Risk-Based Screening of Radionuclide Releases from the Savannah River Site

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1 INTRODUCTION

This report is the product of Phase III of the Savannah River Site[1] (SRS) Dose Reconstruction Project. It estimates the radiation doses and associated cancer risks for hypothetical persons living near SRS and performing representative activities. SRS is a U.S. Department of Energy (DOE) facility that produced nuclear materials such as tritium and Pu-239 for national defense and other programs.

The SRS Dose Reconstruction Project examines the operations of SRS for the 39-year period from its inception in 1954 to the end of 1992, when main production activities ceased. The Project is sponsored by the Radiation Studies Branch, National Center for Environmental Health, Centers for Disease Control and Prevention (CDC) of the U.S. Department of Health and Human Services. The Project is a study of the potential health risks to people exposed to chemicals and radioactive materials released to the environment resulting from historical SRS operations.

This report only addresses radiation doses and risks. A separate report will address the risks from chemicals that may have been released as part of SRS production activities. Previous phases focused on gathering the records necessary for the dose reconstruction and on estimating the quantities of radionuclides and chemicals released from SRS during its 39-year period of production (the source term).

Phase III assessed radiation doses and risks to members of seven hypothetical families (exposure scenarios) that were assumed to live in the SRS vicinity during the 39-year period. Assumptions about the activities of these hypothetical families were developed through collaboration between CDC and the SRS Health Effects Subcommittee (SRSHES).

1.1 Purpose and Scope of the Phase III Report

SRS was operated from 1954 to 1992, first by E.I. duPont de Nemours and Company (Dupont) for the U.S. Atomic Energy Commission (AEC), and later by Westinghouse Savannah River Company for DOE. SRS operated five reactors and two chemical separations operations to produce and purify plutonium, tritium, and other radioactive isotopes. During this time, radionuclides and chemicals were disposed of into the ground or released into surface waters and into the air. These releases potentially resulted in radioactive and chemical exposures to persons living near the site. By 1992, the production reactors and separations facilities had all ceased operation. Some processing and support, waste management, and environmental remediation facilities still operate. These operations may continue to release small quantities of radioactive and chemical materials to the environment.

The SRS Dose Reconstruction Project was begun in 1992 and is being conducted to determine if the health of people who lived near the site was affected by past releases of chemicals and radioactive materials from the site (CDC, 1999). Such a determination is not straightforward, and an analysis of the public health consequences of SRS operations must confront the following technical challenges:

- The site is large with many points of release at different locations.
- The site operations were complex, varied, and changed over time; a large variety of radionuclides and chemicals were released at various rates over time.
- The quantities and physicochemical nature of the released materials are uncertain; this is especially true for early site operations for which records are incomplete;

[1] The SRS was known as the Savannah River Plant (SRP) until 1989.

- Air and water transported some of the released material offsite within a geographically large and complex physical and ecological system.

- Some human exposures involved contaminant transport through the food chain, which is both complex and uncertain.

- The exposed population was potentially large, geographically dispersed, and engaged in a variety of behaviors that could affect the potential doses received from site releases.

- The doses received by the population in the vicinity of SRS were generally low and could not be measured directly by conventional dosimetry instruments; consequently, these doses must be inferred from models of releases, transport in the environment, and exposure.

- Concentrations in environmental media (air, water, biota), which are precursors to exposure, were low and often difficult to quantify using standard monitoring techniques.[2]

Therefore, radiological health risks from past SRS operations may best be estimated using a dose reconstruction process. This process consists of quantitative modeling of estimated doses and scientific and technical evaluations that support and enable the quantitative modeling. The quantitative modeling entails:

- Modeling releases using historical information to estimate the annual quantities of radioactive materials released from all significant SRS sources.

- Modeling the migration of radionuclides in air, water, and the food chain to estimate the concentrations of radionuclides in environmental media that may be contacted by a human receptor over time.

- Performing exposure assessments to estimate radiation doses.

- Estimating risks that may be caused to the receptor from exposure to these radionuclides.

A variety of strategies was used to overcome these technical challenges. These strategies included:

- Appropriate simplifications of highly complex processes (e.g., the use of standard models for internal and external dose and cancer risks)

- Use of hypothetical scenarios to bracket the behavior of persons living near SRS.

- Quantitative estimation of dose uncertainty due to uncertainties in model input variables.

1.2 CDC Phased Approach to Dose Reconstruction

At the initiation of the SRS Dose Reconstruction Project in 1992, CDC designed the project to consist of five phases as summarized in Table 1-1 (1).

[2] The ability to detect and quantify radionuclides and chemicals in media has improved since SRS began operations.

Table 1-1 Phases of SRS Dose Reconstruction Project

Phases	Description
Phase I	A systematic review of available documents at SRS and the development of a document database.
Phases II	Initial source-term development and pathway analysis. This work consisted of estimating the amount of radioactive materials and toxic chemicals released to the environment from the SRS from 1954 to 1992.
Phase III	Screening dose and exposure calculations.
Phase IV	Developing methods for assessing environmental pathways and environmental doses.
Phase V	Calculation of environmental exposure and doses.

Source: (1).

The design of the project ensured open public participation. Among other citizen outreach activities, the SRS Health Effects Subcommittee (SRSHES) was established to advise CDC on the adequacy of their health research and public health activities associated with SRS. An Advisory Committee to CDC constituted under the Federal Advisory Committee Act, the SRSHES is comprised of citizens selected to reflect the diversity of the communities impacted by SRS (2).

Phase I of the study was a search of SRS to find and copy documents and other records of potential value to the project. This effort was completed in 1995. About 50,000 boxes of SRS records were examined, and numerous SRS workers were interviewed. Many of the records were formerly secret reports that were declassified. An electronic document database was created to store information about the records. An additional product was a description of SRS areas and processes organized by location (3).

Phase II of the study began in October 1995 to develop an estimate of the releases of the most significant radionuclides and chemicals from various facilities at SRS from 1954 to 1992. This estimation included a list of radioactive materials and chemicals that were used or produced at the site as well as descriptions of key processes at SRS. In addition, the results of past SRS environmental monitoring programs were reviewed.

In September 1998, CDC provided the results of the Phase II study to outside reviewers, including the National Academy of Science and the SRSHES. After considering and addressing comments, the final Phase II report was produced in April 2001. This 1,400-page report, titled "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 (Phase II)," is available on the Internet at http://www.cdc.gov/nceh/radiation/savannah.

1.3 Modifications to the Original CDC Approach

CDC's original plan for the Phase III effort was to use "scenarios provided by CDC and a screening protocol approved by CDC" and to "perform screening calculations to determine which radionuclide releases from the Savannah River Site may have biological significance." The implication was that those radionuclides not screened out as unimportant would warrant further analysis (in Phases IV and V) primarily to estimate doses. In a presentation to the SRSHES in June 2002, CDC stated that they intended to use Safety Series Report No. 19 issued by the International Atomic Energy Agency (IAEA) as the model to perform the screening analysis (4).

The screening analysis would have used conservative modeling assumptions, and the main focus of the analysis would have been the determination of radionuclides for further study in Phases III and IV. Two similar screening analyses, based on the total amount of radionuclides released from SRS, were incorporated in the Phase II report. The Level 1 screening analysis considered doses from all pathways, while the Level 2 screening analysis was a more refined analysis in which the role of a radionuclide in the doses for each individual pathway was considered.

However, CDC recognized that the process set forth in Table 1-1 would take considerable time, perhaps several years, to complete through Phase II. During this time, questions would remain about the possible public health consequences from past SRS operations. In addition, there was concern about the availability of the funding required to complete the remaining phases given other competing priorities.

Consequently, in late 2002 and early 2003, CDC expanded the scope of the Phase III effort to include a more detailed estimation of representative doses and risks using the CDC scenarios. In effect, the expanded scope went beyond the previously defined Phase III scope, but stopped short of the detailed modeling of environmental pathways contemplated for a Phase IV study. The CDC scenarios included several hypothetical sets of individuals performing realistic, but in some cases extreme, activities on and near the site. Each hypothetical scenario represented a family that lived, worked, and engaged in recreational activities in the vicinity of SRS, and raised children born during years of large SRS releases of radioactive material to the environment. As the basic source term for environmental assessment, CDC used the estimates of release into the atmosphere and surface water as provided in the Phase II study. In addition, the uncertainty of the calculated doses was to be addressed.

CDC initially developed the scenarios for Phase III that were then further refined by CDC, the SRSHES, and the preparers of this report. Originally, CDC proposed the following six scenarios:

1. A rural family just downwind of the site boundary.
2. An urban/suburban family just downwind of the site boundary.
3. A delivery person scenario.
4. An outdoors person (hunting, fishing, camping, etc.
5. A family living near the river.
6. A migrant worker family living mostly outdoors.

CDC presented proposed assumptions about these six scenarios at a meeting of the SRSHES held in January 2002 in Charleston, South Carolina. The SRSHES considered CDC's proposed scenarios and presented comments to CDC on the proposed scenarios at a meeting held on September 6, 2002. These comments included suggestions about modifying the scenarios (5).

The preparers of this report had several additional suggestions including the addition of a second rural family scenario (6). The seven scenarios considered in Phase III are described in detail in Chapter 3.

The revised approach adopted by CDC allowed the levels of dose and risk, and their main contributors, to be identified and addressed in a more focused manner than the screening analysis that was originally intended.

1.4 Technical Challenges

In addition to the technical challenges delineated in Section 1.1, other significant challenges had to be addressed.

1.4.1 Scenario Implementation

Although CDC and the SRSHES provided the descriptions and scopes of the exposure scenarios considered for the study, many of the details of the scenarios were either unspecified or had to be adjusted to enable mathematical modeling. Chapter 3 summarizes the detailed scenario specifications and Appendix E discusses these scenario specifications in detail.

1.4.2 Merging of Air Release Sources

The Phase II report identified 15 principal SRS locations for release of radionuclides into the air plus several other smaller sources (Phase II). Given the large computational requirements needed to model the transport of radionuclides from each of these sources to each of the exposure locations considered in the study, all of these release locations were merged into four virtual locations. Chapter 6 summarizes the procedures used in creating these four virtual sources, and Appendix A discusses the procedures in detail.

1.4.3 Doses and Risks from Radionuclides Discharged to Surface Water

The evaluation of doses and risks from radionuclides released to onsite surface water bodies had to be performed in a somewhat different way than the evaluation for radionuclides released to air. Doses and risks were calculated for exposure to radionuclides discharged to the Savannah River and for exposure to radionuclides in Lower Three Runs Creek. To determine the concentrations of radionuclides released annually to the Savannah River, a procedure was developed that considered delay in surface water sediments, biota, etc. To determine radiation exposures from radionuclides in Lower Three Runs Creek, environmental monitoring data were used directly in the analysis (See Chapter 7).

1.4.4 Radionuclide Retention in the Streams and Swamp

Many radionuclides discharged into onsite streams were not immediately transferred off the SRS site but were sorbed or taken up by minerals, sediments, plants and biota. These processes reduced the quantities of radionuclides that were annually released from SRS to the Savannah River. A procedure was developed in Phase II to mathematically account for these processes and their influence on the transport of radionuclides to the Savanna River. This procedure was applied to three radionuclides. For Phase III, the procedure was expanded to all the radionuclides in the Phase III source term that were released to surface water. A description of this procedure is found in Chapter 7, Release of Radionuclides to Water and Transport to an Exposure Location.

1.4.5 Completion and Qualification of the Contaminant Release Database

To complete this phase of the SRS dose reconstruction study, quantified estimates were needed for all the major radionuclides released into air and surface water during each year of SRS operation. Although the Phase II report was the basis for these estimates, it did not provide all the information that was needed. For example, the Phase II report lacked annual estimates of release to air for some radionuclides for the years 1954 through 1989 and for most radionuclides for the years 1990 through 1992. The information provided in the Phase II report was expanded using data from the SRS monitoring program and other sources (see Chapters 5 and 7).

1.4.6 Input Data Determination

To model the migration of radionuclides in air, water, and the food chain, and subsequent human radiation exposures through various exposure pathways, values had to be determined for more than 250 parameters used in the analysis. Some parameters pertained to physical conditions in the SRS vicinity such as the densities of soils and sediments. For these parameters, values were selected that considered several references such as SRS-specific environmental assessments (see Appendix F).

Many parameters pertained to transport of radionuclides through the food chain (i.e., into plants and animal products eaten by humans). A three-step process was used to determine transfer factors used as measures of the partitioning between soil and plants, animals and humans consuming animal products, and fresh water and fish (see Appendix F.4).

1. Site-specific data were used when available (7).

2. If no site-specific data were suitable, data were considered from a detailed handbook of parameter values addressing a variety of environmental settings (8).

3. If no data were available and suitable from these sources, default values used in Version 2 of the GENII code (9) were used.

A document providing much site-specific information (10) and other references were used to determine values for additional parameters used in the analysis such as crop-growing periods and feed-consumption rates by animals.

Finally, some parameters pertained to activities conducted by the human receptors, including activities such as breathing rates and the amounts of nine different foods eaten each year by each receptor (Appendix E). Each parameter value had to be specified consistent with the age and gender of the receptor. Age-specific data for these parameter values were obtained mainly from standard references such as EPA's *Exposure Factor Handbook* (11).

1.4.7 Determination of Probability Distributions

A sensitivity and uncertainty analysis was performed on the doses that were calculated in this study. This analysis included a process called a stochastic assessment that quantitatively analyzed the uncertainties associated with the values used in the computer model. The stochastic assessment required the development of probability distributions (which are graphs, tables or formulas that give the probability of occurrence for each value of the variable) for the parameter values, and numerous computations were performed where parameter values were randomly selected according to their probability distributions. Assessments were then made concerning the influence of these parameters on the calculated doses.

The computational requirements for this effort were reduced by the following process. First, a detailed analysis was performed of the doses calculated for all the exposure scenarios. Second, those exposure pathways and radionuclides that contributed the least to the doses received by the receptors were eliminated from the stochastic assessment. Third, parameters were eliminated from the uncertainty assessment if they either had values that were considered fixed or were shown to be small contributors to variance. From this process, a reduced list of parameters and radionuclides was produced for the stochastic assessment (see below and Chapters 4 and 12).

Probability distributions were determined for 14 parameters selected from the process described above. All but one of the probability distributions were lognormal distributions. Distributions for this analysis were selected after considering a handbook of parameter values (8) and other references, and applied site-specific values when available (see Chapter 12).

1.4.8 Deer and Game Dose

One of the principal concerns raised by the SRSHES early in Phase III was the possibility for significant radiation exposures from eating contaminated game animals such as deer. For a variety of reasons, it was

difficult to model radiation exposures and doses through this pathway (see Appendix D.1.1.2.2).[3] Radiation exposures from eating venison and wild fowl were modeled as exposures from eating additional contaminated quantities of beef and poultry (see Chapter 3 and Appendix D).

1.4.9 Calculational Needs

The most daunting challenge was the sheer size of the computation effort required. The doses and risks that were calculated for Phase III were performed by each receptor (i.e., each scenario family member) by summing the incremental doses and risks received each year by each receptor from each radionuclide and through all exposure pathways. This analysis included the following factors:

- Sixteen radionuclides released to the air and 22 radionuclides released to surface water.
- Thirteen exposure pathways for radionuclides released to air and five exposure pathways for release to surface water.
- Thirty-nine years of radionuclide release to air and water.
- For each receptor and year, calculation of effective dose and doses to 23 bodily organs or tissues.
- For each receptor and year, calculation of total cancer risk and risk to 16 cancer sites in the body.
- Assessments of calculational uncertainty including stochastic analysis of important variables and dominant radionuclides.

Data storage and handling requirements for the analysis were large and led to the development of custom software to perform the detailed computations for the study.

A dose assessment program was created having three components: a preprocessor, a dose calculation module, and a postprocessor (Figure 1-1**Error! Reference source not found.**). The preprocessor compiled input data such as the quantities of radionuclides released annually into the air and water, and prepared the data for use by the dose calculation module. Using standard dose assessment models, the dose calculation module performed the transport and exposure pathway computations that estimated the movement, dilution, and concentration of radionuclides in the environment and the human intake of and exposure to the radionuclides. The postprocessor extracted results from output files and compiled them in a readily useable format.

An existing environmental assessment code was adapted for use as the dose calculation module. After a rigorous code selection process (summarized in Appendix G), Version 2 of the GENII family of computer codes was selected. The original version of GENII was developed in the late 1980's for use at DOE's Hanford Reservation although the codes were designed with the flexibility to accommodate input parameters for a wide variety of generic sites. GENII has been included in the VAMP project, an international effort to compare environmental radionuclide transport models with measured environmental data.[4] GENII Version 2 incorporates improved transport models, exposure options, dose

[3]The concentrations of radionuclides measured in deer in the SRS vicinity are similar to (and sometimes smaller than) concentrations of radionuclides measured in deer well away from the SRS vicinity. It was difficult to model radiation exposures and doses through this pathway (see Appendix D).

[4] VAMP stands for Validation of Model Predictions, an acronym for the Coordinated Research Program on Validation n of Models for the Transfer of Radionuclides in Terrestrial, Urban and Aquatic Environments, an international effort to compare environmental radionuclide transport models with measured environmental data. Results for test scenario CB, based on

and risk estimates, and user interfaces. It implements dosimetry models recommended by the International Commission on Radiological Protection (ICRP) and is designed to function within the Framework for Risk Analysis in Multimedia Environmental Systems (FRAMES). FRAMES allows GENII to execute with, and provide inputs to, other related programs (9,12,13).

