2. Dividing the value obtained in Step 1 by the grand total release.

Considering the calculated values of the weighted averages of Sigma Y Bars for water and air, an overall log Standard Deviation of 0.2 was chosen to accompany a log mean value of 0.

Tab 21 of Spreadsheet M11, provided below, contains more details regarding the release factor F than Spreadsheet M1.

M1	M2	M3	M4	M5
Sigmas and Totals1.xls	Annual_reactor_releasesASM122903.xls	Annual_tritium_facility_releasesASM12290	Est_I-131_Releases_(Reactors)ASM12290	Revised_I-131_Releases_(F,H)

M6

Estimated_Source_T
ermASM122903.xls

M7

Water_ReleasesASM
122903.xls

M8

Air Master
Templete_Revised_U

M9

SR Liquid Release
Cat 13 Master_Revise

M10

Sr-89_Sr-90_Sr-8990
_UN BetaGamma_Cat

M.2 Probability Distributions and Their Parameters for Uncertain Variables

The natural logarithm of the point estimate for each lognormally distributed variable was considered to be the log mean of the distribution. In other words, the point estimate of each lognormally distributed variable was treated as the geometric mean or the arithmetic median.

Spreadsheet M11, provided below, and the following paragraphs provide the values, the references, and the resulting statistics leading to the identification of the log mean (log of point estimate) and log standard deviation, or arithmetic mean and arithmetic standard deviation of the probability distribution of the uncertain variables considered in the uncertainty analysis.

The numbered tabs in Spreadsheet M11 correspond to the uncertain variables with the same numbers. Tab "A" provides more details regarding variables number 1, 2, and 3 than Tab "1-6" does.

M11

UVS021004.xls

M.2.1 CLBFF, Cs-137; CLBFF, Sr-90; and CLBFF, P-32 (Variables 1, 2, and 3)

Tab "A" of Spreadsheet M11 provides the detailed information, references, and the computation leading to the parameters of the lognormal distributions for the bioconcentration in fish.

CLBFF, Cs-137 was assumed to be lognormally distributed. The log standard deviation was computed based on the three mean values obtained from Friday 1996 and the expected value was obtained from IAEA Technical Report No. 364.

CLBFF, Sr-90 was assumed to be lognormally distributed. The standard deviation was computed based on the two maximum values obtained from Friday 1996, and the expected value was obtained from IAEA Technical Report No. 364.

CLBFF,P-32 was assumed to be lognormally distributed. The standard deviation was computed based on the natural log of the ratio of maximum over minimum divided by 3.92. The data used were from IAEA Technical Report No. 364, p.45.

M.2.2 CLFMK, I-131; CLFMT, I-131 (Variables 4 and 5)

In addition to providing a summary of information on Variables 1, 2, and 3, Tab "1-6" of Spreadsheet M11 shows how the parameters for the lognormally distributed CLFMK, I-131 and CLFMT, I-131 (Variables 4 and 5, respectively) were found.

Page 35 of IAEA Technical Report No. 364 provides the following information for CLFMK, I-131:

- Expected value (point estimate) = 0.01 d/L
- 95% confidence interval: 0.001 - 0.035 days/Liter (d/L)

The log mean was determined as Ln (0.01) = 4.60517 and the log standard deviation was determined as the natural logarithm of the ratio of upper bound over lower bound of the confidence interval divided by 3.92 = 0.90698

Page 37 of IAEA Technical Report No. 364 provides the following information for CLFMT, I-131:

- Expected value (point estimate) = 0.04 d/L
- 95% confidence interval: 0.007 - 0.05 d/L

The log mean was determined as Ln (0.04) = -3.21888 and the log standard deviation was determined as the natural logarithm of the ration of upper bound over lower bound of the confidence interval divided by 3.92 = -0.50156

M.2.3 ABSHUM (Variable 6)

A normal probability distribution was assumed for ABSHUM (Variable 6) with an arithmetic mean of 0.01125 kg/m^3 and a standard deviation of 0.00053 kg/m^3 (Hamby 1993, p. 34). Tab "1-6" of Spreadsheet M11 reflects the said values in their corresponding columns.

M.2.4 BIOMA2, 5&6 (Variable 7)

Tab "7" of Spreadsheet M11 provides the information used, along with its corresponding reference (NUREG/CR-5512, Vol. 3, Table 6.56), to determine the lognormal distribution for BIOMA2, 5&6 (Variable 7). The log mean (-1.203973) was determined as the natural log of the point estimate. The log standard deviation was calculated as 0.081393.

M.2.5 BIOMA2, 3 (Variable 8)

Tab "8" of Spreadsheet M11 provides the information used, along with its corresponding reference (NUREG/CR-5512, Vol. 3, Table 6.52), to determine the lognormal distribution for BIOMA2, 3 (Variable 8). It is noted that the arithmetic mean and the arithmetic standard deviation of the lognormal distribution are provided as 1.43156 and 0.02909, respectively.

M.2.6 BIOMAS, 1 (Variable 9)

As indicated in Tab "9" of Spreadsheet M11, the ratio of standard deviation over mean (ASD/AM) has been calculated for each row, then, the arithmetic mean of the ratios has been found as 0.034859. As explained in the main report, rations like the one found for BIOMAS, 1 were found for all of the 21 uncertain variables. The ratio was used as a factor contributing to the determination of the variable's rank, which, in turn, helped the analysts consider 7 of the 21 variables as "certain" variables.

M.2.7 WTIM, (Variable 10)

Tab "10" of Spreadsheet M11 shows how the log standard deviation for WTIM (1.403107) was computed from the minimum, maximum, and mode values obtained from page 6-16 of Attachment C of NUREG/CR 6697. Like any other lognormally distributed variable discussed before, The log mean was considered to be the natural log of the point estimate of the variable (WTIM).

M.2.8 CONSUM 5 (Variable 11)

Tab "11-12" of Spreadsheet M11 shows how a normal distribution was assumed for CONSUM, which had a gamma distribution with the given parameters (NUREG/CR-5512, Vol. 3, Table 6.69). Because of the similarity between Gamma and normal distributions, through scaling and the use of the point estimate value, the standard deviation of the normal distribution was calculated as 8.63005. The mean value was considered to be the same as the point estimate value.