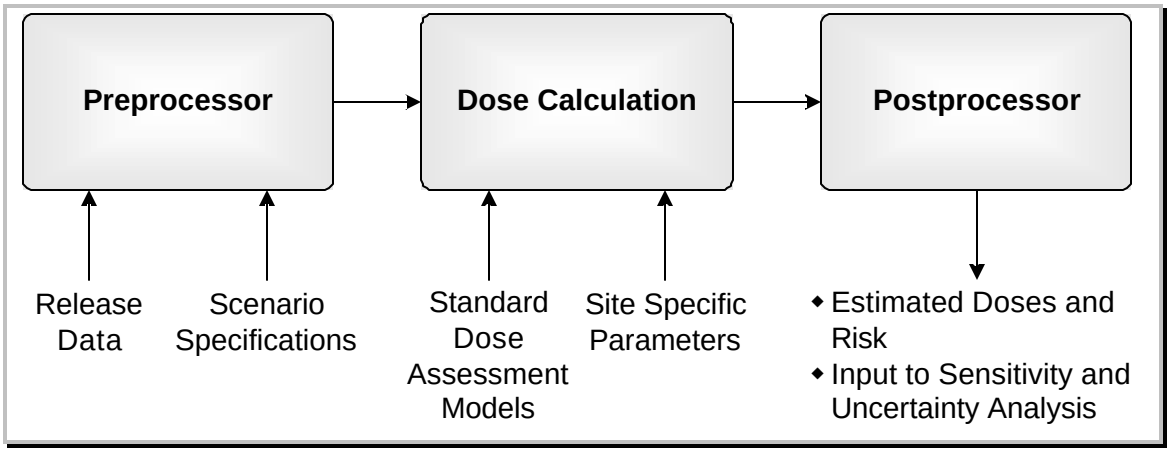

Figure 1-1 Conceptual Configuration of SRS Dose Assessment

However, using the GENII Version II code in accordance with the revised objectives of the study dictated the need to investigate, justify, and document more than 250 parameter values for use in GENII [5]. Therefore, it became desirable to make some simplifying assumptions to make the model more tractable although still representative. In particular, it became desirable to combine the air release points into a smaller number of virtual release points and to merge some of the possible exposure locations.

A strong effort was initiated to document all decisions made in the design and execution of this study. Some decisions could be explained in a few sentences, while others required detailed analyses. A variety of assessments and "white papers" were developed to document and justify decisions. Most were submitted to CDC for review and, through CDC, to the SRSHES for information and comment. The following decision documents are either incorporated into the text of this report or referenced:

- **"Combining Sources of Air Releases for the SRS Dose Reconstruction."** This document contains the methodology and decision process for combining 15 major sources of air releases and several minor sources into 4 virtual sources while maintaining the ability of the data to accurately represent the contaminant exposure conditions over the period of the study.

- **"Soil-to-Water Distribution Coefficients for Radionuclides Considered in the Dose Reconstruction of Savannah River Site."** This document describes the distribution coefficients selected for evaluating potential doses and health risks to individuals residing in the vicinity of SRS during the period of concern (1954-1992). The principal application of these distribution coefficients is to model leaching of radionuclides from soil.

environmental measurements following the Chernobyl accident, indicated that dose estimates from GENII were comparable to, although slightly higher than, those of other participating models (12).

[5] Unless otherwise noted, all references to "GENII" in this study mean Version 2 of GENII.

- **Treatment of Radionuclide Concentrations in Wild Game in Dose Reconstruction Modeling."** This document describes the decisions made concerning the use of beef consumption data to model venison consumption in the GENII computer model.

- **"Base Case Values for Exposure Activity and Usage Factors for the CDC SRS Dose Reconstruction Project."** This document describes in detail the characteristics of the hypothetical receptor groups modeled in the SRS Dose Reconstruction. The specific characteristics of the receptor families (i.e., exposure pathways and exposure locations) are used in the model to calculate the nature of radioactive exposure to each individual in the families for each of the potential exposure pathways being modeled.

- **"Comparison of Phase II and Phase III Source Terms for Water Releases."** The purpose of this document was to record the similarities and differences between the Phase II source-term values for water releases and the Phase III values used for the dose reconstruction.

- **"Basis for Determining Isotopic Fractions from SRS Environmental Reports for Performing Radiological Dose Assessments."** This document provides the technical basis and assumptions for identifying a release quantity for individual isotopes that have not been specifically identified in SRS environmental reports. Such isotopes include Sr-89, Sr-90, Zr-95, Nb-95, Cs-134, Cs-137, uranium, plutonium; and identified alpha, beta, and gamma.

- **"Documentation for GENII Model Parameters Used in SRS Base Case Calculation."** This document 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, states the units and input value(s) of each variable, and describes how each value was determined.

- **"Position Paper for Use of the Savannah River as an Irrigation Source."** The purpose of this document was to determine if the use of the Savannah River as a source of irrigation water for farming is an appropriate assumption. One of the exposure scenarios involves a family living in Girard, Georgia downstream from SRS and using the river as an irrigation source for growing crops.

- **"Adjustment of Dose Conversion Factors and Risk Factors."** This document describes the appropriate factors to correct the doses and risks contained in the GENII-V2 output files. The GENII-V2 output files are generated assuming an adult. Therefore the calculated doses and risk results have to be corrected for the receptor's current age.

- **"Base Case Values for Receptor Activity and Usage Factors for the CDC SRS Dose Reconstruction Project."** This document describes in detail the characteristics of the hypothetical receptor families modeled in the SRS Dose Reconstruction. The specific characteristics of the receptor families are used in the model to calculate the radioactive exposure to each individual in each family for each of the potential exposure pathways being modeled. Some pathways occur for airborne releases of contaminants, and others occur for waterborne releases.

- **"Proposed Values of Transfer, Bioconcentration, and Bioaccumulation Factors Used for Modeling Dose Reconstruction for Historical Releases from the U.S. Department of Energy Savannah River Site."** This document describes how values were determined for a set of modeling variables known informally as transfer factors. The transfer factors are used in GENII-V.2 modeling software for modeling food chain transport of radionuclides. Many of these variables describe the ratio (at equilibrium) between contamination levels in two media types (e.g., 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 are produced from animals that consume the plant matter at a unit intake rate.

1.5 References

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2 BACKGROUND

2.1 Overview of Site Operations

In 1946, Congress created the U.S. Atomic Energy Commission (AEC) to administer the nuclear programs created for the World War II Manhattan Project. AEC needed new production capacity for nuclear weapons materials used in national defense and, in November 1950, AEC selected a location in South Carolina for the Savannah River Plant. Covering about 300 square miles (780 km^2), the site was chosen because of its low population density, large supply of water, freedom from major floods and storms, and other factors (1).

SRS is located about 19 miles (32 km) south of Aiken, South Carolina, and about 22 miles (36 km) southeast of Augusta, Georgia. It borders the Savannah River for about 17 miles and comprises parts of Aiken, Barnwell, and Allendale Counties in southwestern South Carolina. Figure 2-1 shows the general location of SRS.

The Savannah River Plant was designed, constructed, and operated for the AEC by E.I. duPont de Nemours and Company (DuPont). Construction began in 1951 (2). The basic plant was completed within five years and included five nuclear reactors, two chemical separations plants, and numerous laboratories and support facilities. The primary mission was production of ^{239}Pu and tritium. SRS bombarded fuel and targets containing ^{238}U and ^{6}Li with neutrons in the nuclear reactors, and recovered the ^{239}Pu and tritium from the fuel and targets at the separations facilities. DuPont continued operation of the plant until 1989 when operation was taken over by the Westinghouse Savannah River Company. At that time, the site was renamed the Savannah River Site (Phase II).

As production continued, the need for specific materials waned. As a result, site facilities gradually ceased operation until the primary defense-related mission ended in 1992. Since that time, certain activities continue to manage waste, conduct environmental restoration activities, and perform new missions (2).

Table 2-1 summarizes the SRS facilities of main importance for this study, and shows the principal SRS areas and facilities. Most are located in a rough circle in the approximate center of the site.[1] SRS contains two large ponds, Par Pond and L-Lake, and is drained by five major streams feeding into the Savannah River: Upper Three Runs Creek, Four Mile Branch, Pen Branch, Steel Creek, and Lower Three Runs Creek. With the exception of Lower Three Runs Creek, all of these streams empty into the Savannah River Swamp bordering the east side of the Savannah River.

[1] SRS facilities are identified by a system, using numbers and letters that reference them to a particular onsite area containing a complex of related or supporting operations. For example, each of the two chemical separations areas is identified by a letter of the alphabet (F and H Areas), and each building or structure within an area is numbered in accordance with a century nomenclature (i.e., the reactor areas are the 100-Areas, the separations areas are the 200-Areas, and so forth). A structure in one of the 100-Areas (reactor areas) is identified by a number in the 100's, a structure in one of the 200-Areas is identified by a number in the 200's, etc.

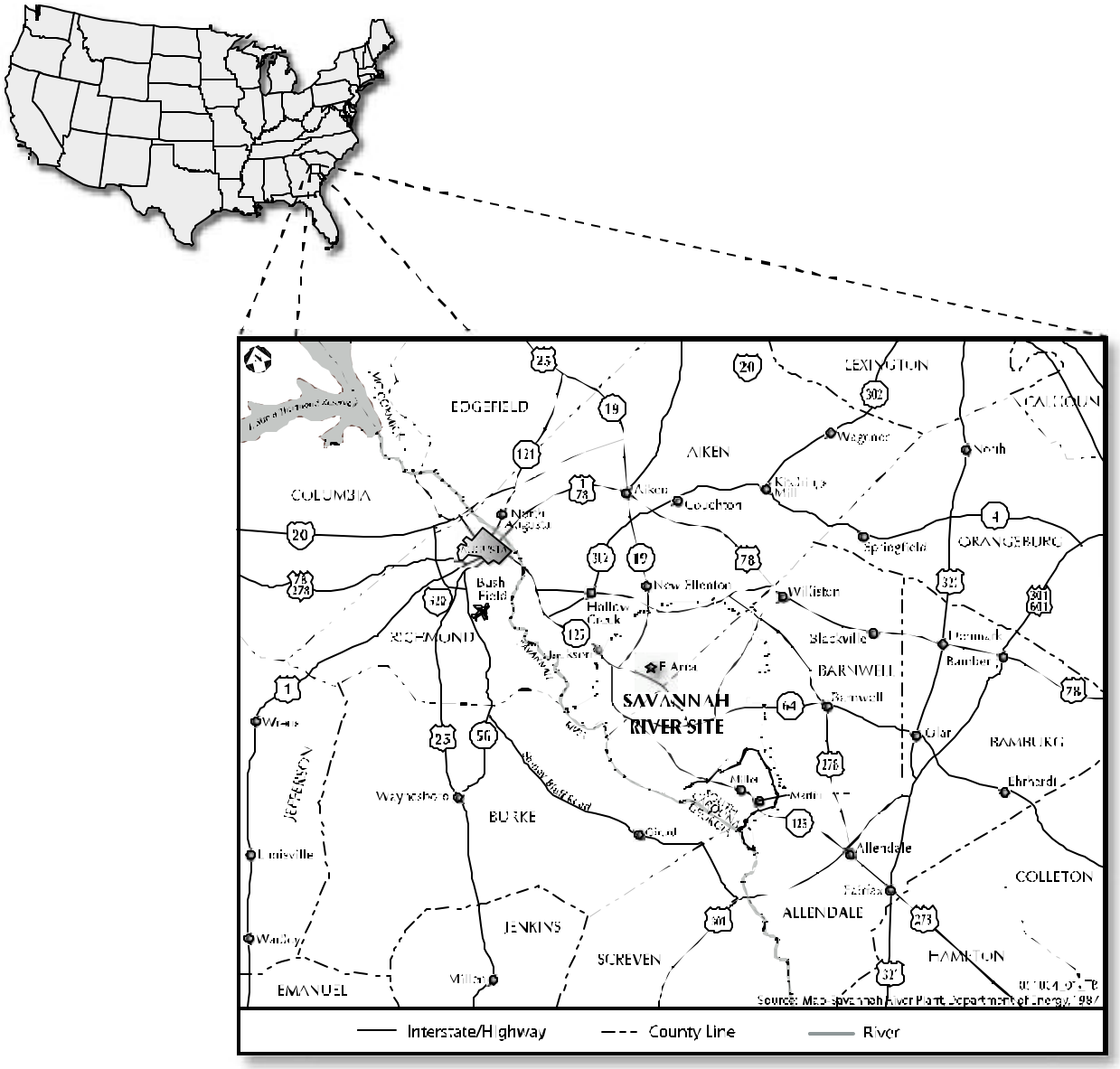

Figure 2-1 General Location of SRS

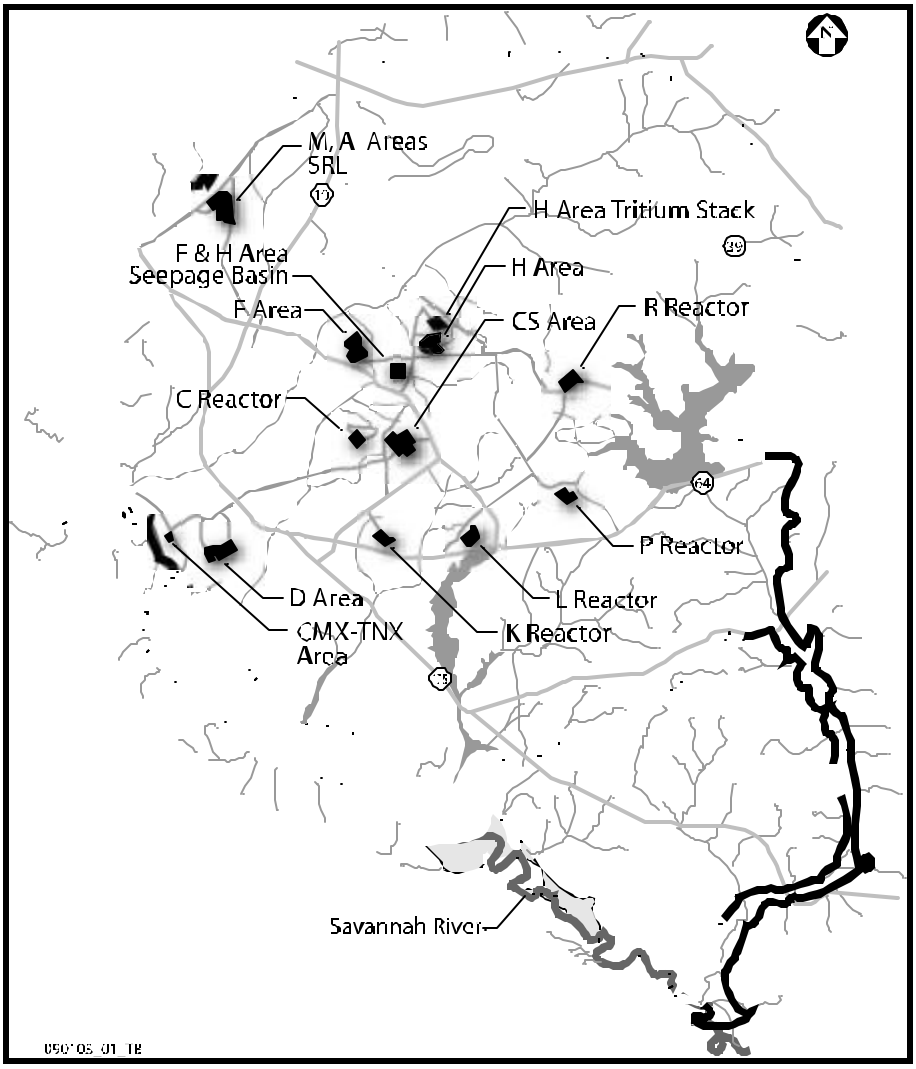

Figure 2-2 Principal SRS Areas and Facilities

Table 2-1 Principal Areas and Facilities

Areas	Facilities	Dates	Notes
100	R-Reactor P-Reactor C-Reactor K-Reactor L-Reactor	1953-1964 1954-1988 1955-1985 1954-1988 1954-1968 1985-1988	Reactors used heavy water as a neutron moderator and primary coolant. L-Reactor operated from 1954 to 1968, and from 1985 to 1988. K-Reactor was the last operating reactor.
200	H-Area Chemical Separations	Completed November 1954	Facilities for chemical separation and purification of plutonium (Pu), tritium (^3H), and other products from irradiated targets and fuel. Also used for recovery of tritium from weapons reservoirs.
	F-Area Chemical Separations	Completed July 1955	
300	M-Area Fuel and Target Production	Completed January 1953	Produced reactor fuel and target assemblies for irradiation in reactors.
400	D-Area Heavy Water Plant	First operating by October 1952; full capacity by May 1953	Concentrated heavy water from Savannah River. Reconcentrated heavy water after contamination with light water in reactors.
600	E-Area Waste Management	First disposals in 1953	Burial grounds located in E-Area between F-and H-Areas. Still in use.
	CMX and TNX Facilities	Completed 1953	Technical support, pilot plant development and training. Located near D-Area Heavy Water Plant.
700	A-Area Administration	Opened with site	Administrative offices. Includes Savannah River Technology Center.

Source: (3).

2.1.1 D-Area: Heavy Water Production and Processing

Some of the first facilities to be constructed were those producing heavy water for use in the reactors. The Extraction Plant, which operated until 1981, concentrated heavy water[2] from a natural level in river water (about 0.015 percent) to a concentration sufficient for reactor operations. The Rework Unit and the Distillation Plant removed light water that, over time, would contaminate the heavy water in the production reactors. Additional facilities included a laboratory, a facility to clean drums used for heavy water storage and transportation, and a coal-fired powerplant (3).

[2] Each molecule of water consists of two hydrogen atoms and one oxygen atom. One or both of the hydrogen atoms in heavy water contains a neutron in the nucleus in addition to a proton. A hydrogen atom containing a neutron and a proton in the nucleus is a deuterium (D).

Because tritium[3] is created from deuterium by neutron bombardment, concentrations of tritium in the reactor moderator built up over time. Consequently, the processes used to reclaim reactor moderator discharged tritium into the air and surface water.

The largest source of tritium released to air from D-Area was the Rework Unit, where releases to air occurred from leaks from the Rework Unit pump room and from the exhausts from the area used for storage of recovered heavy water. Releases also occurred from the drum-cleaning facility and the laboratory (1).

The Rework Unit was also responsible for the largest source of tritium released to surface water from D-Area. Typically, waste distillate was collected in tanks before sampling and discharge to cooling water effluent that drained to Beaver Dam Creek (1).[4] The tritium in the waste distillate was normally in concentrations that were too low for practical recovery (1).

2.1.2 M-Area: Reactor Materials

Fuel and target elements for irradiation in the SRS reactors were fabricated in the M-Area. Major facilities located in the M-Area were the Alloy Extrusion Unit, the Uranium Metal Element Fabrication Unit, the Target Extrusion Unit, and the Metallurgical Laboratory. All uranium for fuel and targets was received from offsite sources (1).

Activities generated airborne and liquid effluents containing uranium isotopes. Air treatment procedures differed depending on the operational processes within each M-Area building. Initially, liquids containing uranium were discharged to Tims Branch and pond beds adjacent to M-Area (1).[5] As of 1977, about 50 percent of the discharged uranium had settled in the stream and beds and had "not reached the main stream leading to the river" (1). After late 1976, most liquids were discharged to the M-Area settling basin (1).

2.1.3 Reactor Areas

Table 2-2 summarizes the dates of operation of the five SRS production reactors. All reactors used heavy water as a neutron moderator and primary coolant. All were housed in buildings constructed of heavy concrete to provide radiation shielding to personnel. Reactor systems and auxiliaries included the primary and secondary coolant systems, the component-handling systems, and the disassembly basins (1).

<u>Coolant Systems</u>

The primary coolant system consisted of heavy water circulating through the reactor core. In each system, coolant entered a plenum and then flowed through the reactor core. Heated coolant then passed through heat-exchangers where heat from the fission process was transferred to a secondary coolant system (1).

At each reactor, water bled from the primary coolant system was circulated through a water-treatment system to maintain ionic purity of the coolant and to reduce radiation exposures to personnel.[6] Typical

[3] A tritium (T) atom is a radioactive atom of hydrogen containing two neutrons and a proton in the nucleus.
[4] This creek flows to the Savannah River Swamp and then follows a meandering route through the swamp to the river, mixing with a portion of the flow from Four Mile Branch.
[5] Tim's Branch empties into Steeds Pond about 1-1/2 miles from the 300-Area. Overflow from Steeds Pond drains into Upper Three Runs Creek, which empties into the Savannah River.
[6] Operation of the reactor resulted in contamination of the coolant with radionuclides due to neutron activation of coolant, cladding, and reactor components; corrosion of cladding and components; and leakage of fission products from fuel.

water treatment equipment included filters, deionizers, and evaporators. An offshoot from the deionizer effluent passed through a distillation unit that removed light-water impurities from the heavy-water coolant (1).[7]

Table 2-2 Summary of Reactor Operations

Reactor	Dates of Operation	Comments
C	1955-1985	Shut down in 1985.
K	1954-1988	Shut down in 1988, but operated briefly in 1992. In 1993, it was put in cold standby as the Nation's tritium source. Shut down permanently in 1996.
L	1954-1968 1985-1988	Shut down for upgrades in 1968. Restarted in 1985. Shut down in 1988.
P	1954-1988	Shut down in 1988.
R	1953-1964	Shut down in 1964.

Source: WSRC 2002.

The secondary coolant system consisted of water from the Savannah River. River water was pumped to reservoirs located in the reactor areas, and from the reservoirs passed through the reactor heat exchangers. As reactor thermal power gradually increased from 1954 to 1962,[8] additional secondary cooling capacity was achieved by measures such as doubling the number of heat exchangers used in the secondary coolant system, by increasing river-pump capacity, and by the construction of Par Pond in 1958 (3).

Par Pond is a 2,700-acre reservoir formed by damming Lower Three Runs Creek. Pond water pumped to the P- and R-Reactors was returned to Par Pond,[9] allowing increased delivery of river water to the L-, P-, and C-Reactor secondary cooling systems. Until 1985 and 1988, respectively, effluent cooling water from C- and K-Reactor heat exchangers flowed back to the river via onsite streams. Until 1988, cooling water from P-Reactor continued to flow to Par Pond. In 1985, SRS formed L-Lake by damming Steel Creek. SRS used L-Lake as a heat sink for L-Reactor when it operated from 1985 through 1988 (3).

Component-Handling System

The component-assembly area of a reactor building was used to receive fresh fuel from the 300-M Area and to discharge irradiated fuel from the reactor[10] to a reactor disassembly basin (1).[11]

Disassembly Basin

A disassembly basin is a deep pool of water used to temporarily store fuel and miscellaneous reactor components removed from the reactor. During the 1950's and 1960's, irradiated material stayed in the disassembly basins for less than nine months. In later years, the storage period was longer (3).

[7] Buildup of light water in the primary coolant system primarily resulted from exposure of the coolant to humid air within the system.
[8] The reactor thermal power, or heat output, is proportional to the rate of fission and the creation of fission products in the fuel. With higher rates of fission, higher reactor core densities of neutrons were achieved resulting in larger rates of production of tritium and other products.
[9] Before construction of Par Pond, cooling water from the heat exchangers was discharged directly into onsite streams.
[10] Control rods and other components were similarly charged into the reactor and discharged as needed.
[11] Also called a fuel and target storage basin or a fuel pool.

Air and Water Treatment and Effluent

Releases of radionuclides to air and water varied over time depending on modifications to reactor operations, reactor equipment, and air- and water-treatment systems. Releases to air and water also resulted from occasional problems with equipment.

Air

Principal sources of airborne release at reactor areas included the reactor building, disassembly basins, and seepage basins (3).

Exhaust from each of the process areas in a nuclear reactor was routed through an air treatment system consisting of moisture separators, filters, and charcoal beds to remove elemental iodine vapor and gaseous iodine compounds.[12] Exhaust was discharged from a 200-foot stack (1). Radionuclides released from the reactor building included tritium and fission and activation products, including iodine isotopes and ^{41}Ar. Tritium was released mainly from evaporation of the moderator (3).[13]

Exhaust from the disassembly basin area was discharged to the air from a roof vent. Releases mainly consisted of tritium in water evaporating from the pool surface. Ground-level release of tritium occurred from evaporation of seepage basin water (3).

Water

Table 2-3 summarizes liquid effluent procedures for each reactor. During operation, some of the radionuclides contaminating the reactor coolant were transferred to secondary coolant water from leakage of the heat exchangers. Thus, coolant water discharged to surface waters contained tritium and other radionuclides.

The disassembly basins were additional sources of contaminated liquid effluent. To ensure visual clarity and maintain personnel exposure levels at acceptable levels, the basins were purged with river water. Until the mid 1960's, basin purge water was continuously discharged to site streams along with secondary cooling water. Sand filters were added to the disassembly basins in the early 1970's, and continuous purging to site streams ceased although periodic purging continued from 1970 to 1977. In 1978, SRS began to discharge water from periodic purges to reactor seepage basins. These seepage basins were constructed at all reactor basins during the second half of 1957 primarily for disposal of water generated from vacuum-cleaning the disassembly basins (3).

2.1.4 F- and H-Separations Areas

Chemical separations facilities at SRS consist of two main complexes: F- Area and H-Area. Each complex contains a shielded separations building divided into two parallel "canyons" as well as auxiliary facilities that include a waste concentration and storage system, seepage basins, powerhouses, and service facilities. F-Area contains a laboratory, the plutonium metallurgical building, and the Plutonium Fuel Form Facility (PuFF). H-Area contains the tritium process buildings, the Receiving Basin for Offsite Fuels (RBOF), and the Resin Regeneration Facility (RRF).

[12] This equipment was typical by the end of 1963 when all reactor ventilation systems had been fitted with charcoal beds and high-efficiency particulate filters. This air-treatment system was installed in R-, P-, and K-Reactors in 1962, and in the remaining two reactors the following year.

[13] Tritium built up due to neutron capture by deuterium and primarily released as either T_2O or DTO.

Table 2-3 Summary of Liquid Discharge Procedures at SRS Reactors

Reactor	Operation	Liquid Effluents
R	1953-1964	To Lower Three Runs Creek, Par Pond, and one seepage basin
P	1954-1988	To Steel Creek, Par Pond, and three seepage basins
C	1955-1985	To Four Mile Creek and three seepage basins
K	1954-1988	To Pen Branch and two seepage basins
L	1954-1968 1985-1988	To Steel Creek, L Lake (built in early 1980's by damming Steel Creek), and a seepage basin

Source: (3).

Separations

Operations at either of the two separations facilities typically began with dissolution of the cladding from the irradiated fuel or targets, followed by dissolution of the declad materials, generally in nitric acid. This process evolved volatile fission products such as iodine isotopes. The solution was then sent through a series of solvent extraction cycles. The first solvent extraction cycle stripped the product (e.g., plutonium and uranium) from the fission products. The product was then purified in subsequent chemical processes. Fission products (and some residual plutonium and uranium) from the first solvent extraction cycle were routed to the high-level waste tanks (3).

Tritium Recovery

The tritium facilities in the H-Area consist of three buildings (i.e., 232-H, 234-H, and 238-H) where tritium was separated from irradiated lithium-aluminum targets, further purified, and packaged (1).

Receiving Basin for Offsite Fuels

This H-Area building houses fuels from offsite reactors. Fuels are received and either stored or cut and packaged for reprocessing. In addition, the RBOF received special fuels from SRS. It is still used for storing spent nuclear fuel (1,3).

Resin Regeneration Facility

This H-Area facility received ion-exchange resin beds and filters from reactor areas for regeneration (1).

Metallurgical Building

This F-Area facility was used to fabricate components for uranium, neptunium, and plutonium reactor elements (1).

Plutonium Fuel Form Facility

This F-Area facility manufactured Pu-238 heat source fuel forms (3).

Analytical Laboratory

This F-Area facility supplied radioanalytical services to the entire plant except for the Savannah River Laboratory (1).

Waste Concentration and Storage

High-activity waste liquids from separations operations were concentrated and stored in tanks. Most notably, high-level liquid wastes from the solvent extraction process were pumped to large underground tanks located in "farms" in each separations area. As of 2002, 37 million gallons of waste remained stored in 49 tanks in 2 tank farms (4).

Air and Water Treatment and Effluents

Air

Both separations buildings were ventilated by systems that directed air from clean areas to areas that were contaminated. Ventilation air was passed through filters before discharge to stacks. The main stacks for both separations areas were 200 feet tall. The F-Area Canyon was also equipped with an auxiliary stack for dissolver off-gas as well as a 160-foot stack for air ducted from the plutonium processing areas (1).

Air from the three tritium facilities (232-H, 234-H, and 238H) was discharged through tall stacks (1)

Off-gas from the RBOF building was filtered and discharged to air through 53-foot stacks. In addition, gases collected from fuel-cask opening or fuel-cutting operations were passed through charcoal and HEPA filters before discharge (1).

Water

Radioactive contamination released to surface water mainly came from two sources: coolant water for the separations process vessels and seepage basins. One coolant-water system, used for areas that were unlikely to become contaminated, recirculated coolant water through a cooling tower. A second system was a once-through system: water was normally discharged to Four Mile Creek if measured levels of contamination were sufficiently low. If water from either system contained contamination above prescribed limits, the water was diverted to seepage basins constructed in each of the two separations areas. If seepage basin limits were exceeded, the water was sent to retention basins for storage pending treatment (1).

Three seepage basins were used at each separations area. Liquid discharged into the seepage basins seeped through the ground until it discharged to a seepline draining to Four Mile Creek. After 1988, when the Effluent Treatment Facility for the separations areas became operational, the F- and H-Area seepage basins were not used (3).

2.1.5 Waste Management Areas

Activities at SRS have generated large quantities of radioactive wastes, most of which were either disposed or stored onsite. Disposal of radioactive wastes has occurred at 20 locations within SRS. The high-level waste is stored in several underground tanks located in the F- and H-Areas (3). These wastes are not of particular interest to this study due to the low levels of radionuclide release from waste storage and disposal operations to air and surface water. However, liquid effluents that have been released to seepage basins are of interest. Seepage basins have been discussed above.

2.1.6 Additional SRS Facilities

Several additional facilities and support areas exist on the SRS and provide small to negligible discharge of radionuclides to water or air.

A-Area: Administrative Area

The Administrative Area contains organizations and facilities that support SRS operations. The only facility that historically contributed radionuclides to air and water was the Savannah River Technology Center (SRTC), which was established in 1951 as the Savannah River Laboratory. For its first few decades of operation, the SRTC fabricated fuel-element prototypes, targets containing radioactive oxides, and sealed radioactive sources. It also performed research and development of separations processes. Airflow through contaminated areas was filtered and vented through either a 100-foot or a 160-foot stack. If within prescribed concentration limits, low-activity contaminated liquids were transferred to laboratory seepage basins; otherwise, they were transported to F-Area for treatment. High-activity-level liquids were transferred to F-Area for storage (1,3).

Other facilities in the A-Area include the U.S. Department of Energy site office, U.S. Forest Service offices, and the Savannah River Ecology Laboratory.

TNX and CMX Semiworks

Although considered part of the SRTC, the TNX and CMX Semiworks are located near the Savannah River next to the 400-D Area. The TNX facilities were used to study chemical-processing problems and test production-scale equipment. Tests were conducted using natural uranium or other surrogates. In later years, the facility researched and developed waste treatment processes. The CMX facility conducted non-nuclear tests of the hydraulic systems of the SRS reactors until it shut down in 1984 (3).

2.2 Principal Radionuclides Released During SRS Operations

During 39 years of operation, SRS released a variety of radionuclides into air and surface water. For the SRS dose reconstruction effort, the Phase II report provides estimates of the release of those radionuclides determined to be most significant for public health concerns (3).

Challenges faced in the Phase II study included incomplete records of radionuclide release, gaps in monitoring data, and questions about early radiation detection and analysis equipment. Releases of radionuclides from times when data were available were scaled in Phase II to times when data were not available based on knowledge of the processes that resulted in the release. SRS procedures for monitoring releases from plant operations were reviewed as was the SRS environmental monitoring program. Estimates of release for some radionuclides were adjusted from those reported by SRS (3).

To focus the effort, a two-step screening analysis was performed using a screening process set forth by the National Council on Radiation Protection and Measurements (6). From the first step of the screening process, the Phase II study identified a list of key radionuclides that had been released into the air and water from SRS operations. The key radionuclides released to air were ^{241}Am, ^{41}Ar, ^{14}C, ^{137}Cs, ^{3}H, ^{129}I, ^{131}I, ^{238}Pu, ^{239,240}Pu, ^{103,106}Ru, ^{89,90}Sr, and uranium. The key radionuclides released to surface water were ^{137}Cs, ^{60}Co, ^{3}H, ^{129}I, ^{131}I, ^{32}P, ^{238}Pu, ^{239,240}Pu, ^{89,90}Sr, ^{35}S, ^{99}Tc, uranium, ^{91}Y, ^{65}Zn, and ^{95}Zr/Nb. From the second step of the screening process, which considered possible exposure pathways in more detail, the Phase II study identified two smaller sets of radionuclides released to the air and water for further detailed analysis. These radionuclides consisted of ^{131}I, ^{3}H, ^{41}Ar, ^{129}I, ^{239,240}Pu, and uranium released to air, and ^{137}Cs, ^{3}H, ^{89,90}Sr, ^{60}Co, ^{32}P, ^{131}I, and uranium released to water (3).

For the Phase III effort, the source term provided in the Phase II report was closely reviewed and refined. Chapters 5 and 7 discuss these adjustments in detail. The radionuclide release data presented in the Phase II report could not be used directly in the Phase III effort due to the following three major concerns:

1. The Phase II report did not provide annual release estimates for all key radionuclides. For some radionuclides, the report provided a 36-year total source term.

2. The Phase II report did not provide release estimates for many radionuclides for the years 1990 through 1992.

3. The Phase II report included estimates for some radionuclides as aggregated quantities (e.g., ^{89,90}Sr, uranium). However, this format was incompatible with the requirements of the GENII code.

The estimates provided in the Phase II report were refined to determine annual release estimates of each of the key radionuclides for all 39 years of the study[14]. To do so, data in SRS reports (7) was examined. For key radionuclides cited in the Phase II report as aggregated isotopes (e.g., ^{89,90}Sr, uranium), the radionuclides were separated into their isotopic constituents based on an understanding of the processes that generated the isotopes.[15] In addition, some of the data in SRS reports were presented in terms of undifferentiated activity (i.e., unidentified [gross] alpha and unidentified [gross] beta-gamma activity). For these data, ^{239}Pu was assumed for reported unidentified alpha activity and ^{90}Sr was assumed for reported unidentified beta-gamma activity. Finally, information was reviewed about the likely chemical forms of the released radionuclides, a consideration needed for certain portions of the analysis. See Chapters 5 and 7, and Appendix B, for additional information about partitioning assumptions and procedures.

Table 2-4 lists the radionuclides and whether they were released via the air or surface water pathway. Appendix B provides lists of the quantities released of each radionuclide through air and water pathways as a function of year.

2.2.1 F- and H-Separations Areas

Chemical separations facilities at SRS consist of two main complexes: F- Area and H-Area. Each complex contains a shielded separations building divided into two parallel "canyons" as well as auxiliary facilities that include a waste concentration and storage system, seepage basins, powerhouses, and service facilities. F-Area contains a laboratory, the plutonium metallurgical building, and the Plutonium Fuel Form Facility (PuFF). H-Area contains the tritium process buildings, the Receiving Basin for Offsite Fuels (RBOF), and the Resin Regeneration Facility (RRF).

2.2.2 F- and H-Separations Areas

Chemical separations facilities at SRS consist of two main complexes: F- Area and H-Area. Each complex contains a shielded separations building divided into two parallel "canyons" as well as auxiliary facilities that include a waste concentration and storage system, seepage basins, powerhouses, and service facilities. F-Area contains a laboratory, the plutonium metallurgical building, and the Plutonium Fuel

[14] ^{106}Ru, ^{144}Ce, and ^{134}Cs were added to the list of isotopes considered in Phase III for release to surface water. ^{91}Y was deleted for release to surface water. Although ^{91}Y was listed as a key radionuclide in the Phase II report, it actually did not pass the screening criteria used for either step of the Phase II screening analysis.

[15] In this report, ^{89,90}Sr was partitioned into ^{89}Sr and ^{90}Sr, ^{95}Zr/Nb was partitioned into ^{95}Zr and ^{95}Nb, and uranium was partitioned into ^{234}U, ^{235}U, ^{236}U, and ^{238}U. It was assumed that activity identified as ^{239,240}Pu was all ^{239}Pu, activity identified as ^{103,106}Ru was all ^{106}Ru, and activity identified as ^{141,144}Ce was all ^{144}Ce.

Table 2-4 Radionuclide Release Pathways

Radionuclide	Released to Air	Released to Surface Water
^{3}H (tritium)	X	X
^{14}C	X	
^{32}P		X
^{35}S		X
^{41}Ar	X	
^{60}Co		X
^{65}Zn		X
^{89}Sr	X	X
^{90}Sr	X	X
^{95}Zr		X
^{95}Nb		X
^{99}Tc		X
^{106}Ru	X	X
^{129}I	X	X
^{131}I	X	X
^{134}Cs		X
^{137}Cs	X	X
^{144}Ce		X
^{234}U	X	X
^{235}U	X	X
^{236}U	X	X
^{238}U	X	X
^{238}Pu	X	X
^{239}Pu	X	X
^{241}Am	X	

*Source: (FGR-13).
†y = years; d = days; h = hours.