M.2.9 CONSUM, 3 (Variable 12)

As indicated in Tab "13" of Spreadsheet M11, the arithmetic mean and arithmetic standard deviation of CONSUM, 3 were provided by Table 6.69 of NUREG/CR-5512, Vol. 3 as 1.71, and 0.262, respectively.

M.2.10 DRYFAC, 1 (Variable 13)

Tab "11-12" of Spreadsheet L12 shows how a lognormal distribution was obtained for DRYFAC, 1 from the gamma distribution parameters provided by NUREG/CR-5512, Table 6.79. The arithmetic mean and arithmetic standard deviation were determined as 0.108753 and 0.002175, respectively.

M.2.11 GRWP, 1 (Variable 14)

Tobacco was used as a surrogate for Variable 14. The usual planting and harvesting dates for states of Georgia and South Carolina were considered for this variable. The duration between each planting date and its corresponding harvesting date was computed for each state. The mean and standard deviation of the computed durations were calculated for each state along with their ratio. These values were 110, 18.27567, and 0.166142 for GA, respectively; and 108, 18.51801, and 0.171067 for SC, respectively. The average ratio (0.168605) was considered to be the ratio of standard deviation over mean for GRWP, 1. The data used were from Usual Planting and Harvesting Dates for U.S. Field Crops December 1997; USDA Handbook Number 628.

M.2.12 GRWPA, 5&6 (Variable 15)

According to personal communication from Dr. Bruce Pinkerton, Clemson University Extension Station, to Norman A. Eisenberg, February 3, 2004, harvesting times for bermuda grass are 3 weeks at the smallest, 6 weeks on average, and 3 months at most. The log standard deviation for GRWPA, 5&6 (0.442337) was calculated by following the steps provided below.

1. Calculating the ratio of the maximum harvesting time (considered as the 95th percentile) over the minimum harvesting time (considered as the 5th percentile).
2. Taking the natural logarithm of the ratio obtained in Step 1.
3. Dividing the results obtained in Step 2 by 3.29.

M.2.13 GRWPA, 3 (Variable 16)

Corn was considered as the milk animal feed (Variable 16). The usual planting and harvesting dates for states of Georgia and South Carolina were considered for this variable. The duration between each planting date and its corresponding harvesting date was computed for each state. The mean and standard deviation of the computed durations were calculated for each state along with their ratio. These values were 146, 6.377042, and 0.043678 for GA, respectively; and 146, 8.539126, and 0.058387 for SC, respectively. The average ratio (0.051033) was considered to be the ratio of standard deviation over mean

for GRWPA, 3. The data used were from Usual Planting and Harvesting Dates for U.S. Field Crops December 1997; USDA Handbook Number 628.

M.2.14 DEPFR1,2 (Variable 17)

Ali A. Sympkins, "Uncertainty in Transport Factors Used to Calculate Dose from I-131 Releases at SRS for Period of 1955-1961," provides the range for DEPFR1and DEPFR2 as 0.09 to 0.9. Considering the given values as the bounds for 95 percent confidence interval, and assuming a lognormal distribution, the log standard deviation is obtained as the natural log of the ratio of upper bound over lower bound divided by 3.92. The value obtained is 0.587394.

M.2.15 LEAFRS, RESFAC;1 (Variable 18)

The resuspension factors associated with seven different activities are obtained from Atmospheric Science and Power Production, 1984, DOE/TIC-27601, Table 12.9, p. 567. A lognormal distribution is assumed for Variable 18. The log standard deviation for the assumed lognormal distribution is calculated as the standard deviation of the natural logarithm of the seven resuspension factors considered. The log standard deviation was determined to be 2.621412906.

M.2.16 DPVRES (Variable 19)

Table F.1 of the source given below provides a default value and a range for the deposition velocity. The sources indicated in that table are Peterson (1983) and NCRP (1989).

Source: Risk Assessment Information System (RAIS), Appendix F (Food Chain Models for Risk Assessment); Website: http://risk.lsd.ornl.gov/homepage/bjcor271/appf.shtml

A lognormal distribution was assumed for this variable, and the given range was considered to be the 95 percent confidence interval. The log standard deviation was determined by

1. Finding the ratio of the upper limit of the interval by the lower limit of the interval
2. Taking the natural log of the ratio obtained in step 1
3. Dividing the value obtained in Step 2 by 3.92.

The value obtained for the log standard deviation was 1.255534931.

It is noted that the point estimate value used for Variable 19 was 0.001, whose natural logarithm was considered to be the log mean value.

M.2.17 Radius (Variable 20)

Phase II, Chapter 4, p. 4.4-14, Table 4-4.3 provides the geometric mean and geometric standard deviation of the mean. Natural logarithm of the geometric standard deviation provided the log standard deviation for the lognormally distributed radius. The value calculated was 0.405465.

APPENDIX N INPUT DATA FOR LJS AND GEN II COMPUTER CODES

The input data provided to the GEN II computer code for stochastic analysis are provided in this appendix. These input data are shown in Table N2 provided below, as a 40 by 14 matrix. These data, in turn, are the output of the LHS code whose input data are provided below in Table N1.

Each row of the input data matrix (Table N2) is one realization (one computer run), resulting in one total dose value (a total of 40 dose values corresponding to 40 realizations) for each receptor. The 14 columns of the input data matrix correspond to the 14 uncertain variables involved in the stochastic analysis. In other words, Variable numbers 1 through 14 in the left column of Table N1 correspond to the column labels X(1) through X(14) in Table N2, respectively.

N1

Document.txt

N2

srs3output.txt

APPENDIX O TOTAL 39-YEAR DOSE FOR EACH RECEPTOR

The results of computer runs (based on the GEN II computer code and post processing) for the seven hypothetical four-member families (a total of 28 receptors) are provided in this appendix. Each family was subjected to a different exposure scenario. Forty one total dose values are listed for each receptor. Each total dose value is the result of a realization (a computer run). Run 0 is a run based on the simplified model (reduced pathways and isotopes) that used the point estimate values. Run 0 results were compared with the results obtained for the point estimate (non-simplified model) run. This comparison showed the impact of the model simplification (pathway and isotope reduction) on the point estimate results.

The results contained in the following seven spreadsheets are discussed in details in Chapter 12.