Form Facility (PuFF). H-Area contains the tritium process buildings, the Receiving Basin for Offsite Fuels (RBOF), and the Resin Regeneration Facility (RRF).

2.2.2.1 Iodine and other Beta-Gamma-Emitting Particles

Radioactive iodine and other beta-emitting-radionuclides were released mainly from the separations areas. In particular, iodine and other volatile isotopes evolved from dissolution of reactor fuels and targets.

Iodine releases included elemental iodine (I_2) and organic iodides (e.g., CH_3I). The Phase II report observed that releases if iodine for the early years of operation (through about 1961) contained significant uncertainties. The Phase II estimates of ^{131}I release included a significant correction to release estimates provided by SRS[16] (3).

Release of other beta-gamma-emitting isotopes also occurred, mainly from the F- and H-Areas. These isotopes included $^{89,90}Sr$, $^{95}Zr/Nb$, $^{103,106}Ru$, ^{137}Cs, and $^{141,144}Ce$ (3).

2.2.2.2 Activation Products

Activation products are generated when neutrons produced during fission interact with reactor materials such as control rods and structural members, with fuel and target cladding, with air within the reactor, and with impurities and anti-corrosion chemicals in the moderator. Table 2-5 lists the principal activation products generated in SRS reactors (3). The principal activation product of concern for release into the air is ^{41}Ar. Because argon is a noble gas, it was released from SRS facilities (primarily reactors) without capture by the air treatment and filtration systems.

Table 2-5 Characteristics of Activation Products

Radionuclide	Primarily Produced From	Half-Life
^{32}P	^{31}P	14.3 days
^{35}S	^{35}Cl	87.3 days
^{41}Ar	^{40}Ar	1.83 hours
^{51}Cr	^{50}Cr	27.7 days
^{60}Co	^{59}Co	5.27 years
^{65}Zn	^{64}Zn	244 days

Source: (3).

2.2.2.3 Alpha-Emitting Radionuclides

Alpha-emitting radionuclides? principally isotopes of uranium and plutonium? were released to air at SRS primarily from the M-Area, the reactors, and the separations facilities. Measured releases were small from M- Area and the reactors, and larger from the separations facilities. Most plutonium emissions occurred from 1955 to 1969 from F- and H-Area stacks. Uranium releases were largest during 1955, 1968, and 1969 from H-Area stacks; and during 1955, 1956 and throughout the 1960s from F-Area stacks (3).

[16]SRS revised its iodine monitoring and sampling systems and procedures over time. According to the Phase II report, about 99 percent of the ^{131}I released into the air came from the separations areas. Until September 1961, only elemental ^{131}I was measured at the separations areas. SRS estimated organic iodide activity from elemental ^{131}I release assuming that organic forms represented 70-90 percent of all iodine released from separations. The Phase II report addressed measurement uncertainties such as sample collection efficiencies as well as measurement biases resulting from deposition of elemental iodine in sampling lines. The Phase II report concluded that SRS underestimated the release of ^{131}I to air during early years (1950's and early 1960's). Hence, the ^{131}I release estimates in the Phase II report are much larger in early years than those of SRS. SRS staff (8) has criticized these Phase II estimates. After 1961, however, the Phase II estimates of ^{131}I release more closely correspond to those reported by SRS (with few exceptions). Annual ^{131}I releases after 1961 were much smaller than in earlier years (3).

2.2.3 Release of Radionuclides to Surface Water

2.2.3.1 Tritium

The major sources of tritium released to surface water were reactor and separations area effluents discharged to streams and seepage basins. Lesser quantities of tritium were released to surface water from the D-Area (3).

2.2.3.2 Iodine and other Beta-Gamma-Emitting Particles

The major sources of iodine, ^{137}Cs, and other beta-gamma-emitting particles released to surface water were reactor and separations area effluents discharged to streams and seepage basins (3).

2.2.3.3 Activation Products

The major sources of activation products released to surface water were reactor and separations area effluents discharged to streams and seepage basins (3).

2.2.3.4 Alpha-Emitting Radionuclides

Alpha-emitting radionuclides released to surface water included isotopes of uranium and plutonium. Uranium isotopes were released from M-Area and the separations areas. Plutonium releases to surface water came mainly from the separations areas (3).

2.3 SRS Environmental Setting

This section provides a background discussion of human and environmental factors within the vicinity of SRS that are of interest to this study. Primary references are (1), (3), (4), and (9).

2.3.1 Population and Land Use

The area was sparsely populated when SRS was created. Although the only towns on the plant site were Ellenton (population 600) and Dunbarton (population 251), the communities of Leigh, Hawthorn, Robbins, and Meyers contained isolated groups of families (1). About 6,000 persons comprising 1,500 families (10) were relocated. Some moved to New Ellenton, which was established north of the SRS boundary to replace Ellenton (4).

Construction of SRS employed a peak force of 38,500 workers (4). The operating work force initially numbered 5,000 workers (1), climbed to 7,500 by 1980, and totaled nearly 26,000 by 1992 (4). As of 2000, it numbered 14,000 (4).

When SRS was sited, about 67 percent of the land was forested and about 33 percent was pasture and cropland. The main crops were cotton and corn (1). Abandoned fields gradually became pine forests. Current land use on SRS is about 56 percent pine forest, 35 percent hardwood, 7 percent in SRS facilities and open fields, and 2 percent water (9). Except for three roads and a rail line near the edge of the site, public access to SRS is restricted to environmental studies, guided tours, and controlled deer hunts (9). Adjacent to SRS, about 21 percent of the land is devoted to agriculture and about 70 percent comprises forests, wetlands, water bodies, and unclassified, predominately rural lands. Less than 8 percent is urban or built-up (9).

2.3.2 Environmental Characteristics

2.3.2.1 Meteorology and Climatology

The climate in the region of SRS is subtropical, characterized by long, warm, and humid summers and short, mild winters. The average annual temperature at SRS is 64.7°F and the average precipitation is 49.5 inches. The driest season is fall, with an average monthly rainfall of 3.3 inches; the wettest season is summer, with an average monthly rainfall of 5.2 inches. The average annual relative humidity is 70 percent. The average daily maximum relative humidity is 91 percent, and the average daily minimum is 45 percent. Winds currently blow most frequently from the northeast and southwest. Current SRS atmospheric conditions have been classified as unstable about 56 percent of the time (9).[17]

2.3.2.2 Geology and Hydrology

Regional Geology

SRS is located on the Upper Atlantic Coastal Plain. Most soils at SRS are sandy over loamy or clayey subsoil. Annual erosion rates for regional soils, including cropland, range from 1.5 to 2.0 $kg/m^2/yr$. Two soil profile horizons are commonly noticed. The upper horizon (A Horizon) typically consists of structureless fine- to medium-grain quartz sand up to 3 meters thick. The lower horizon (B Horizon) contains iron and aluminum compounds and may range in thickness from 0.6 to 3 meters (9).

Ground Water Hydrology

The shallow ground water on the site is contained within the Floridian Aquifer System, comprising the lowermost Gordon aquifer unit, the Gordon confining unit, and the uppermost Upper Three Runs aquifer unit that contains the water table (4,9). The water table varies from ground surface to a depth of about 100 feet. In F- and H-Areas, the ground-water velocity ranges from a few hundredths of a foot per day to one foot per day near streams (1).

The shallow aquifers beneath the industrial areas that make up about to 10 percent of the SRS have been contaminated with industrial solvents, metals, tritium, and other constituents used or generated at SRS. In general, DOE does not use these aquifers for SRS process operations although there are a few low-yield wells in the Gordon Aquifer and the lower zone of the Upper Three Runs Aquifer. The shallow aquifer units of the Floridian System discharge to SRS streams and eventually the Savannah River (4).

Despite the contamination in some of the shallow aquifers on the site, "there is no data available to suggest that groundwater containing radionuclides has migrated off the SRS to the surrounding communities" (11). Rather, as stated above, localized contaminated ground water on the SRS discharges into onsite streams that ultimately discharge to the Savannah River (11).[18]

Surface Water Hydrology

Operations at SRS caused large withdrawals of cooling water from the Savannah River as well as discharge of heated water to onsite streams. Thermal discharges were reduced after construction of a cooling tower to support K-Reactor operation and L-Lake to support L-Reactor operation (3).

[17] More detailed historical information about wind speeds, directions, and stability classes are more difficult to obtain. Of interest to this report would be detailed meteorological data from the mid 1950's to the 1990's. SRS lacked a formal meteorological program until the early 1970's, leaving a gap of about 20 years in SRS-specific meteorological data.

[18] The Phase II report concludes, in Appendix J, that "although groundwater contamination from SRS releases may be a potential exposure pathway for the future, the evidence suggests that it did not impact offsite residents before 1992" (3).

Five major tributaries to the Savannah River drain SRS: Upper Three Runs Creek, Four Mile Branch, Beaver Dam Creek, Steel Creek, and Lower Three Runs Creek. Figure 2-3 shows the major river and stream system at SRS. These streams meander for several miles through SRS and—except for Lower Three Runs Creek— through the Savannah River Swamp before emptying into the river. A sixth stream, Pen Branch, joins Steel Creek in the Savannah River Swamp. One stream in the northeast area of SRS drains to the Salkehatchie River. The natural flow of SRS streams ranges from about 10 cubic feet per second (cfs) in smaller streams to 245 cfs in Upper Three Runs Creek (4). For several years, coolant and effluent discharges greatly increased flow in these streams above their natural rates. Savannah River flow in 1995 averaged about 10,000 cubic feet per second at SRS (4).

F- and H-Areas are situated on a divide that separates drainage into Upper Three Runs Creek and Four Mile Branch. About half of each area drains into each stream. The F- and H-Areas are drained by Upper Three Runs Creek to the north and west and by Four Mile Branch to the west. The surface aquifer for both F- and H-Areas discharges at seeplines along both Four Mile Branch and Upper Three Runs Creek (3,4).

Upper Three Runs Creek is the only major tributary on SRS that has not received thermal discharges (4). One of Upper Three Run Creek's tributaries? Tim's Branch? received (at Road C) effluents from A-Area and M-Area. Steed's Pond, located on Tim's Branch just north of Road 2, was a mixing and settling pond for A-Area and M-Area wastes (3,4).

Four Mile Branch originates near the center of SRS and flows southwest before emptying into the Savannah River (4). It drains much of the F-, H-, and C-Areas and received C-Reactor cooling water about 0.5 miles south of Road 3. It flows parallel to the Savannah River behind natural levees and enters the river through a breach downriver from Beaver Dam Creek. In its lower reaches, Four Mile Branch broadens and flows via braided channels through a delta formed by the deposition of sediments. Downstream from the delta, the channels rejoin into one main channel (3,4).

Steel Creek and Lower Three Runs Creek both received significant quantities of reactor effluents. Steel Creek received discharges from the L- and P-Reactor Areas before Par Pond was built in 1958. K-Reactor effluent from Pen Branch was discharged to Steel Creek via the swamp through one major and one or more minor streams about a half mile above Steel Creek's mouth (3). Lower Three Runs Creek received some discharge from the R-Reactor area before 1958. Overflow from Par Pond carried runoff from the northeast portion of the plant and any contaminants leaking to the reactor secondary cooling water system (3).

The mouths of Steel Creek, Pen Branch, and Four Mile Branch have built sedimentation deltas from erosion of stream banks caused by stream channels carrying many times their natural flows. In the late 1950's and early 1960's, L- and P-Reactor effluents increased the flow in Steel Creek from its natural level of 35 cfs to 250-400 cfs (3).

The Savannah River Swamp borders the river for about 10 miles (16 km) and has an average width of about 2.4 km (1.5 miles). From 1958 to 1967, the swamp flooded about 74 days per year. The river historically overflowed its channels when flows were equal to or exceeded 438 cubic meters per second. The highest levels in the Savannah River typically occur in winter and spring, and the lowest levels occur in fall and winter (3).

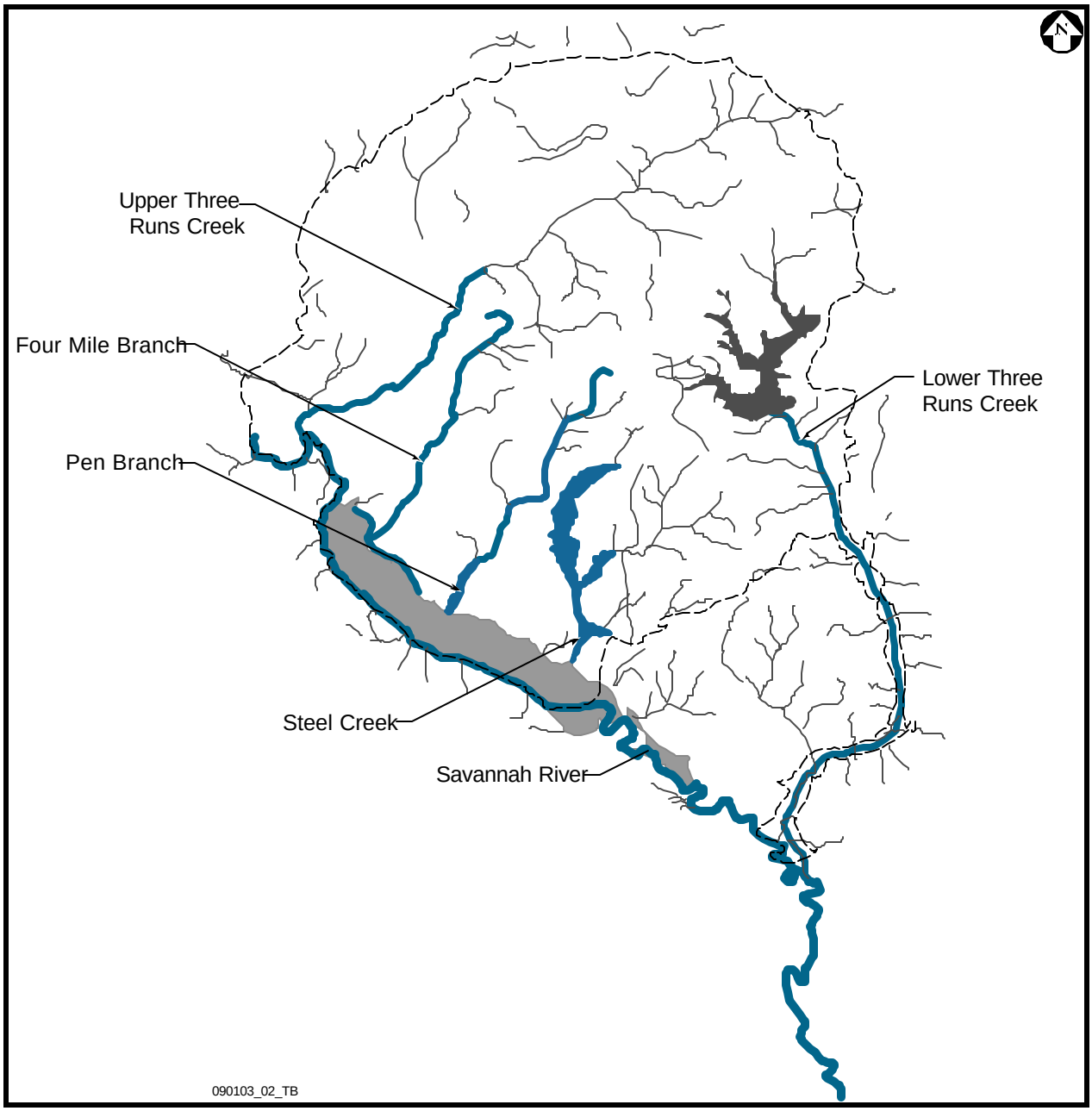

Figure 2-3 Major River and Stream Systems at SRS

2.3.3 Ecology

Because public use of the Savannah River Site was restricted, and because the production and support facilities occupy only a fraction of the total site area, SRS is a natural preserve for biota typical of the southeastern Coastal Plain.

2.3.3.1 Vegetation

The site is about evenly divided between the Aiken Plateau and three Coastal terraces: Brandywine, Sunderland, and Wicomico. The Aiken Plateau is hilly and deeply dissected by streams and contains

extensive growths of scrub oak and longleaf pine. Soils are sandy in the Aiken Plateau and sandy loam in the terraces (1).

Little timber management occurred before Federal acquisition of the site. Generations of logging had depleted stands of timber except for floodplain hardwoods, which were not generally exploited. Much of the site consists of managed pine forests. Dry, sandy areas of the site are typically covered with scrub oak and contain longleaf pine, turkey oak, blue jack oak, black jack oak, dwarf post oak, and huckleberry. Trees available in moister soils along streams and on old floodplains include tulip poplar, beech, sweetgum, willow oak, swamp chestnut oak, water oak, loblolly pine, and ash. Bald cypress and tupelo gum are dominant trees in the Savannah River Swamp (1).

2.3.3.2 Mammals

Mammal populations? particularly deer? increased rapidly after closure of the site to the public on December 14, 1952. By the mid 1970's the deer population grew to more than 20 deer per square mile or about 5,000 to 8,000 deer on the plant site. Controlled hunts open to the public were begun in 1965. Thousands of deer have been taken in public hunts. In addition, feral hogs are present. These were domestic animals that reverted to a semiwild state after abandonment in 1952. Similar to deer, the hogs grew sufficient in number to warrant hunts. About 125 were taken between 1969 and the mid 1970's (1).

Additional wild mammals common to the site include mice, rats, shrews, gray and red foxes, raccoons, wildcats, striped skunks, opossums, fox squirrels, and beavers (1).

2.3.3.3 Birds

Biologists have identified more than 200 species of birds on the plant site. Of note is the wild turkey population, which was small at the time the site opened. However, wild turkey populations have increased as the result of a program initiated in 1972 that used the site as a breeding ground for stocking other parts of the States. In addition, large numbers of coots and ducks spend winters on and near the site (1).

2.3.3.4 Aquatic Animals

Diverse populations of reptiles and amphibians exist onsite, including numerous species of turtles, lizards, snakes, salamanders, frogs, and toads. Alligators have been seen in ponds and streams. Onsite fish species include largemouth bass, black crappie, bluegill, redbreasted sunfish, flat bullhead, and blueback herring (1).

Hundreds of species of aquatic insects have been identified on SRS (e.g., a study conducted from 1976 to 1977 identified 551 species in the Upper Three Runs Creek system including species and genera that were new to science). Otherwise, populations of fish and aquatic insects in some of the onsite streams were adversely affected during SRS's nuclear production period due to thermal loadings, principally from reactor discharge of heated cooling water. But as operational changes (e.g., reactor shutdown) reduced the volumes of heated water discharged to onsite streams, the fish and aquatic insects have returned (4). For example, since C-Reactor was shut down in 1985, macroinvertebrate communities have recovered in Four Mile Branch and, in some parts of the stream, have resembled those in other nonimpacted SRS streams. Macroinvertebrate communities of Four Mile Branch currently tend to show more diversity in downstream than in upstream reaches (4).

2.4 References

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3 SCENARIO DESCRIPTIONS

This chapter presents the seven exposure scenarios used in Phase III of the Savannah River Site (SRS) Dose Reconstruction Project, including the behavior of the four receptors comprising each scenario (28 receptors total). The behavior of each receptor, which was based on the scenario descriptions provided by CDC, were used to develop values for many of the parameters in the radiological assessment.

Appendix E, Receptor Activities and Usage Rates, presents the derivation of point-estimate values for those parameters that depend on the receptors' behavior (e.g., times spent in various exposure locations). Appendix F, Parameter Values for Base Case Evaluation, presents model parameter values that are not clearly receptor-specific (e.g., food crop production rates).

The exposure scenarios considered for this report evolved over time. The six exposure scenarios that were originally proposed in 2002 by the Centers for Disease Control and Prevention (CDC) were modified and refined by the Savannah River Site Health Effects Subcommittee (SRSHES) and by preparers of this report.

3.1 Scenarios Proposed by CDC and Considered by the SRSHES

CDC originally proposed the following six scenarios (1):

1. A rural family just downwind of the site boundary.
2. An urban/suburban family just downwind of the site boundary.
3. A delivery person.
4. An outdoors person (e.g., hunter, fisherman, camper, etc.).
5. A family living near the river.
6. A migrant worker family living mostly outdoors.

These scenarios, which describe hypothetical families that might have lived in the SRS vicinity, were meant to represent a range of activities that were typical, and in some sense bounding, for the area. The activities postulated for these scenarios were intended to represent a broad range of lifestyles.

In January 2002, CDC presented proposed assumptions about these six scenarios at a meeting of the SRSHES in Charleston, South Carolina. The SRSHES formed a work group to consider the proposed scenarios. The SRSHES Work Group presented its comments and recommendations about the proposed scenarios at a September 2002 SRSHES meeting (1). Table 3-1 summarizes the CDC's proposed scenarios (as modified) and the SRSHES Work Group's comments and recommendations (1).

The SRS Dose Reconstruction Team discussed the proposed scenarios with CDC staff in early 2003 (2, 3). These discussions principally addressed overall decisions about the number of exposure scenarios to be considered, and where the hypothetical families comprising these exposure scenarios would live, work, attend church and school, obtain food, and recreate.

Table 3-1 CDC Proposed Scenarios and SRSHES Comments and Recommendations

CDC Proposed Scenarios and Descriptions	Summary of SRSHES Work Group Comments and Recommendations
Rural	
▪ Use the closest downwind location where there could have been farms in 1955. ▪ Consider an adult and infants born in 1955 and 1964 (year of largest iodine release). ▪Use default consumption values. ▪ Assume lots 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" to include 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 W of the Savannah River, SW of SRS. Population about 200 in 1950s.) ▪ 1950s: 2 parents, 5 children. 1960s: 2 parents, 3 children. ▪ Schools: Girard Elementary, Waynesboro High School. ▪ Cash crops: peanuts, corn, cotton. Vegetables grown for family consumption. ▪ Religion: Methodist. ▪ In 1950s, 50% of meat & vegetables grown on farm. In 1960s, 25% grown on farm; most milk from one of two Girard dairies. Family had dairy cows. ▪ Family had dogs for pets and chickens. ▪ Some swimming, but minimal camping. No boating. ▪ Fishing from Briar Creek, 2 miles east of Girard. Hunting for deer, quail and dove. Limited trapping.
Urban/Suburban	
▪ Use closest downwind location where urban or suburban families could have lived in 1955. ▪ Consider an adult and infants born in 1955 and 1964 (year of largest iodine release). ▪ Use default consumption values. ▪ Assume the adult worked at the nearest industrial location downwind in 1955. ▪ Assume milk from the nearest dairy or rural neighbor. ▪ Assume the adult worked on-site at SRS in lieu of the "nearest industrial location." ▪ Assume the onsite work location was associated with higher radiological exposures -- e.g., SRS Canyons.	▪ Family lived in Augusta, GA near Broad and Greene Streets. ▪ 1950s: 2 parents, 2 children. 1960s: 2 parents, 3 children. ▪ Schools: Augusta neighborhood schools ▪ Father worked in the SRS F-Area Canyon Building from 1955 to 1992. The mother worked on site until well into her first pregnancy, but stayed home after birth of first child to raise the children. ▪ Attended local church in Augusta, GA. ▪ Food and milk were from local grocery stores in Augusta, GA. Milk was supplied to local stores from dairies in the Aiken and Augusta area. Include backyard cow. ▪ Include a family pet. ▪ Swimming & boating in Clark's Hill Lake. ▪ No hunting. Fished Clark's Hill Lake, 2 weekends/month.
Migrant	
▪ Use the closest downwind location. ▪ Consider an adult and infants born in 1955 and 1964 (year of largest iodine release). ▪ Use default consumption values ▪ Assume always outdoors contacting 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 ▪ 1950s: 2 parents, 2 children. 1960s: 2 parents3 children. ▪ Schools: TBD ▪ Work: TBD ▪ Religion: TBD ▪ Food Sources: TBD ▪ Swimming, Boating, Camping, Hunting, & Fishing: TBD.
Delivery	
▪ Same as Urban/Suburban Family. ▪ Use closest downwind location where urban or suburban families could have lived in 1955. ▪ Consider an adult and infants born in 1955 and 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	▪ Family lived in Barnwell, SC. Father provided weekly beverage deliveries to SRS. ▪ 1950s: 2 parents, 2 children. 1960s: 2 parents, 3 children. ▪ Schools: Barnwell, SC school system. ▪ The delivery person worked at the Allendale Coca Cola Bottling Plant in Allendale, SC, and made routine deliveries to SRS, spending 8 hours/week on-site. No dosimetery. ▪ Consider backyard chickens and/or rabbits at home. ▪ Attended Mount Hope Baptist Church, Martin, SC.

Table 3-1 CDC Proposed Scenarios and SRSHES Comments and Recommendations

CDC Proposed Scenarios and Descriptions	Summary of SRSHES Work Group Comments and Recommendations
dairy or rural neighbor. ▪ Assume that the person spent 8 hours per week on site.	▪ 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. ▪ Hunting at Lower Three Runs Creek area (known for poaching). Fishing at Lower Three Runs Creek, and Savannah River's Smith Lake. ▪ Family drank carbonated drinks, including beer.
Outdoor	
▪ Assume camping at the nearest downwind location making sense with the season (hunting, fishing, etc.) ▪ Assume that the person was always outdoors. ▪ Use default consumption values. ▪ 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.)	▪ Family lived in Jackson, SC ▪ 1950s: 2 parents, 2 children. 1960s: 2 parents, 3 children. ▪ Schools: (1950) Jackson Elementary. (1986) Redcliff Elementary. Jackson High School. ▪ Worked as a hunter/trapper subcontractor to the primary SRS Contractor or the US Forest Service. Some potential exposure from trapping activities, streams, ponds, etc. ▪ Scenario includes the hypothetical poacher. ▪ Hunting dogs were family pets. ▪ Religion: First Baptist Church, Jackson, SC ▪ 50% of vegetables locally grown and irrigated from a surface creek. 75% of meat obtained from SRS. Fish from the Savannah River. Water from a well on home property. ▪ Boating in Savannah River from Jackson, SC, boat ramp. ▪ Took deer, hogs from work at SRS. Fished in Savannah River.
Near River	
▪ Use the nearest docking location downwind where people could have lived on houseboats in 1955. ▪ Consider an adult and infants born in 1955 and 1964 (year of largest iodine release). ▪ Use default consumption values. ▪ Assume always outdoors contacting the 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; if so, define a location. ▪ If not plausible, replace with a new scenario: a site construction worker living in a trailer.	▪ Scenario Location: Consider Martin-Millet area ▪ Family: TBD ▪ Schools: TBD ▪ Work: TBD ▪ Religion: TBD ▪ Food Sources: Shell fishing, shrimping, crabbing ▪ Swimming, Boating, Camping, Hunting, & Fishing: TBD.

Source: (1).

3.1.1 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 sixteen sectors defined by the sixteen major compass directions. 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. This is shown in Figure 3-1. It shows the relative radionuclide concentration from a unit source at a distance of ten miles from the source. In each sector, the relative concentration is constant across the sector width.

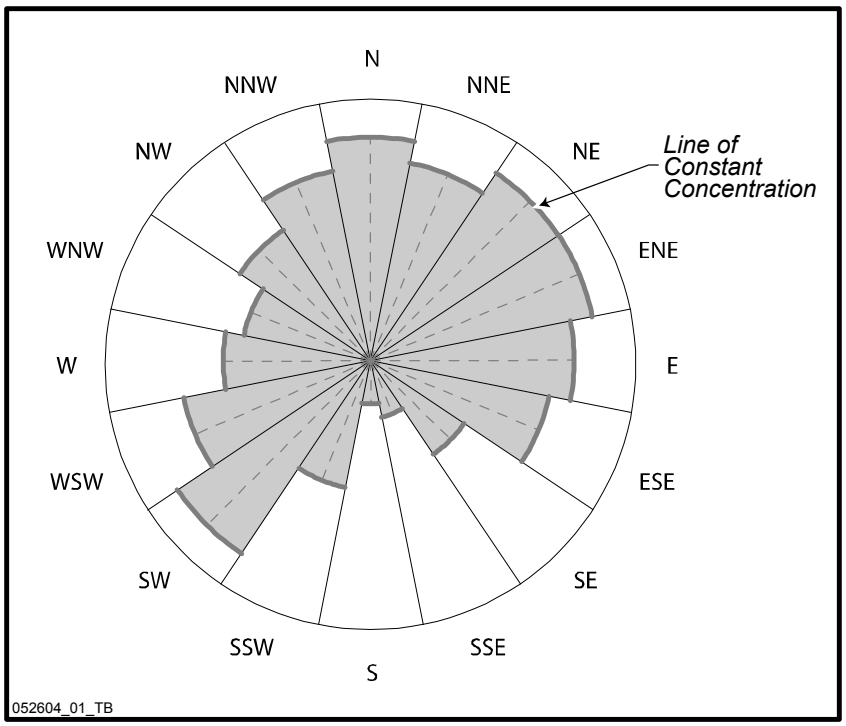

Figure 3-1 Example of Modeled Radionuclide Concentration at Ten Miles from a Unit SRS Source

The meaning of this modeling simplification is that at a given distance from a source, the same concentrations will be determined anywhere the concentration in a given sector is modeled as constant. Thus, two hypothetical exposure locations that are fairly close together will generally not differ significantly in modeled concentrations.

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 #2 – was added with concurrence from CDC and the SRSHES.

In each scenario, exposure locations were identified to represent where family members lived, worked, attended school, engaged in recreational activities, where their food was grown, and other activities. For all seven scenarios, exposures to radionuclides were modeled at ten locations for radionuclides released to the air and two locations for radionuclides released to water.

The exposure locations assumed for the seven exposure scenarios are shown in Figure 3-2. Table 3-2 summarizes the exposure locations for contamination released into the air, while Table 3-3 summarizes 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.

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

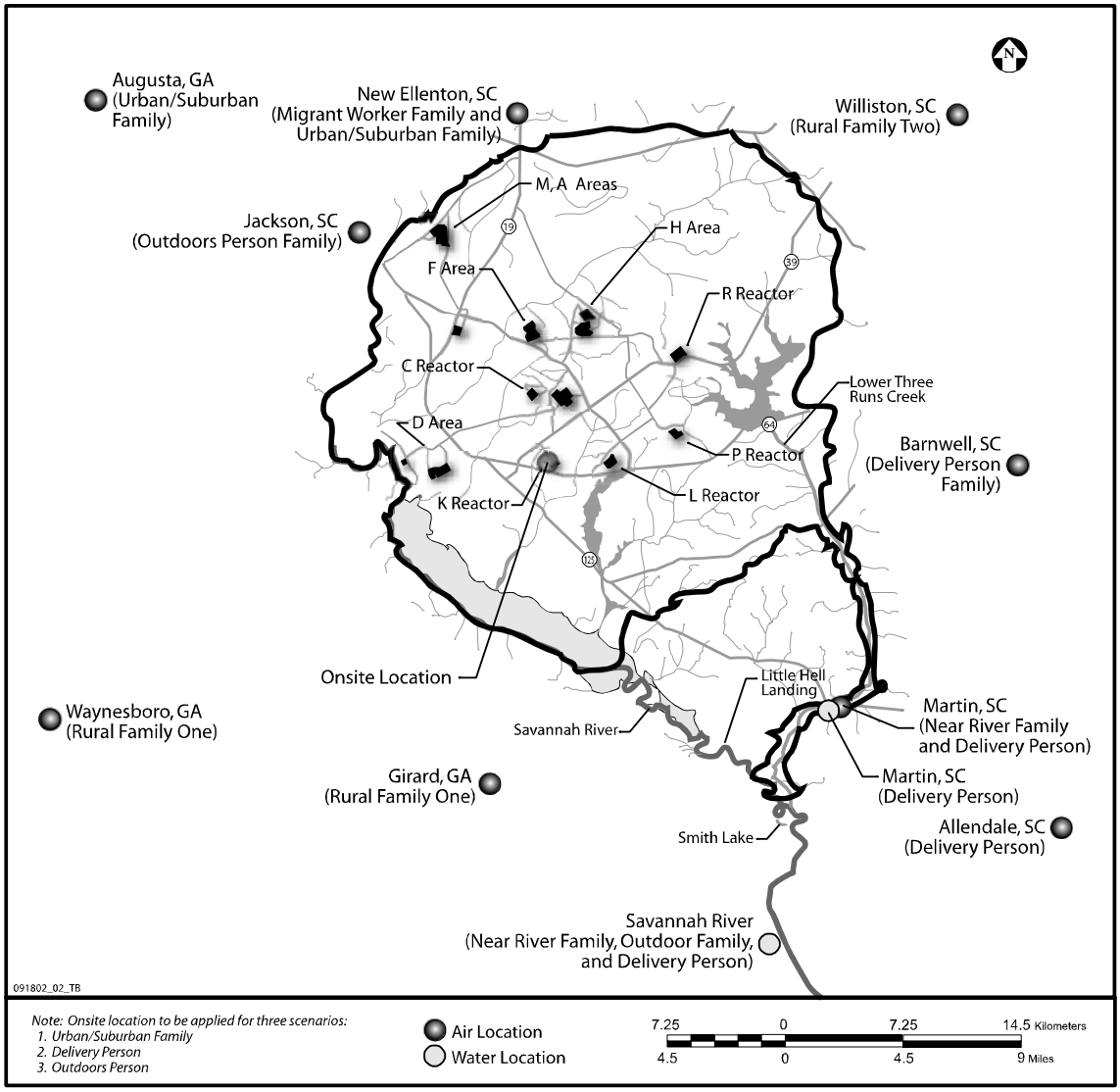

Figure 3-2 Exposure Locations for Exposure Scenarios

located in New Ellenton, South Carolina. The father worked onsite at SRS. The children also worked onsite at 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

Table 3-2 Summary of Exposure Locations for SRS Releases to Air

Exposure Scenario	Activity*	Exposure Location									
		Girard, GA	Waynesboro, GA	Martin, SC	Augusta, GA	Williston, SC	SRS Onsite Location	Barnwell, SC	Allendale, SC	Jackson, SC	New Ellenton, SC
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				
Migrant Worker Family	All activities										X
Delivery Person Family	All except those below:							X			
	Employment								X		
	Employment						X				
	Church, grocery (partial), swimming, boating, hunting, fishing			X							
Outdoors Person Family	All except employment									X	
	Employment						X				
Near River Family	All activities			X							

* Activities included school, work, recreation, church, production of foodstuffs, and indoor and outdoor activities around the home.

† For all receptors, excluding the children of Rural Family One, the same exposure location was used for their high school as for their residence. Children of all scenarios attended grade school at the same exposure location that was used for their residence.

Table 3-3 Summary of Exposure Locations for SRS Releases to Surface Water

Scenario	Activities / Pathways	Downstream Savannah River	Lower Three Runs Creek	No Exposure to Water Affected By Liquid Releases*
Rural Family One	All activities†			X
Rural Family Two	All activities†			X
Urban/Suburban Family	All activities†			X
Migrant Worker Family	All activities†			X
Delivery Person Family	Fishing, swimming, shoreline		X	
	Fishing, shoreline, boating	X		
Outdoors Person Family	Fishing, shoreline, boating	X‡		X§
	Swimming			
Near River Family	All activities†	X		

*Exposure occurred in water not affected by releases from the SRS to water.
†"All activities" included fishing, boating, swimming, and shoreline.
‡Shoreline exposures were only received at work by the Adult Male and the children when they each reached age 18. Recreational shoreline activities by all family members were in unaffected water.
§For the entire family while recreating on the Savannah River.

Barnwell and some from Martin. The father worked in Allendale, South Carolina, and onsite at SRS. (So did the children 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.[1] The family boated on, and ate fish from, the Savannah River at this same exposure location. The family also ate fish that were 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.[2] 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.

[1] Exposures from air immersion and deposition that were received while conducting water-related activities were modeled assuming the Martin exposure location.
[2] All boating occurred below the confluence of the Savannah River with Lower Three Runs Creek.

- Near River Family. This family lived in Martin, South Carolina.[3] 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 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 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, in order 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 SRS, at neither location would receptors have experienced radiological exposures from radionuclides released by SRS to surface water. The only exposures would have been from radionuclides that had been released into the air. But Augusta is closer to SRS than Clark's Hill Lake, and both locations are northeast of SRS. For this reason, 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, fishing) were assumed to occur at a location below the confluence of the Savannah River with Lower 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

[3] Note that Martin, South Carolina, is not directly on the river.