O1
Delivery Family Sensitivity.xls

O2
Migrant Family Sensitivity.xls

O3
Near Water Family Sensitivity.xls

O4
Outdoor Family Sensitivity.xls

O5
Rural Family One Sensitivity.xls

O6
Rural Family 2 Sensitivity.xls

O7
Urban Family Sensitivity.xls

APPENDIX Q INHALATION AND EXTERNAL EXPOSURE DATA TABLES

The inhalation and external exposure rates that were used in the GENII V2 model are provided in this appendix.

Inhalation And External Tables

APPENDIX R BASIS FOR DETERMINING ISOTOPIC FRACTIONS FROM SRS ENVIRONMENTAL REPORTS FOR PERFORMING RADIOLOGICAL DOSE ASSESSMENTS

The quantification of environmental releases on an isotopic basis is needed to perform radiological dose assessments. Each isotope has a different half-life, thus making its contribution to the total radioactivity released from the site different from other isotopes. Each isotope also has a unique dose conversion factor, making it important to know the specific isotopes released to conduct the radiological dose assessments. Because a number of constituents are not delineated by isotope in environmental release reports, assumptions need to be developed based on nuclear physics and knowledge of the process history of the SRS facilities.

Throughout much of the history of the Savannah River Site (SRS), technology and programmatic limitations have restricted the ability to differentiate environmental releases on an isotopic basis. Gross alpha (α) and gross beta + gamma ($\beta + \gamma$) measurements were primarily used to measure radioactive releases (Cummins et al., 1991) to the air, seepage basins, and surface waters in many facilities. SRS has historically had a practice of reporting specific isotopes from the gross alpha/beta/gamma measurements if the isotopes are known to be in the effluent (Evans et al., 1992).

This appendix provides the technical basis and assumptions for quantifying environmental releases by isotopes that have not been specifically identified in SRS environmental reports.

R.1 Constituents

As stated above, the environmental release reports being used for the radiological dose assessments do not, in some cases, delineate individual isotopes but instead show total radioactivity for a combination of isotopes (or constituent). Constituents shown in various SRS environmental reports whose total radioactivity needs to be fractioned into individual isotopes include:

- Sr-89, Sr-90
- Zr-95, Nb-95
- Cs-134, Cs-137
- Uranium
- Plutonium
- Unidentified alpha
- Unidentified beta + gamma

Technical information and general assumptions for determining the fraction an individual isotope contributes to the total radioactivity of the constituent are described below with more detailed application to site facilities as applicable. When appropriate, each of the above constituents is analyzed on the basis of the process to which it is related to determine the fraction of the activity to be designated to individual isotopes. Table R-1 summarizes how the radioactivity of each constituent should be fractioned for the applicable SRS site areas.

Table R-1 Summary of Assumed Isotopic Distributions

Constituent	SRS Area	Isotopic Distribution (by Curies)
Sr-89, 90	F&H Areas	75% Sr-89; 25% Sr-90
	A Area	100% Sr-90
	D Area	100% Sr-90
	Central Shops	100% Sr-90
Zr, Nb-95	Reactor Areas	35% Zr-95; 65% Nb-95
	F, H, and D Areas	31% Zr-95; 69% Nb-95
Cs-134, 137	D Area	100% Cs-137
Uranium	Reactor Areas	91.73% U-234; 1.79% U-235; 6.45% U-236; 0.03% U-238
	F Area	1.27% U-235; 98.73% U-238
	H Area	91.73% U-234; 1.79% U-235; 6.45% U-236; 0.03% U-238
	M Area	Air emissions: 49.49% U-234; 2.25% U-235; 48.26% U-238 Liquid emissions: 1.27% U-235; 98.73% U-238
	A Area (SRL)	91.44% U-234; 1.8% U-235; 6.4% U-236; 0.36% U-238
	CMX/TNX	49.49% U-234; 2.25% U-235; 48.26% U-238
	D Area	91.73% U-234; 1.79% U-235; 6.45% U-236; 0.03% U-238
Total Plutonium	All Areas	100% Pu-239
Unidentified Alpha	All Areas	100% Pu-239
Unidentified Beta + Gamma	All Areas	100% Sr-90

R.2 Isotopic Fraction Evaluation

R.2.1 Strontium-89, 90 (Sr-89, 90)

Sr-89 and Sr-90 are shown together in the Cummins et al. historical report as a single constituent (Cummins, 1991) for liquid releases from SRL to seepage basins, liquid releases from D Area to streams, atmospheric releases in F and H Areas, and liquid releases to seepage basins in Central Shops. It is necessary to determine what curie fraction contributes to the total value reported for each of these facilities and environmental pathways.

Sr-89 and Sr-90 are fission products generated from the bombardment of U-235, U-238, and Pu-239 with neutrons. Carlton et al. calculated the number of curies related to the generation of Sr-89 and Sr-90 in the production reactors, assuming a typical fuel element composition. The number of curies associated with each of these strontium isotopes is summarized in Table R-2.

Based on Table R-2, the percentage of curies of Sr-89, 90 associated with Sr-89 is calculated and presented in Table R-3.

Table R-2 Accumulated Fission Yields (Carlton et al., 1994a)

Isotope	Half-Life	Curies Remaining at Various Times After End of Irradiation				
		0 seconds	24 hours	100 days	200 days	2 years
Sr-89	53.21 days	9.080E7	8.962E7	2.468E7	6.707E6	6.685E3
Sr-90	28.28 years	2.219E6	2.219E6	2.204E6	2.189E6	2.113E6

Table R-3 Percentage of Sr-89 to the Total Curies Associated with Sr-89, Sr90

Isotope	0 seconds	24 hours	100 days	200 days	2 years
Sr-89	98%	98%	92%	75%	0.3%

The percentages in Table R-3 are used to determine the fraction of Sr-89 and Sr-90 assumed to be released for the situations in which releases are shown for the combined Sr-89, 90 data as following:

Separations Areas: Fuel and target elements were stored in the reactor basins for a nominal period of 200 days after completion of irradiation before being processed in F and H Areas (Carlton et al., 1994a). For F and H Areas, it should be assumed that the environmental releases to the atmosphere occur 200 days after completion of irradiation in the reactors. Sr-89, 90 atmospheric releases should therefore be fractioned to 75% Sr-89 and 25% Sr-90 for these releases.