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.

3.1.2.2 Additional Refinements to Proposed Exposure Scenarios

In addition to the overall decisions described above, several refinements were made to the specifics of the exposure scenarios proposed by the 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 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 trapping. It was assumed for several scenarios that the adult male spent time outdoors while hunting and trapping. Radiation exposures received through consumption of game animals was modeled for the two rural families, the Delivery Person Family, and the Outdoors Person Family by assuming that meat from game animals could be represented as either a form of beef or poultry (see Section 3.2.2).

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 potential for the crustaceans cited by the SRSHES to be present at the scenario locations was considered very remote. The habitat for the crustaceans cited is located a significant distance downriver in brackish water, far enough away from SRS so that the levels of radiation in the crustaceans would be quite small.

Irrigation. Irrigation with water contaminated with radionuclides from 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). Modeling additional children would not provide significantly different information from that already obtained from the two children already studied. 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, in the air. Given that a generally accepted model for exposure to radionuclides from contaminated pets is not available, that many modeling assumptions were pessimistic, and that doses from this pathway were not expected to be large, dose estimates for this pathway were not included in this Phase of the dose reconstruction.

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 to simulate this pathway was not readily available. However, the Phase III radiological assessment did consider the consumption of contaminated foodstuffs by infants, including contaminated cow's milk, which should have simulated these exposures.

***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.[4]

3.2 Additional Assumptions About Scenarios

To perform the Phase III radiological assessments, it was necessary to add several additional assumptions to those provided by the CDC and the SRSHES to address specific features of the exposure scenarios. These assumptions are addressed in detail in Appendix E and summarized here:

3.2.1 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 in order to allow direct comparison of the effect of being born at different times.

[4]The dose and risk coefficients that were 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).

Figure 3-4 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 3.2.2), the times spent performing different activities (Section 3.2.3), and breathing rates (Section 3.2.4). In 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 (three years from age 2-4), to a grade-school aged child (seven years from age 5-11), to a teenager (six years from age 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.

3.2.2 Food Products

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 SRS. (See Appendix E for details.)

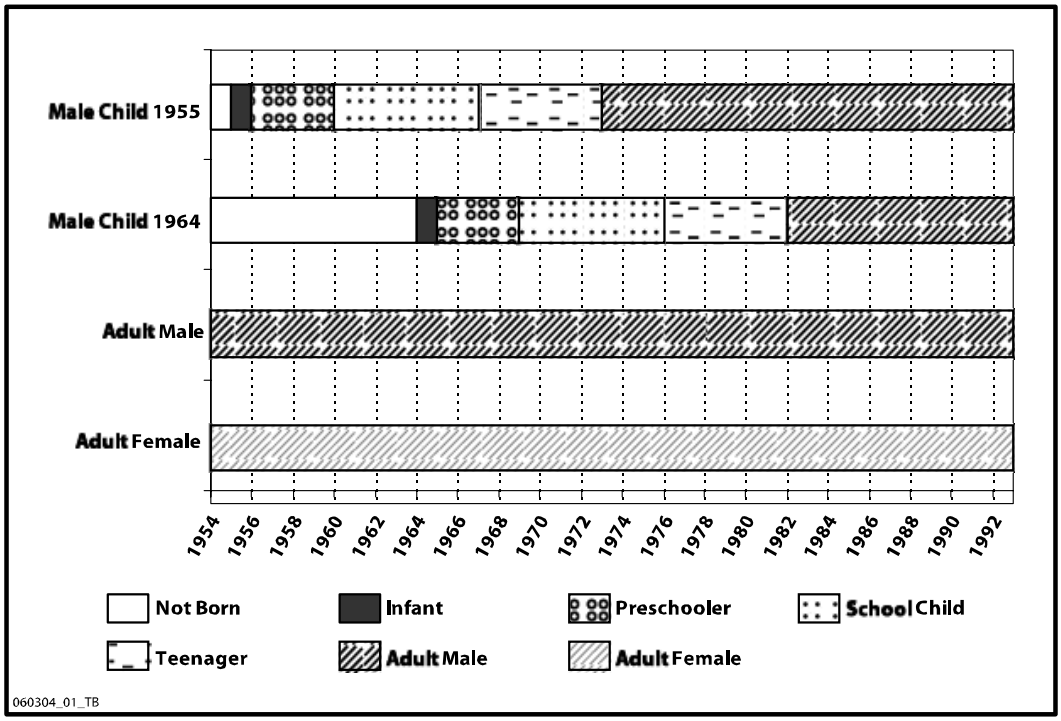

Figure 3-4 Age and Gender Categories of Modeled Receptors by Year

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 and gender 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. When each child reached age 18, they thereafter 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.

For beef, poultry, fruit, and vegetables, a time-dependent, locally-produced fraction was assumed for Rural Families One and Two consistent with the SRSHES Work Group recommendations for meat and vegetables (see Table 3-1). The fraction that was eaten that originated from the farm was reduced after the end of 1959. For other scenarios it was assumed that half of the beef, poultry, fruit, and vegetables from stores was produced locally.

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.

3.2.3 Times Spent Per Activity

Each member of each scenario was assigned a home area, a work area for the Adult Male (and for the children after they became adults), food procurement areas, and areas for activities including church, school, work, hunting, fishing, swimming, and boating. Times spent in each area not derived from the suggestions of the SRSHES Work Group (1) were mainly determined using EPA's Exposure Factors Handbook (5) and an SRS report on land and water use characteristics in the vicinity of the Savannah River (6). Times spent performing each activity were used in assessing radiation exposures through several exposure pathways (e.g., the radiation dose received at an exposure location from immersion in a plume of contaminated air depended on the time spent at that exposure location). Assessments of radiation exposure from contaminated soil depended on the time spent either indoors or outdoors.

Home. The time spent at home depended on assumptions for each member of each scenario about work, church, school, and recreation. The times spent by each family member either indoors or outdoors were

assumed based on data from EPA's Exposure Factors Handbook (5). Different times indoors and outdoors were assumed based on whether the family member was an adult male, an adult female, or a child within a particular age group.

Food Procurement. It was generally assumed that food for family members was obtained locally to their residences. As noted above, some food was obtained from stores and some was locally grown. However, half the milk for the Urban/Suburban Family scenario was obtained from an exposure location away from their residence, and half of all food products (other than fish) for the Delivery Person Family scenario was obtained from an exposure location away from their residence. For these situations, the difference in external or inhalation exposures that may have occurred during the limited time spent in these locations obtaining food was not assessed. However, the assessment did consider the location where the food was grown.

Church. All members of each scenario spent 104 hours per year (52 weeks/year x 2 hours/week) at church. All church hours were assumed to be part of the time all receptors spent indoors.

School. Children and teenagers attending school each spent 1,260 hours per year in school. Of these 1,260 hours, 900 hours were spent indoors and 360 hours were spent outdoors (5 hours indoors/day, 2 hours outdoors/day x 180 days/year). It was assumed that no food obtained was grown in the school locations.

Hunting/Fishing. For most scenarios, it was assumed that when the Adult Male was hunting (Rural Families One and Two, and Delivery Person Family), the amount of time spent hunting was included in the residential outside hours. The Outdoors Person hunted as part of work, and all hunting hours were spent outside.

Swimming, Shoreline, and Boating. Most members of most scenarios were assumed to swim for 21 hours each year and spend 85 hours each year along a river or creek shoreline based on data from the SRS report on land and water use characteristics in the vicinity of the Savannah River (6). But members of the Near River Family spent 91 hours per year swimming (an hour per day during the summer for each member) as well as 365 hours per year along the Savannah River shoreline. These assumptions were based on the statement by the SRSHES Work Group to "assume they were always in contact with the Savannah River" (1). All hours were spent outdoors. The Adult Male of the Outdoors Person Family annually spent 260 additional hours on the Savannah River shoreline as part of work.

Consistent with the recommendations of the SRSHES Work Group (1), members of Rural Families One and Two and the Migrant Family did not go boating. Members of the Urban/Suburban, Delivery Person, and Outdoors Person Families boated in the Savannah River for 96 hours per year based on data from the SRS report (6). Members of the Near River Family boated in the Savannah River vicinity for 192 hours per year – i.e., twice the value in the SRS report (6). These assumptions were based on the statement by the SRSHES Work Group to "assume they were always in contact with the Savannah River" (1).

3.3 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:

Section 3.3.1: Rural Family One in Girard, Georgia.

Section 3.3.2: Rural Family Two in Williston, South Carolina.

Section 3.3.3: Urban/Suburban Family in Augusta, Georgia.

Section 3.3.4: Migrant Worker Family in New Ellenton, South Carolina.

Section 3.3.5: Delivery Person Family in Barnwell, South Carolina.

Section 3.3.6: Outdoors Person Family in Jackson, South Carolina.

Section 3.3.7: Near River Family in Martin, South Carolina.

3.3.1 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 3-5 shows the exposure locations of Rural Family One.

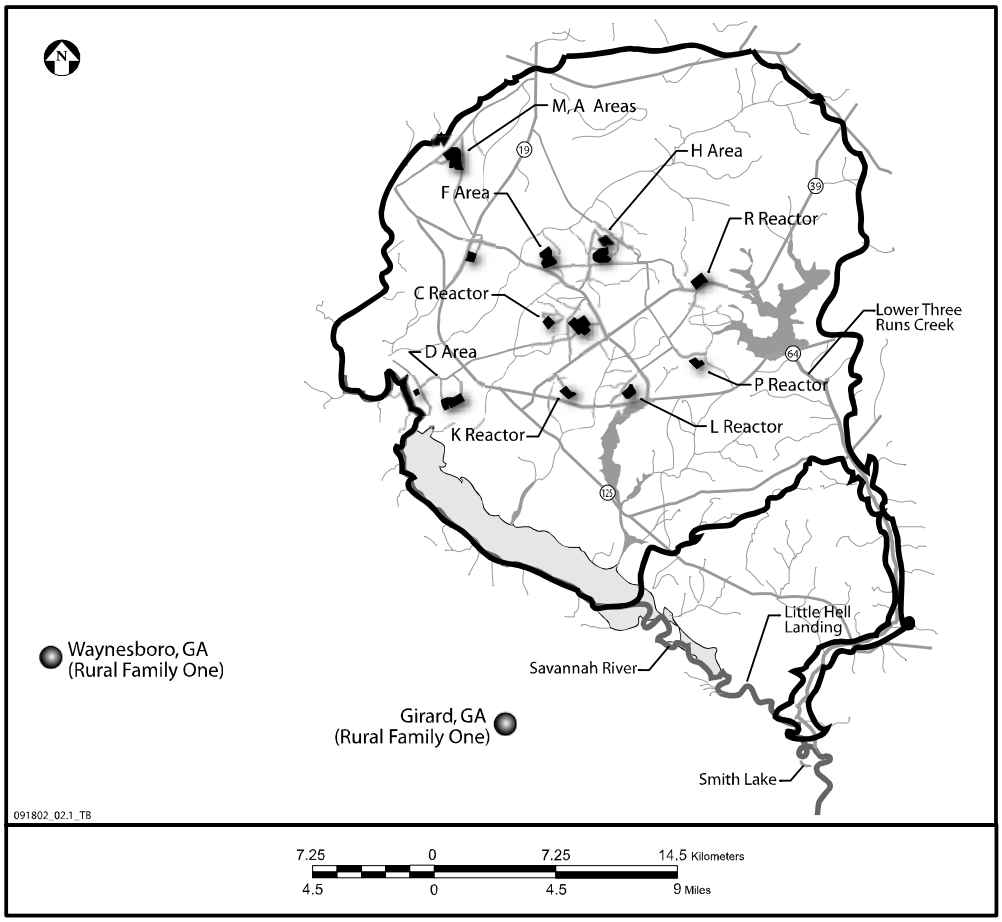

Figure 3-5 Exposure Locations of Rural Family One

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 SRS, none of the fish consumed by the family was affected by SRS release of radionuclides to surface water. During the 1950s, 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% of their beef, poultry, vegetables, and fruit was grown or produced on the family farm. The remaining 75% 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 assumed to be unaffected by SRS releases.

3.3.2 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 3-6 shows the exposure location of Rural Family Two.

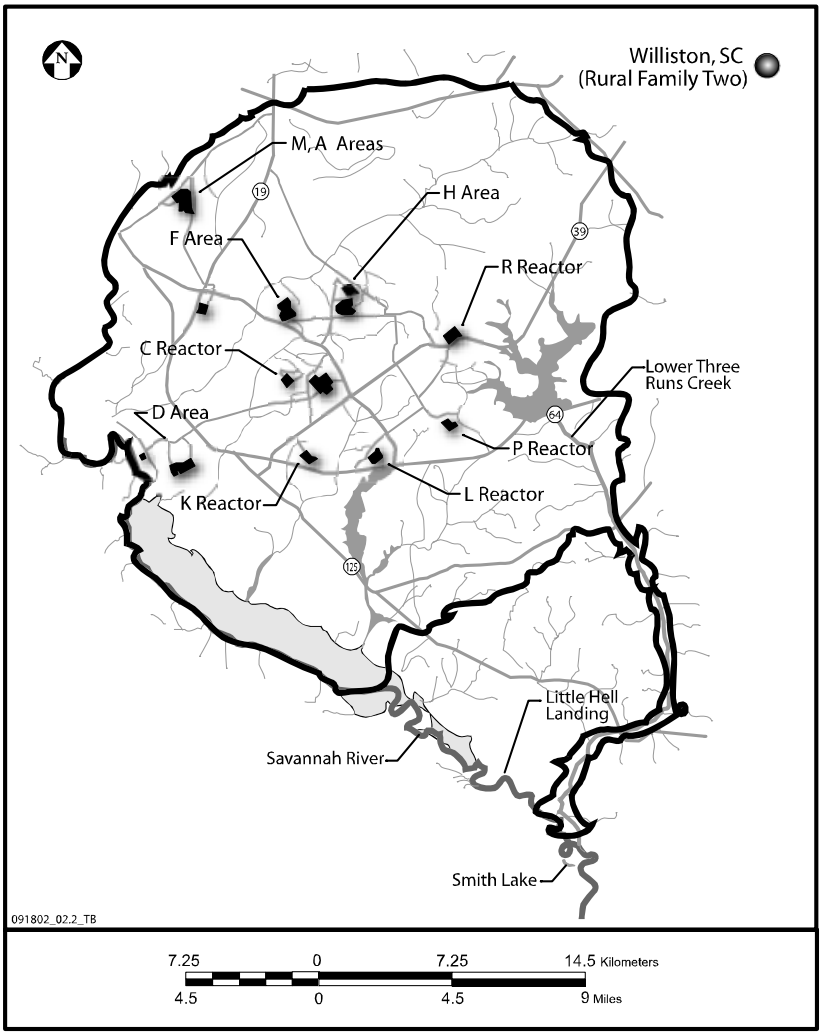

Figure 3-6 Exposure Location of Rural Family Two

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 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 was caught in streams or ponds in or near Williston. Because these streams

[5] This assumption was made for all receptors and scenarios. As discussed in Appendix E, 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. Although corn may have been consumed as a vegetable, uptake of radionuclides by corn is appropriately modeled as grain uptake.

and ponds are not hydrologically downstream from SRS, none of the fish eaten by the family was affected by SRS releases of radioactive material to surface water.

During the 1950s, 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% of their beef, poultry, vegetables, and fruit was grown or produced on the family farm. The remaining 75% 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

3.3.3 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 SRS for the duration of the study period (39 years). The children worked onsite at 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 SRS. Figure 3-7 shows the exposure locations of the 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 non-local sources. All locally-grown grain eaten by the family was corn. Fish came from sources unaffected by liquid releases from SRS (e.g., from the nearby Savannah

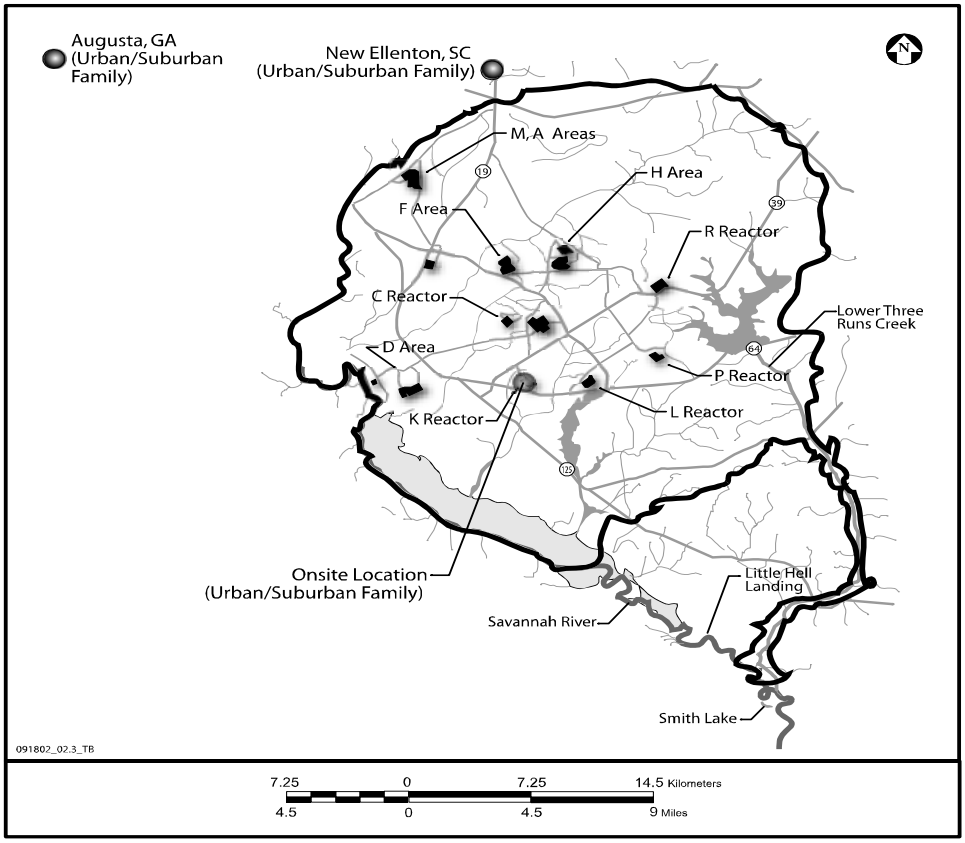

Figure 3-7 Exposure Locations of Urban/Suburban Family

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

3.3.4 Migrant Worker Family

All family members spent much of their work, home activities, and recreation time outdoors in New Ellenton, S.C. Figure 3-8 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.