Administration Area (A): Environmental releases of Sr-89, 90 in A Area are attributed to releases from SRL to the SRL seepage basins. SRL conducted research using various forms of uranium and plutonium. Strontium isotopes were generated as a result. SRL also worked with Cf-252 for several years, and Sr-90 is daughter product of this isotope. It cannot be determined to what proportion Sr-89 to Sr-90 was generated by operations at SRL; therefore it should be assumed that all of the environmental releases attributed to Sr-89, 90 are attributed to Sr-90 for conservatism in dose calculations since Sr-90 has higher inhalation and ingestion dose conversion factors than Sr-89.

D Area: D Area was used to separate light water from used moderator from the reactors (Carlton et al., 1994a). This process can be assumed to occur within one year after receipt of the moderator from the reactors. It is unclear as to how long the moderator was typically removed from the reactor before it was processed in D Area; therefore it should be assumed that all of the environmental releases attributed to Sr-89, 90 are attributed to Sr-90 for conservatism in dose calculations since Sr-90 has higher inhalation and ingestion dose conversion factors than Sr-89.

Central Shops: The Central Shops (CS) were used for repairing equipment from the reactors and separations areas. Prior to repair of the equipment, the equipment was cleaned with water. The discharge water was discharged to seepage basins. The discharge of the water is assumed to occur approximately 2 years after the Sr-89, 90 contained in the discharge water was originally generated. The curie content of Sr-89, 90 from Central Shops should therefore be attributed to Sr-90 for conservatism in dose calculations.

R.2.2 Zirconium-95, Niobium-95 (Zr, Nb-95)

Zr-95 and Nb-95 are fission products. Nb-95 is also the only daughter product of Zr-95. Zr-95 has a half-life of 64.02 days and Nb-95 has a half-life of 34.975 days. Table R-4 shows that these isotopes are initially generated as fission products in equal mass amounts (KAERI, 2003).

Table R-4 Accumulated Fission Yields

Fissile with Neutron Energy	Accumulated Yield	
	Zr-95	Nb-95
U-235 with 0.0253 eV	0.06	0.06
U-235 with 1.0 MeV	0.06	0.06
U-238 with 1.0 MeV	0.05	0.05
Pu-239 with 0.0253 eV	0.05	0.05
Pu-239 with 1.0 MeV	0.05	0.05

Equation 1 can be used to determine the initial curie content in the production reactors assuming equal masses of Zr-95 and Nb-95 are produced in the reactors and assuming the reactors operate with neutron thermal energies shown in Table R-4:

$$A = \lambda N \qquad \text{(Eq. 1; Hankins, 1988)}$$

at t (time) = 0; A is the activity; λ is the radioactive decay constant; and N is the number of atoms. At any time t greater than 0, equation 2 applies:

$$A(t) = A_0 e^{-\lambda t} \qquad \text{(Eq. 2; Hankins, 1988)}$$

Since the fission yields (the number of atoms emitted) of Zr-95 and Nb-95 are equal, their contribution to the gross activity of Zr-95, Nb-95 is calculated to be 35% for Zr-95 and 65% for Nb-95 immediately upon their generation in the reactor.

The half-life of the daughter is less than (but not much less than) the half-life of the parent isotope. The time (t_{max}) at which the maximum activity of Nb-95 will occur, based on its production from the decay of Zr-95, is 67 days, calculated from the following equation (Hankins, 1988):

$$t_{max} = \frac{\ln \frac{l_{Nb}}{l_{Zr}}}{l_{Nb} - l_{Zr}} \qquad \text{(Eq. 3; Hankins, 1988)}$$

After 67 days, the activity of Nb-95 begins to decline at the same rate as the decline in activity of Zr-95 (this is called transient equilibrium). This ratio can be calculated by the following (Hankins, 1988):

$$\frac{A_{Nb}}{A_{Zr}} = \frac{l_{Nb}}{l_{Nb} - l_{Zr}} = 2.2 \qquad \text{(Eq. 4; Hankins, 1988)}$$

Based on the decay chain and the calculated ratio after the 67 day maximum, the ratio of isotopic activity approaches a constant value where 31% of the total activity is due to Zr-95 and 69% of the activity is due to Nb-95. These percentages are appropriate for operations which would occur after the removal of the fuel and targets from the reactors. By SRS process area, then, the following isotopic fractions can be used:

Reactor Areas:	35% Zr-95	65% Nb-95
All other areas:	31% Zr-95	69% Nb-95

These assumed values are based on assumptions that are meant to best reflect actual operating conditions and environmental releases. Carlton and Denham, in determining the potential dose to individuals from these same isotopes, used more conservative assumptions that are based on the impact on dose (Carlton and Denham, 1997).

R.2.3 Cesium-134, 137 (Cs-134, 137)

The cesium isotopes were generated at SRS as fission products and, in the case of Cs-137, was at times isolated for further use as an energy source. The combined constituent Cs-134, 137 is shown (Cummins et al., 1991) in environmental releases in D-Area. Cs-134 has a half-life of 2.06 years while Cs-137 has a half-life of 30.07 years. Table R-5 shows the yield of Cs-134 and Cs-137 that is assumed for reactor operations (KAERI, 2003).

Table R-5 Accumulated Fission Yields

Fissile with Neutron Energy	Accumulated Yield	
	Cs-134	Cs-137
U-235 with 0.0253 eV	0.0000001	0.06
U-235 with 1.0 MeV	0.0000005	0.06
U-238 with 1.0 MeV	0.000000003	0.06
Pu-239 with 0.0253 eV	0.00001	0.07
Pu-239 with 1.0 MeV	0.00001	0.07

Because the fraction of Cs-134 is so small, Cs-137 is expected to contribute to nearly 100% of the activity of the combined constituent Cs-134, 137. The activity measured for this constituent should therefore be attributed to Cs-137.

R.2.4 Uranium ("U-Nat", or "U-235, 238")

The relative abundance of the various uranium isotopes in air and water releases from SRS facilities is dependent on a number of factors. The primary factor is the enrichment level of the uranium being handled at the facilities. Enrichment increases the relative abundance of the lower weight isotopes (U-234 and U-235) and decreases the proportion of the higher weight isotopes (U-238). A second factor is whether the uranium has been subjected to neutron radiation (in a reactor). Reactor irradiation would result in the production of U-236. While it is fairly certain that the uranium at SRS facilities, in particular the reactors and separations facilities, were irradiated in reactors, there is only limited information on the enrichment levels of uranium in these and other facilities. Therefore, the analysis of the isotopic composition of uranium found in air and water discharges is largely based on general assumptions. However, due to two key properties of the various uranium isotopes, changes to the composition will not have a substantive effect on the results of the SRS dose reconstruction. The first key property is half-life. All of the uranium isotopes have very long half-lives (240,000 years and longer) in comparison to the period being studied (~40 years). Therefore, radioactive decay will not have a significant effect on the relative abundance of the isotopes after they are released. The second key property is the dose conversion factor. The dose conversion factors for the uranium isotopes fall within a ~15% range; therefore, the doses received from equal amounts of the different isotopes will be about the same (+/- ~15%).

Until the mid-1990s, alpha-emitting radioisotopes were detected using instrumentation that measured gross alpha. This gross alpha count was attributed to a combination of primarily uranium and plutonium. The fraction of the gross alpha assigned to each of these elements varied depending on the facility or

process emitting the alpha radioactivity. In M Area where reactor fuel was manufactured, alpha radioactivity was solely attributed to uranium. When dose calculations were conducted, assumptions were made as to the type of uranium present (natural, enriched, or depleted), with the corresponding isotopic fractions used (Hefner, 2003). This approach is used below to estimate the curie fraction of each uranium isotope for the applicable SRS facilities.

In Cummins report, "U-Nat" (natural uranium) represents "U-235, 238" (Cummins et al., 1991). U-235 and U-238 represent the majority of the mass of naturally occurring uranium. It should not be assumed, however, that all uranium measured in environmental releases at SRS is natural uranium. Despite the nomenclature being used in Cummins report, uranium actually occurs in three basic forms in the SRS environment: natural, depleted, and enriched. Natural uranium is processed to remove U-238 so that a higher concentration of U-235 is achieved, thus creating enriched uranium. The enrichment process creates a byproduct called depleted uranium. Depleted uranium is either disposed as a waste or reused in target materials for producing plutonium isotopes. Evans et al. provides approximate isotopic compositions for each of these waste forms, shown in Table R-6 (Evans et al., 1992). Note that for enriched uranium, two basic types of fuel were manufactured and used at SRS: Type M and Type F. Since it is unclear as to how much Type M fuel versus Type F fuel was used, Table R-6 shows an average isotopic composition for enriched fuel, assuming the same mass of Type M and Type F fuel. Note that these compositions include U-234 and U-236. While the original data sources only reference U-235/U-238, it is assumed that these other uranium isotopes are also present.

Table R-6 Isotopic Composition of Savannah River Uranium Wastes (Evans et al., 1992)

Isotope	Isotopic Composition (wt %)**			
	U-234	U-235	U-236	U-238
Half-Life (years)*	2.45E+5	7.03E+8	2.34E+7	4.47E+9
Natural	0.0055	0.7200	n/a	99.2745
Depleted	n/a	0.2	n/a	99.8
Enriched***	1.45	81.55	9.8	7.2

* (KAERI, 2003).
** Evans et al.
*** Average of Isotopic Composition for Type M and Type F fuels

Using the above weight percentages, the contribution to the activity for each isotope is calculated using Equation 1 and presented in Table R-7.

Table R-7 Activity Fraction for Specific Isotopes in Uranium Wastes

Isotope	Activity Fraction (%)			
	U-234	U-235	U-236	U-238
Natural	49.49	2.25	n/a	48.26
Depleted	n/a	1.27	n/a	98.73
Enriched	91.73	1.79	6.45	0.03

These activity fractions can be used in the dose assessments, taking into account the prevalent form of uranium in each process area at SRS at the time of release, as presented below.

Reactor Areas: Any environmental releases of uranium in the reactor areas to streams and seepage basins are assumed to occur after the storage of spent fuel (containing enriched uranium) and target

materials (containing depleted uranium) in spent fuel basins and disassembly basins (Evans et al., 1992). Basin purge water was normally discharged to the plant streams and seepage basins along with the reactor secondary cooling water. Uranium releases from the reactors to the atmosphere occurred due to the venting of "harps" (storage containers located underwater in the reactor basin which contained failed fuel and target elements) to the reactor stack (Carlton and Denham, 1997). The ratio of enriched to depleted uranium that was used in the production reactors is not known and cannot be calculated. Since it can be assumed that there was most likely more enriched uranium, on a mass basis, than depleted uranium that was used in the reactors, the fraction of uranium isotopes in Table R-7 for enriched uranium should be used for environmental releases from the reactors.

Separations Areas: Based on Evans et al., the F Area facilities primarily isolated Pu-239 from U-238 target material comprised of depleted uranium. The curie fraction in Table R-7 associated with depleted uranium should therefore be used for environmental releases from F Area. In H Area, U-235 was recovered from enriched fuels. According to Evans et al., enriched fuel in H Area could contain from 1.1% to 94% U-235 (Evans et al., 1992). The curie fraction in Table R-7 associated with enriched uranium should therefore be used for environmental releases from H Area.

M-Area: The fuel and target materials used in the reactors were fabricated in M-Area. Atmospheric releases of uranium were very small compared to the releases in F Area. Based on Evans et al., these releases were in the form of natural and depleted uranium, although it is unclear to what proportion these two forms of uranium were released (Evans et al., 1992). For the purposes of this study, natural uranium fractions from Table R-7 should be assumed for atmospheric releases since U-234 is known to have been emitted and is present in natural uranium in measurable quantities. Depleted uranium has been found in stream sediments (Evans et al, 1992), so curie fractions for depleted uranium from Table R-7 should be used for all liquid releases.

A Area (SRL): SRL worked with all forms of uranium and there is no method for determining the quantity of each form used; therefore an average of the activity fractions for all three forms of uranium may be used, assuming an equal mass of natural, depleted, and enriched uranium was released. This assumption results in the following percentages of uranium isotopic activity: 91.44% for U-234; 1.8% for U-235; 6.4% for U-236; and 0.36% for U-238.

CMX/TNX: Some natural uranium was used in fuel and target development at TNX (Evans et al, 1992). Activity fractions from Table R-7 for natural uranium should therefore be used.