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 SRS, none of the fish eaten by the family was affected by SRS liquid 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.

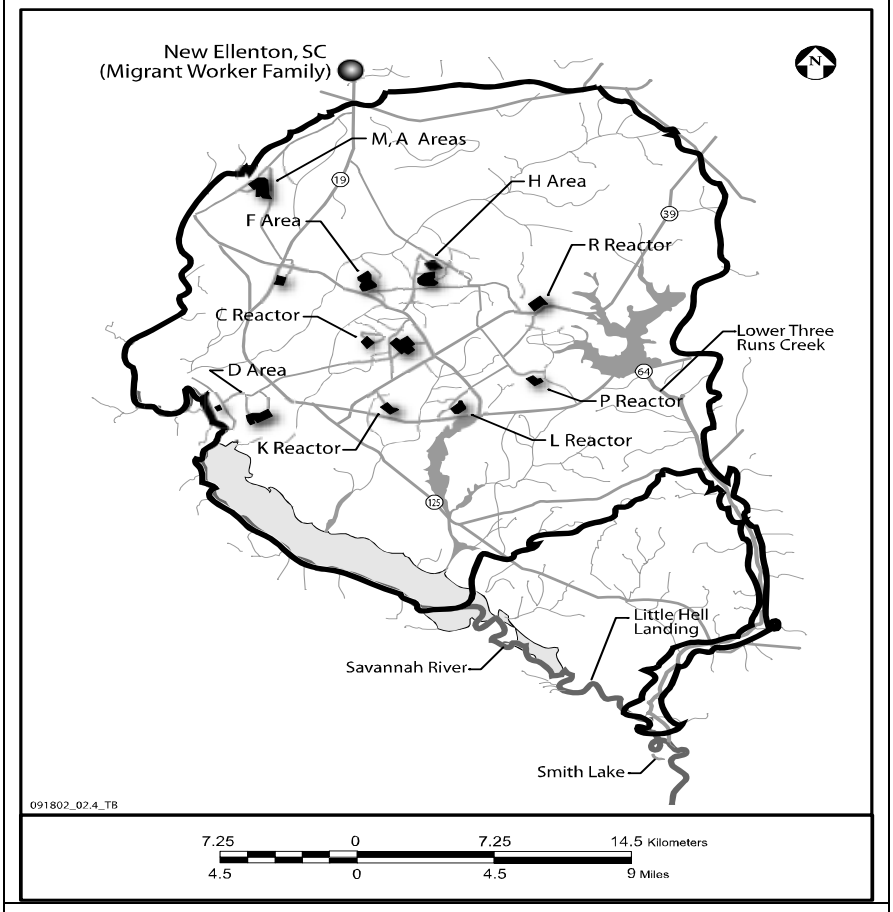

Figure 3-8 Exposure Location of Migrant Worker Family

3.3.5 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 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 3-9 shows the exposure locations of the 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% consisted of meat from hunting deer and wild fowl. That is, 25% of the beef from Martin consisted of locally-hunted venison while 25% of the poultry from Martin consisted of locally-hunted wild fowl. Of the remaining 75% of the beef and poultry from

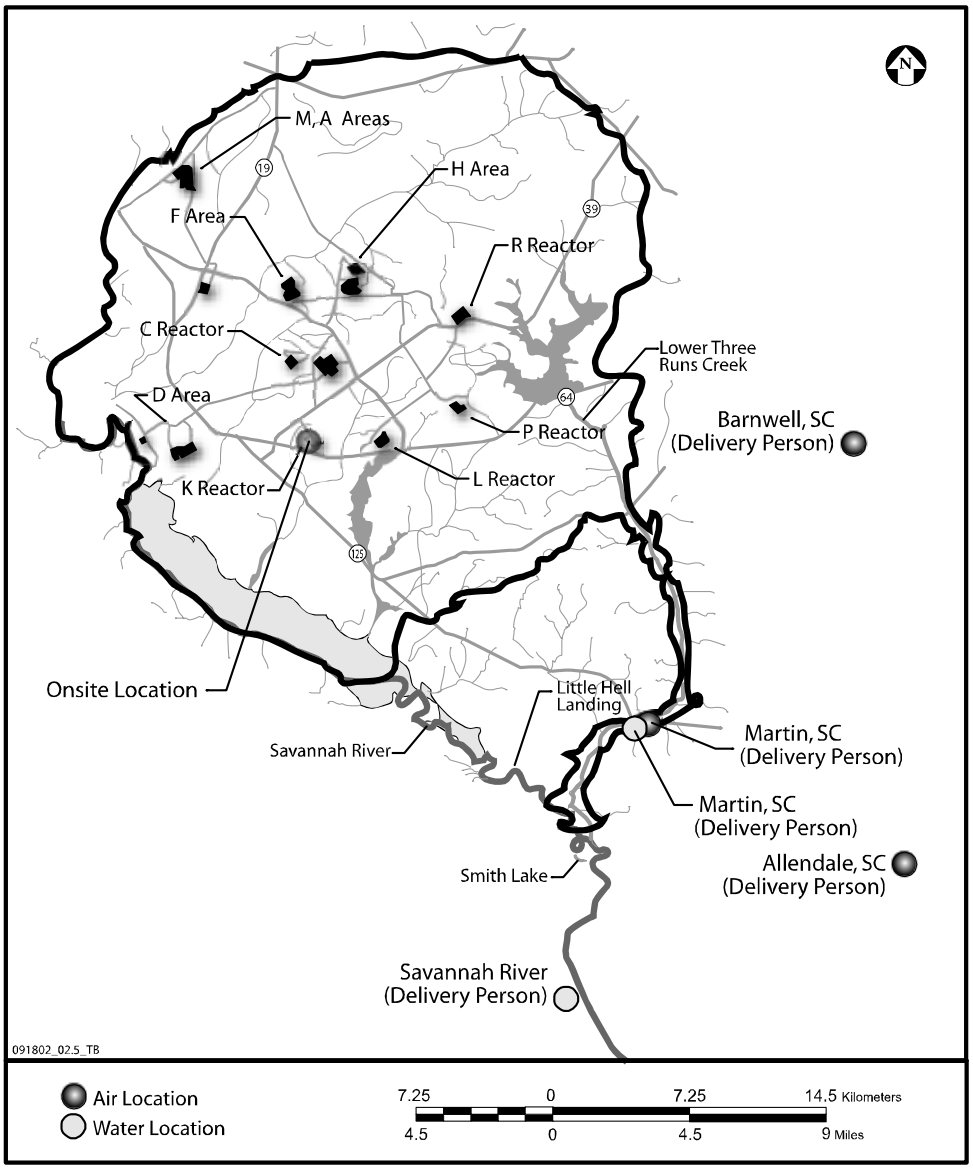

Figure 3-9 Exposure Locations of Delivery Person Family

Martin, half was produced in the Martin area and half was acquired (e.g., by stores) from sources well away from the SRS.[6]

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.

3.3.6 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 activities for the Adult Male nor during employment activities for the children after they each reached age 18. The Adult Male worked onsite at SRS as a hunter, as did the children when they grew up. During the time the Adult Male spent onsite at 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 3-10 shows the exposure locations of the Outdoors Person Family.

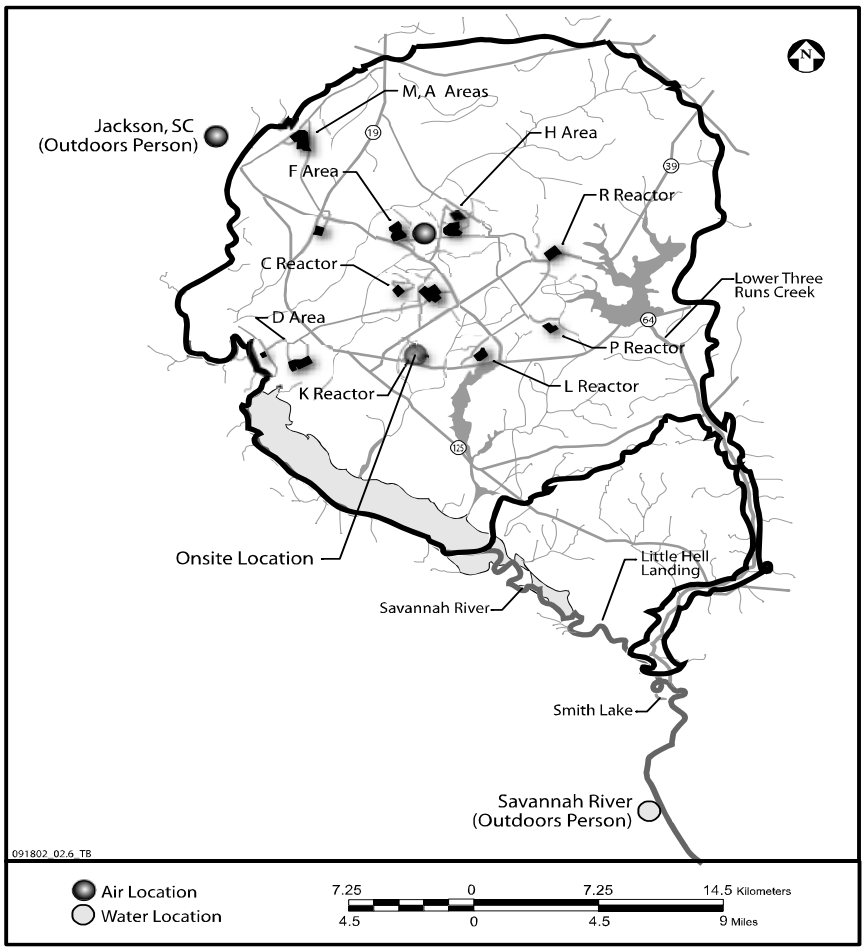

Figure 3-10 Exposure Locations of Outdoors Person Family

[6] Combining the venison and wild fowl obtained from hunting with other beef and poultry obtained in Martin, it was assumed that 62.5% of all beef (including venison) obtained from Martin potentially contained radionuclides from the SRS, as did 62.5% of all poultry (including wild fowl) eaten by the 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 SRS.[7]

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 SRA 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.

3.3.7 Near River Family

This hypothetical family lived in Martin, SC. 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 3-11 shows the exposure location of the Near River Family.

[7] 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.

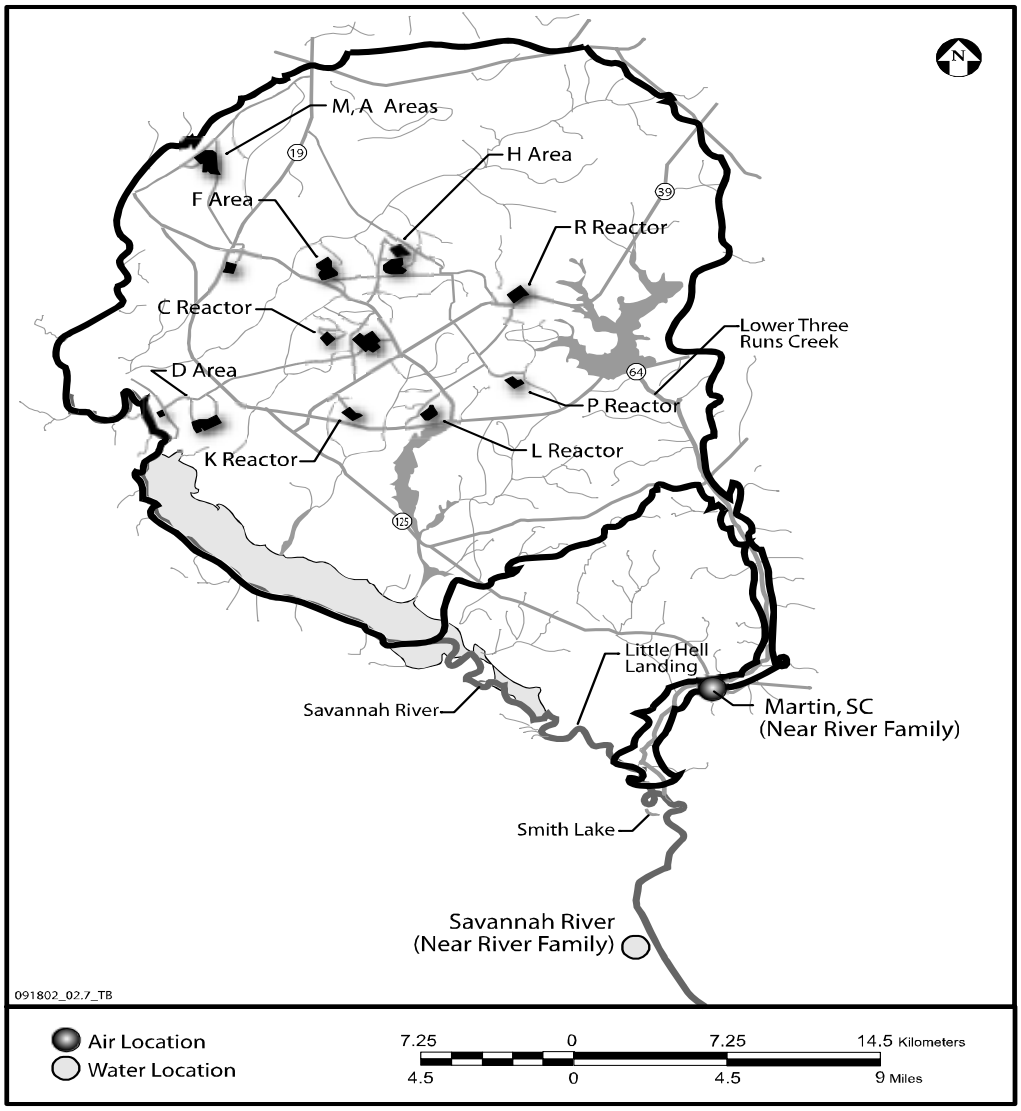

Figure 3-11 Exposure Locations for Near River Family

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 assumed to be unaffected by SRS releases.

3.4 References

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4 OVERVIEW OF APPROACH

4.1 Statement of Goals and Constraints

The goal of this phase of the Savannah River Site (SRS) Dose Reconstruction Project is to estimate the doses and cancer risks to hypothetical receptors from SRS releases of radioactive materials to the air and water over 39 years of operation. The behaviors of the hypothetical receptors were designed to represent a range of plausible activities for the population living near SRS, but these projections were in some sense bounding without being unrealistic. This is an intermediate phase dose reconstruction that provides more detail and precision than a screening analysis, but it lacks the detail and precision of a full dose reconstruction that is based on the behavior of real people.

Although the overall goal for this dose reconstruction is simply stated, it was necessary for the analysis to address the particular characteristics of the area surrounding the SRS and the level of detail sought for this phase of the dose reconstruction. The following considerations shaped the choice of approach:

- Radionuclide releases:
  - -- Vary substantially with time.
  - -- Several radionuclides.
  - -- Releases to air and water.
  - -- Multiple locations for releases.
  - -- Base release estimates and their uncertainties on Phase II.
- Working group scenarios:
  - -- Seven scenarios with four receptors each.
  - -- Age of receptors is an important factor to explore.
  - -- Scenarios incomplete as work commenced.
  - -- Many different types of activities for each receptor.
  - -- One home location for each scenario; additional locations for several receptors.
- End points of analysis:
  - -- Dose.
  - -- Risk.
  - -- Organ doses as needed.
  - -- Evaluate uncertainty in dose.
  - -- Use generic environmental models.
  - -- Estimate dose and risk by radionuclide, year, receptor, pathway, etc.
- Comprehensive approach:
  - -- Use site-specific data or, if unavailable, appropriate generic data.
  - -- Model dose-significant aspects of the scenarios.
  - -- Model all important transport and exposure processes.
  - -- Use representative variable values not intended to overestimate or underestimate dose.

The approach described in this chapter responds to these particular aspects as well as to the overall goal of the study. These aspects were addressed by the choice of: an overall approach, the models used, and the implementation of the models, the data input to the calculation, the data obtained from the calculation, and the software used to automate the calculations.

4.2 Analytical Framework

The analytical framework may be described in terms of the assessment process, the modeling process, and the analysis steps. Although these aspects are related, they address different facets of the overall analytical framework.

4.2.1 Assessment Process

A dose reconstruction is a special type of retrospective dose assessment or radiological assessment based on past releases of radioactive material to the environment. The essence of a radiological assessment has been succinctly summarized (1) as:

> "The ultimate goal of radiological assessment is to show the relationship between the 'source term,' or quantity and types of released radionuclides, and the potential effect on human health. The assessment process must proceed in a logical fashion, following the radioactive pollutant of interest from its point of origin along various exit pathways to the environment, then considering its transport in air, water, soil, or food sources to man. Once transport and intake are determined, the dose from radiation and resulting risk to health can be calculated."

In other words, the dose reconstruction starts with the release of radionuclides from SRS; continues with the transport by air, water, and the food chain; models the exposure of the hypothetical receptors to contaminated media (air, water, soil, and food); and results in an estimation of doses and risks.

Figure 4-1 shows the risk assessment approach (2), and Section 4-3 discusses the approach in more detail. The INPUT is the set of site information including the releases compiled in Phase II (3) and the specification of the hypothetical scenarios. The OUTPUT is the health risk to each individual receptor estimated by the radiological assessment. Note that the output of any step of the overall assessment is the input to the next step of the assessment.