D Area: The rework of degraded moderator from reactor areas was the most likely source of alpha activity, which is assumed to be uranium (Evans et al, 1992). The moderator most likely contained a mixture of uranium isotopes representing both depleted and enriched uranium. To be consistent with the assumptions for the reactor areas, activity fractions from Table R-7 for enriched uranium should be used for environmental releases in D Area.

R.2.5 Plutonium

Pu-238, Pu-239 and Pu-240 were the primary plutonium isotopes of interest in environmental releases at SRS. Pu-239 and Pu-240 were often reported as Pu-239 since these two isotopes are indistinguishable in alpha spectroscopy measurements (Carlton et al., 1994b). All three of these isotopes were produced by the reactors and were present in the F and H Area processes. The most common form of plutonium produced at SRS was weapons-grade plutonium. Weapons-grade plutonium had an isotopic composition similar to that shown in Table R-8.

Table R-8 Isotopic Composition of Weapons-Grade Plutonium (Mark, 1993)

	Pu-238	Pu-239	Pu-240	Pu-241*	Pu-242
Mass Fraction (Mark, 1993)	0.00012	0.938	0.58	0.0035	0.00022
Activity Fraction (using Equation 1)	0.0047	0.1337	0.0302	0.8313	0.0000

* Pu-241 plus Am-241

Despite comprising a very small mass fraction of weapons-grade plutonium, Pu-241 (plus its daughter product Am-241) contributes approximately 83% to the curie content. Am-241 is addressed as a separate constituent; therefore Pu-241 is indirectly addressed in the dose assessments. Also, the dose contribution of Pu-241 is approximately 100 times less than Pu-238, Pu-239 and Pu-240. Since Pu-239 was the primary plutonium product at SRS and it has nearly identical dose conversion factors with Pu-238 and Pu-240, all "Total Plutonium" releases to the environment can be assumed to be Pu-239.

R.2.6 Unidentified a/Unidentified b + g

As mentioned in the beginning of this appendix, many of the radioactive releases at SRS were detected with gross α and gross $\beta + \gamma$ measurements. If the isotopes were known due to process knowledge, then the measurements were assigned to the isotopes in the environmental release reports. If the isotopes were not known, then the environmental release reports reflected unidentified α and unidentified $\beta + \gamma$ measurements (Evans et al.). The unknown constituents comprising unidentified α and unidentified $\beta + \gamma$ measurements most likely were a combination of several isotopes.

Since SRS could not assign the unidentified α and unidentified $\beta + \gamma$ measurements to specific isotopes, it is not possible to proportion these measurements among several isotopes for this effort. These unidentified measurements can be attributed, however, to a single isotope to allow for a conservative estimate. In the case of unknown α, the unidentified α will be assigned to Pu-239. Pu-239 has greater dose conversion factors than the uranium isotopes for many of the exposure pathways. Pu-239 is also one of the more prevalent plutonium isotopes at SRS. Other transuranic isotopes have been produced and used at the SRS (such as Neptunium-237, Curium-244 and Californium-252) that have contributed to the measurement of unidentified α, but these isotopes were primarily produced during brief periods and have dose conversion factors 100 to 1000 times less than Pu-239. Using Pu-239 for unidentified alpha values therefore is the most conservative assumption.

Many isotopes could contribute to the unidentified $\beta + \gamma$ measurements. For conservatism, the unidentified $\beta + \gamma$ measurements will be attributed to Sr-90. Commonly found in environmental releases throughout the facilities at SRS, Sr-90 has dose conversion factor values 10 to 100 times higher than the other beta and gamma emitting isotopes of concern. With a half-life of 28 years, Sr-90 will also remain in the environment longer than most of the other beta and gamma emitting isotopes of concern.

R.3 References

Carlton WH, Evans AG, Geary LA, Murphy CE, Strom RN, "Assessment of Strontium in the Savannah River Site Environment," WSRC-RP-92-984, May 6, 1994a.

Carlton WH and Denham M, "Assessment of Selected Fission Products in the Savannah River Site Environment," WSRC-TR-96-0220, April 1997.

Carlton WH, Evans AG, Geary LA, Murphy CE, Pinder JE, Strom RN, "Assessment of Plutonium in the Savannah River Site Environment," WSRC-RP-92-879 Rev. 1, 1994b.

Cummins CL, Hetrick CS, Martin DK, Radioactive Releases at the Savannah River Site 1954 – 1989, WSRC-RP-91-684, February 1991.

Evans AG, Bauer LR, Haselow JS, Hayes DW, Martin HL, McDowell WL, & Pickett JB, "Uranium in the Savannah River Site Environment," WSRC-RP-92-315, Rev. 0, 12/09/92

Hankins O., "Selected Readings for NE 301," Fall 1988.

Korea Atomic Energy Research Institute (KAERI) (January 10, 2003), "Table of Nuclides" <http://www2.bnl.gov/ton/>, 2000-2002.

Mark JC, "Explosive Properties of Reactor-Grade Plutonium," Science& Global Security, Vol. 4, pp. 111-128, Gordon and Breach Science Publishers, 1993.

Hefner J., telephone conversation, 1/21/03.

APPENDIX S ESTIMATION OF RIVER FLOW RATE FOR LOWER THREE RUNS CREEK AT MARTIN, SOUTH CAROLINA

S.1 Background

As part of CDC's SRS Dose Reconstruction Project, ATL has included exposure pathways to surface water contaminated with water discharges from SRS. One of the CDC-specified exposure locations occurs on Lower Three Runs Creek at the town of Martin, South Carolina (LTRC-Martin). To calculate exposure, data are needed in two areas: (1) the flowrate of the creek at LTRC-Martin and (2) the quantities of radionuclides discharged. This analysis addresses the approach for determining flowrates at LTRC-Martin and presents the methodology, assumptions, and analytical results.[1]

The modeling approach for this project requires the use of constant annual creek flowrates and constant annual releases. Therefore, an average annual creek flowrate value is needed for each year of modeled releases, from 1954 to 1992. Because direct measured flowrate data for LTRC-Martin do not appear to be available, ATL estimated flowrates based on other available flowrate measurements.[2]

S.2 Analysis

ATL identified two sets of data usable in estimating 1954-1992 LTRC-Martin average flowrate values:

- LTRC-Snelling monthly flowrate data for 1974 – 2001 (USGS 2003a, Attachment 1).
- LTRC-Martin monthly flowrate data for 1998 – 2001 (USGS 2003b, Attachment 2).

USGS flowrate monitoring station at LTRC-Snelling is located approximately 6 miles downstream of the Par Pond dam and 8 miles upstream of the LTRC-Martin flowrate monitoring station (See Figures 1 and 2).

When comparing the monthly flowrate data from LTRC-Martin to LTRC-Snelling for 1998 to 2001, it was observed that the flowrate at Martin was generally twice the flowrate at Snelling. This ratio can be used to estimate the flowrate of LTRC-Martin based upon the data obtained for the LTRC-Snelling using the following basic formula:

[LTRC-Martin Flowrate] = [LTRC-Snelling Flowrate] x [Martin-to-Snelling Ratio]

The ratios calculated by comparing the monthly flowrate at LTRC-Martin and LTRC-Snelling are shown in Attachment 2. In calculating the Martin-to-Snelling ratio, only data from 1998 to 2000 is considered since no data is available at Martin for October, November, and December, 2001, omitting an entire season of data. However, a review of the 2001 LTRC-Martin monthly flowrates shows them to be comparable to those for 1998 to 2000. The calculated ratios are summarized in Table S-1.

The standard deviation and corresponding percent error show that the average ratio is relatively consistent over the 1998 – 2000 period, taking into account possible seasonal and annual fluctuations for this time period.

[1] Data on the quantities of discharged radionuclides used in this analysis are based on Risk Assessment Corporation 2001 and supporting references.
[2] USGS monitoring data for LTRC-Martin for 1954-1992 are not available (USGS 2003b). SRS also does not have LTRC-Martin flowrate data (Heffner 2003).

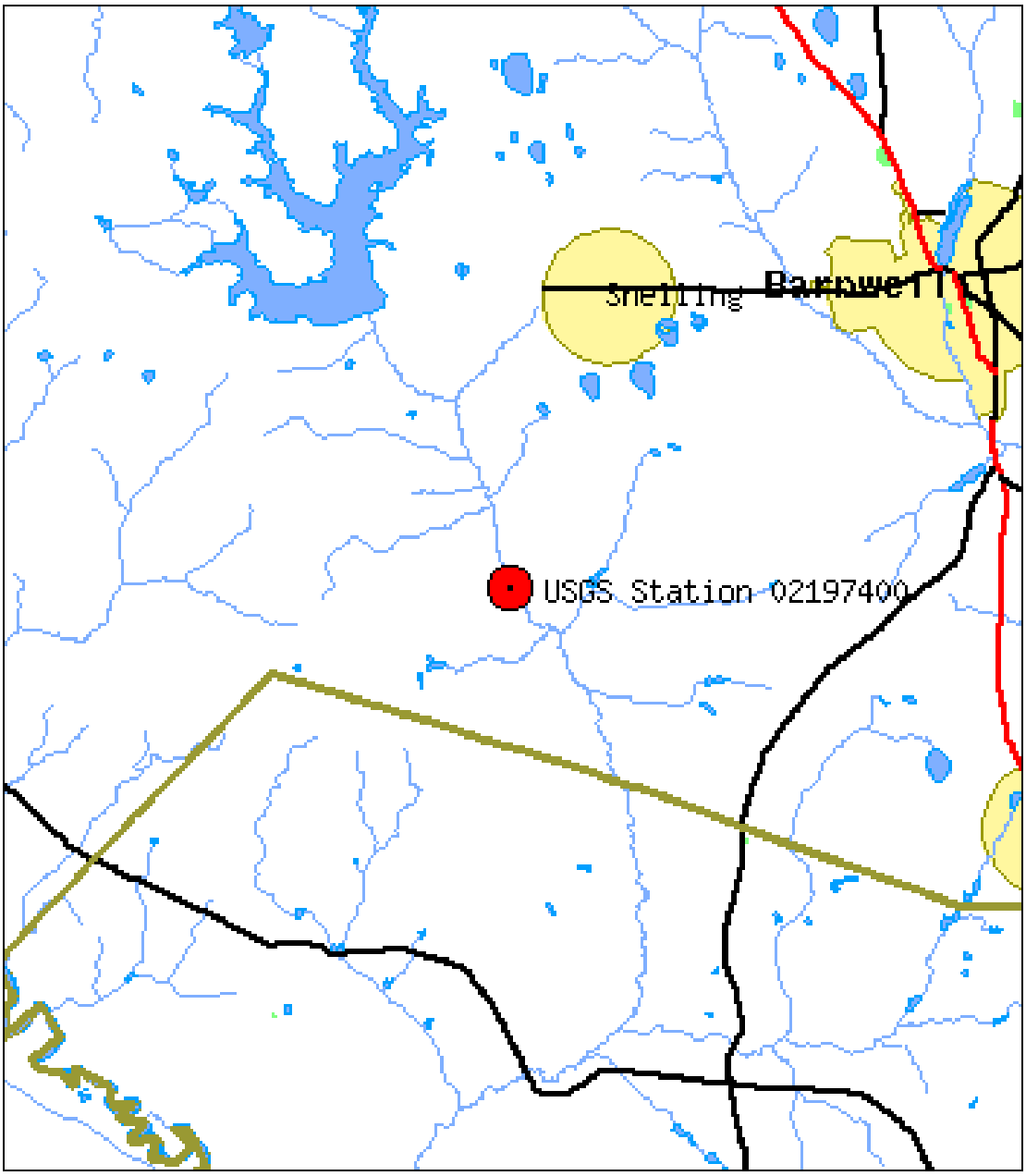

Figure S-1 LRTC-Snelling Monitoring Station Location

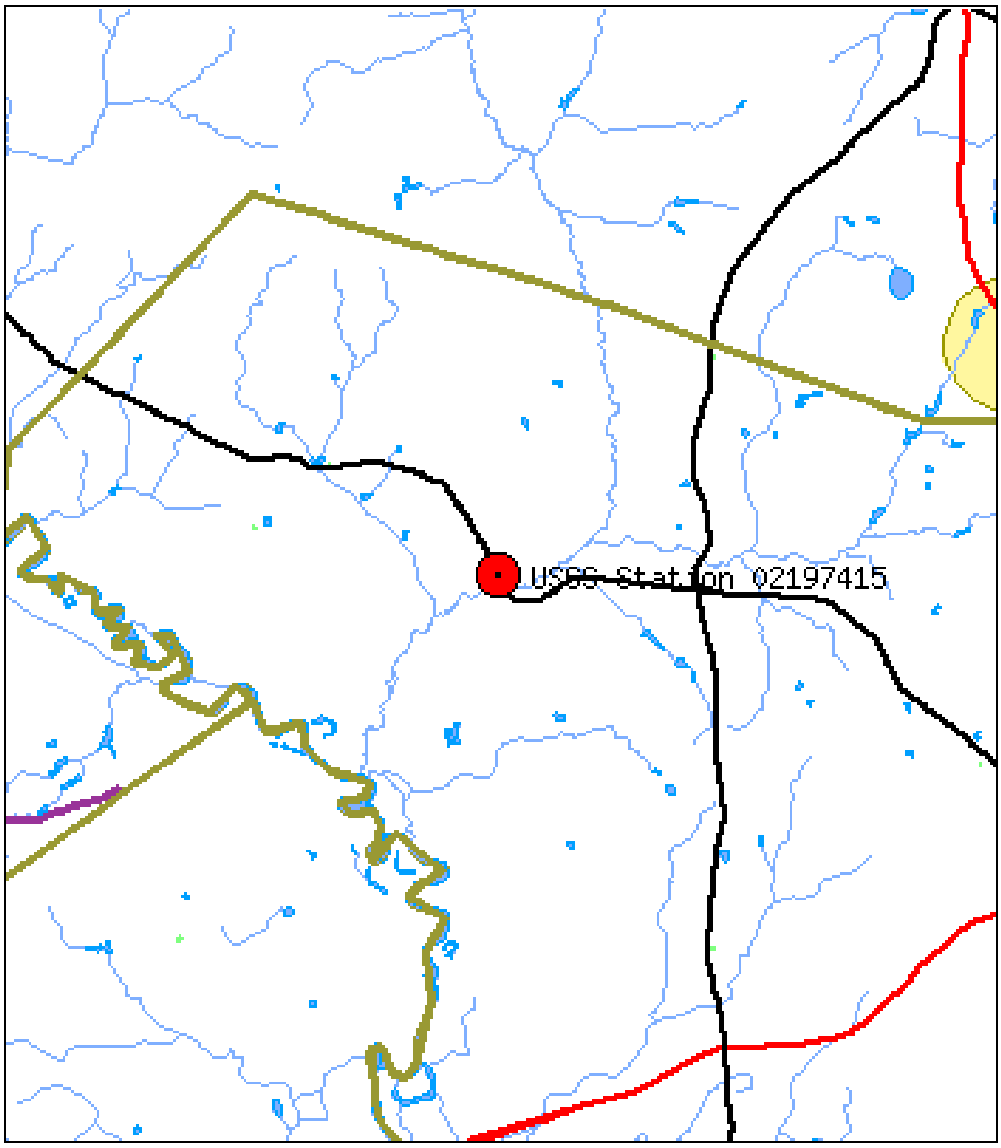

Figure S-2 LRTC-Martin Monitoring Station Location

Table S-1 Average Ratio of Monthly Flowrate Data

Martin:Snelling from 1998 to 2000	Standard Deviation	Percent Error
2.2	0.3	16.0%

1974 – 1992 Flowrates. For the purposes of dose reconstruction, it is assumed that the average Martin-to-Snelling ratio is applicable for the entire project study period. Attachment 3 shows the calculated monthly and annual flowrates at LTRC-Martin for the 1974 – 1992 period, based on the measured monthly flowrates at LTRC-Snelling during the 1974 – 1992 period and the average Martin-to-Snelling ratio. The calculated annual flowrate value is used as the LTRC-Martin flowrate in the dose reconstruction modeling calculations.

1954 – 1973 Flowrates. The approach described above was suitable for the 1974 – 1992 period because flowrate measurements for LTRC-Snelling were available for this period. To estimate flowrates for the first part of the modeled period (no flowrate measurement data for the 1954 – 1973 period are available), this approach had to be adjusted.

For this calculation, , it was assumed that the monthly flowrate at LTRC-Snelling during the 1954 – 1973 period was equal to the average monthly flowrate during the 1974 – 1992 period (calculated in Attachment 1). LTRC-Martin flowrates for this period were then calculated using the 1974 – 1992 average monthly flowrate and the previously calculated Martin-to-Snelling ratio. The resulting LTRC-Martin monthly and annual flowrates for the 1954 – 1973 period are shown in Attachment 3.

Data Gaps. In applying the approaches described above, two minor data gaps had to be addressed. Flowrate measurements for LTRC-Snelling were not available for January, February, and March of 1974, and October of 1984, as shown by shaded cells in Attachment 1. For the 1974 data gap, it was assumed that the average monthly flowrates for the corresponding months for the period 1975 to 1992 could be applied to 1974. For the 1984 data gap, it was assumed that the October 1984 flowrate is the average of the flowrate of September and November for that year. Data gaps for January through May of 1997, and October through December of 2001 are not addressed because flowrates are not required for these time periods to determine flowrates at LTRC-Martin from 1954 through 1992.

S.3 References

1. Risk Assessment Corporation. Final Report, Savannah River Site Environmental Dose Reconstruction Project, Phase II: Source Term Calculation and Ingestion Pathway Data Retrieval, Evaluation of Materials Released from Savannah River Site. U.S. Centers for Disease Control and Prevention. April 30, 2001.

2. Heffner J. Re: LTRC Flow Rate [unpublished email]. Savannah River Site. March 24, 2003.

3. USGS. Monthly Streamflow Statistics for South Carolina, USGS 02197400 Lower Three Runs near Snelling, SC [online]. 2003s. [cited 2003 March 28]. Available from URL: *http://waterdata.usgs.gov/sc/nwis/monthly/?site_no=02197400*.

4. USGS Monthly Streamflow Statistics for South Carolina, USGS 02197415 Lower Three Runs at Martin, SC [online]. 2003b. [cited 2003 March 28]. Available from URL: *http://waterdata.usgs.gov/sc/nwis/monthly/?site_no=02197415*.