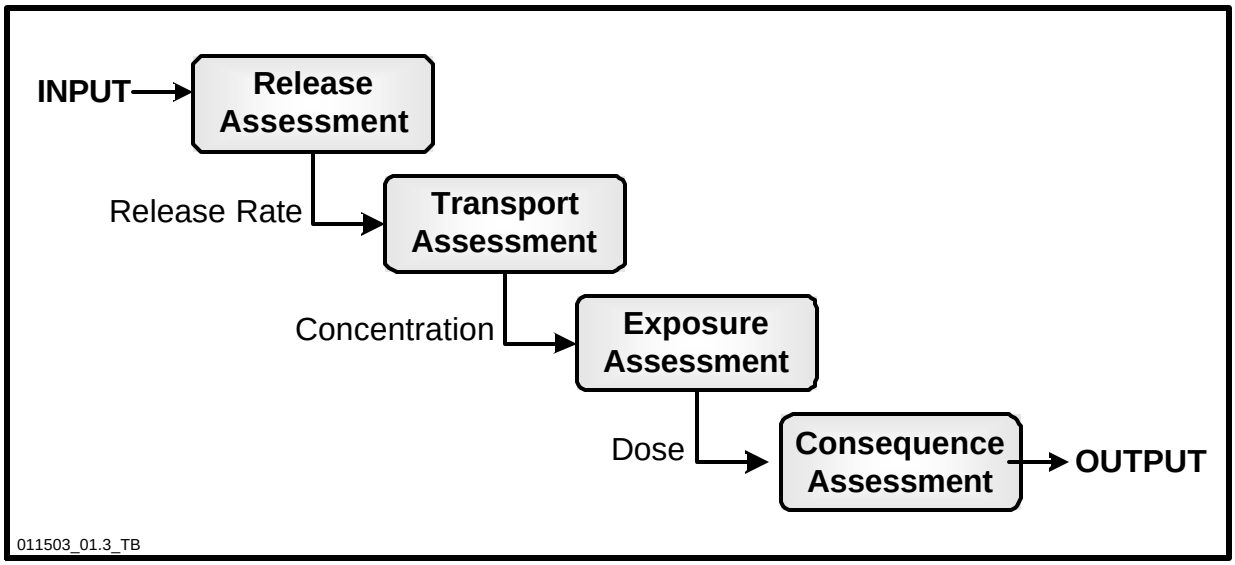

Figure 4-1 Risk Assessment Approach (2)

This dose reconstruction process can be viewed as four linked assessments (2). In the case of a radiological assessment, these linked assessments provide the following data:

- The Release Assessment provides the rate of release of radionuclides as a function of time and location of the source.
- The Transport Assessment provides the concentration of radionuclides in the environment (i.e., concentrations in air, water, soil, and foodstuffs as a function of time and location around the SRS).
- The Exposure Assessment provides the dose to a particular receptor based on their contact with contaminated media (air, water, soil, or foodstuffs).
- The Consequence Assessment provides the risk of cancer incidence and mortality.

The assessment process is described in a greater level of detail in Figure 4-2 for air releases and Figure 4-3 for liquid releases. Figure 4-2 for air releases shows how the transport assessment links concentrations in different media: air, soil, plants, and animals. These contaminated media lead to exposure of receptors by different pathways (4 of the 13 pathways for air releases are shown explicitly; "plant ingestion" represents 5 distinct pathways; "animal ingestion" represents 4 distinct pathways). Receptors are exposed through three exposure routes: inhalation and ingestion of radionuclides and exposure to direct radiation (external dose). Doses and risks are estimated using standard dose conversion factors. Figure 4-3 for liquid releases shows how the transport assessment links concentration in the water to concentration in fish. These contaminated media lead to exposure of receptors by different pathways (all of the 5 pathways for water releases are shown). Each of the four major parts of the assessment is primarily supported by different sources of information, as shown at the bottom of the figures. The Release Assessment is based primarily on the Phase II Report; the Transport Assessment is based primarily on the Phase II Report and Site Data; the Exposure Assessment is largely based on the scenarios specified by the CDC; and the Risk Assessment is based on Federal Radiation Guidance 11, 12, and 13.

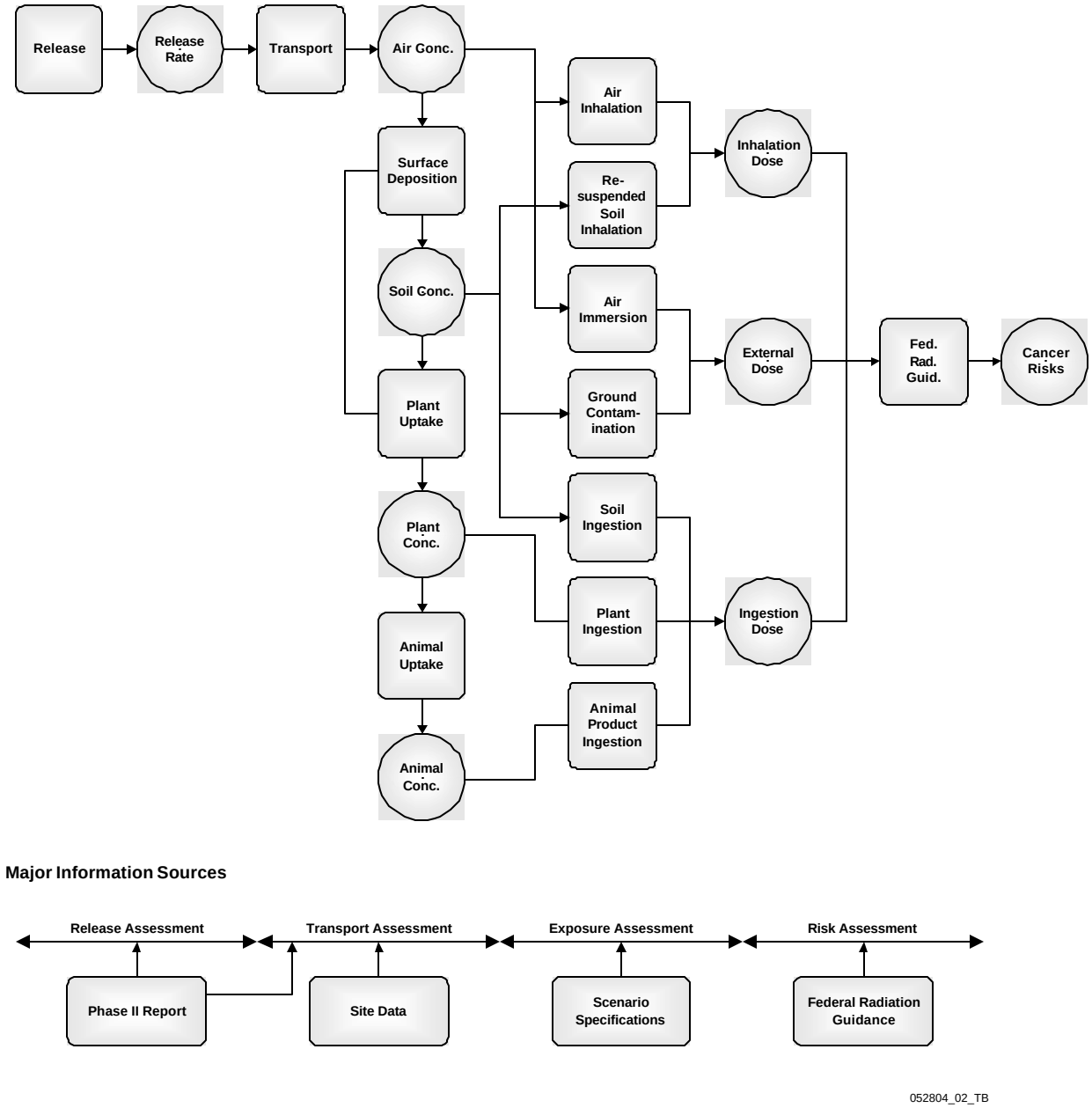

Figure 4-2 Overall Modeling Approach for Air Releases

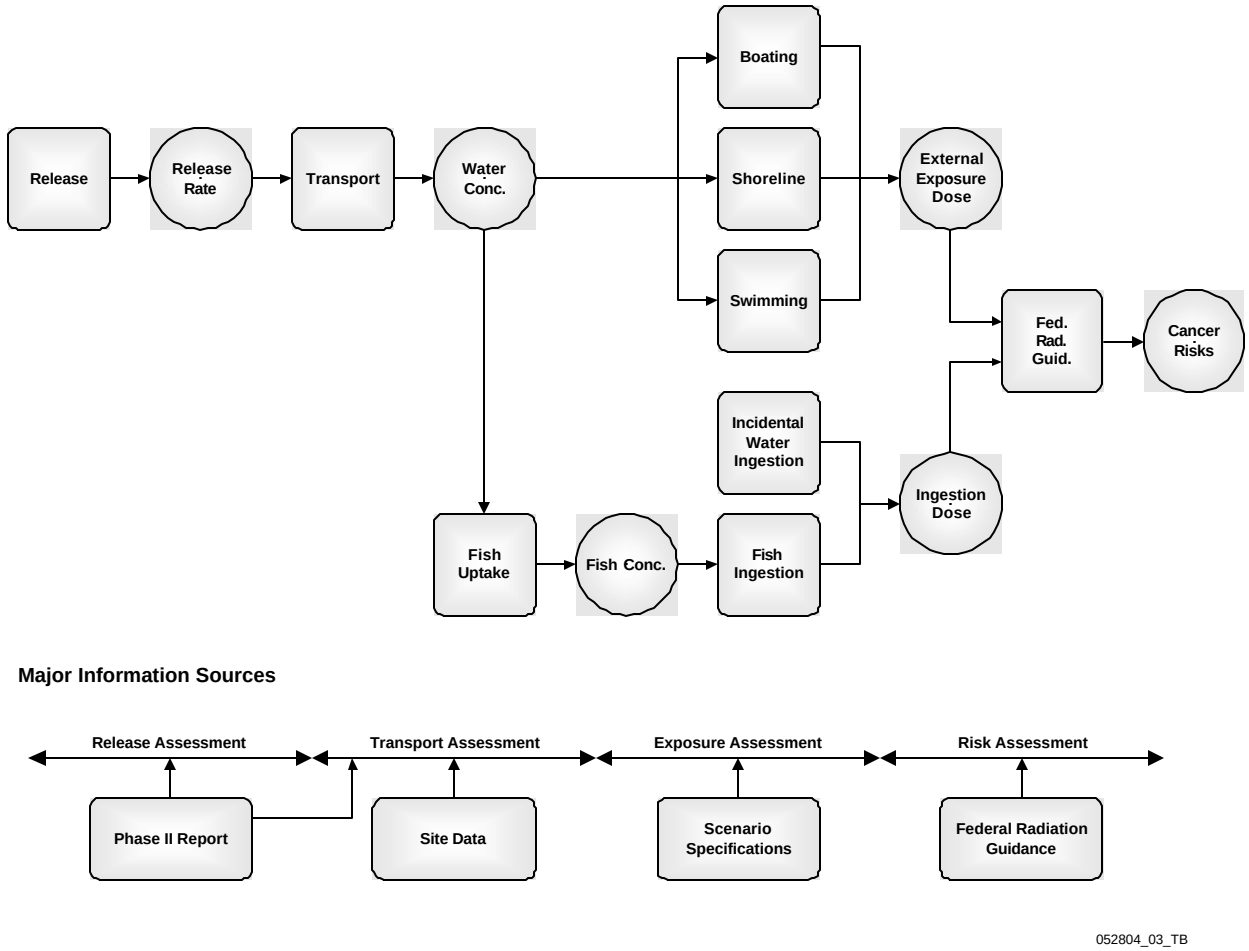

Figure 4-3 Overall Modeling Approach for Liquid Releases

4.2.2 Modeling Process

These steps, described above in the text and Figure 4-1, provide a general procedure used to conduct this dose reconstruction; however, there are several other dimensions to the study. One important dimension is the modeling sequence followed in this and most environmental studies. The modeling sequence, shown schematically in Figure 4-4, consists of three components: 1) conceptual model, 2) mathematical model, and 3) numerical model.

The conceptual model is developed first and is a qualitative or semi-quantitative representation of the processes, conditions, features, and behaviors involved in the release and transport of radionuclides, the exposure of receptors to contaminated media, and the risks incurred in each receptor from these exposures. Section 4.3 presents many of the aspects of the conceptual model. For example, this dose reconstruction requires consideration of a time-varying release of radionuclides, the release of multiple radionuclides together, releases of radionuclides into air and water, releases of radionuclides from multiple locations, and receptors engaged in varied activities at several locations. If any of these aspects were different, the entire modeling approach would be different. For example, if we were studying pollution from the morning rush hour in a large urban area, the pollution would be released over a relatively short time (not years) and it would be released relatively uniformly over a large area (not released at a point).

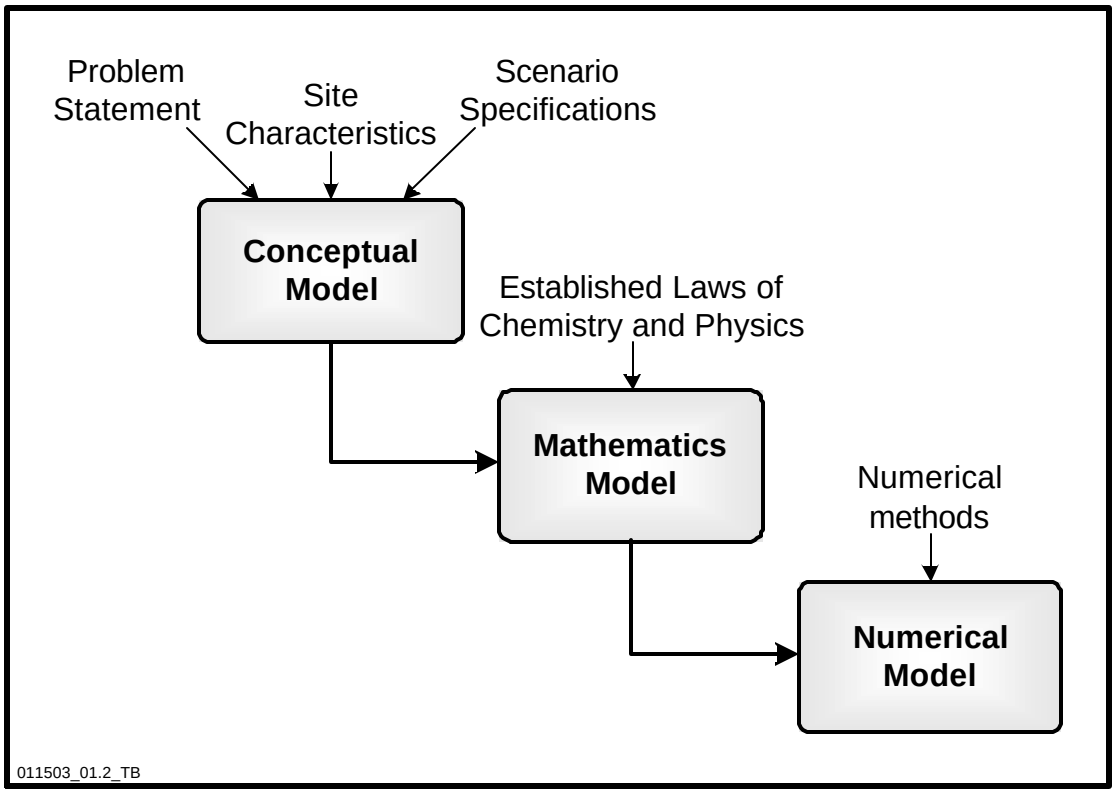

Figure 4-4 Schematic of Modeling Process

The mathematical model is derived from the conceptual model. It represents all the aspects of the conceptual model as a set of mathematical equations that usually involve a number of variables (quantities that may change with location, time, events, releases, receptors, or particular activities). These equations use well-established laws of physics, chemistry, and biology to represent the four dose reconstruction assessments

In turn, the numerical model is derived from the mathematical model. The numerical model is essential because it provides the quantitative estimate of dose to each receptor that is the study end goal. The numerical model may be little more than a bookkeeping method or a very complex numerical procedure; for this study, the numerical model included both ends of this spectrum. To obtain the quantitative estimate, values for all the variables employed in the mathematical model must be supplied. For this study, a very large number of variables needed to be carefully specified because the variable specification must represent the characteristics of the site and the surrounding area and the behavior of the receptors.

As described in more detail in Section 4.4, the numerical model used for this dose reconstruction is encoded in the GENII computer code. Although this generic dose assessment computer code has already encoded a large variety of mathematical models, a major and crucial task of this project was to configure the GENII code to represent the conceptual model for this dose reconstruction. This configuration was achieved in two main ways:

1. The GENII code is comprised of many modules, and each module represents a particular process in the overall approach presented in Figure 4-1 (e.g., the uptake of radionuclides by a plant from the soil in which it grows). Incremental doses to a receptor are estimated by linking together a sequence of these modules. For example, a particular sequence might include: 1) transport of some of the release by air dispersion to a specified location, 2) deposition onto the soil, 3) incorporation into the soil, 4)

uptake by a plant, 5) ingestion of the edible portion by the receptor, 6) dose to the receptor, and 7) resulting risk to the receptor. A fundamental decision was determining which modules to use and how they should be interconnected. Some modules, although available in GENII, were deliberately omitted (e.g., contamination of soil by irrigation with contaminated water was not used because agricultural practices in the SRS vicinity did not include irrigation by river water.) Each complete set of modules leading to a receptor dose has been termed "an exposure pathway" as described in Chapters 9 and 11. A total of 18 different exposure pathways were used in this study: 13 for air releases and 5 for water releases.

2. Providing the number and location of places where radionuclides were released and receptors were exposed was essential in representing the site. Chapter 3 describes the choice of the exposure locations based on the CDC/SRS Health Effects Subcommittee (SRSHES) scenarios. Chapter 6 describes the choice of locations for the release of radionuclides to air; four virtual sources were used to represent time-varying releases from multiple facilities. Chapter 7 describes how concentrations of radionuclides in water were estimated at two locations based on releases from multiple facilities.

An essential aspect of the analytical framework is the central importance of the conceptual model. Very simple environmental and radiological analyses may be performed by choosing a computer code, supplying a set of input data, and directly obtaining the answer. However, all but the simplest environmental analyses require careful development of the conceptual model. For this study it was necessary to consider: 1) the complex geometrical configuration of sources and receptors, 2) the time-varying characteristics of the releases and receptors, 3) the complex processes governing transport of radionuclides in air and water, and 4) the uncertainties in release data and other information. For this dose reconstruction, determination of the conceptual model required careful research and in some cases extensive analyses. These enabling analyses are incorporated in this report; several were supplied to the CDC and SRSHES as independent white papers for review and comment as the work was in progress.

4.2.3 Analysis Steps

The analysis was conducted in two steps: 1) a deterministic step resulting in a point-estimate of dose for each receptor and 2) a probabilistic step resulting in many estimates of dose (a dose distribution) for each receptor. Although the two steps had different scopes, goals, and results, they yield complementary information that provides a more comprehensive understanding of how the SRS releases induced doses in the hypothetical receptors. Table 4-1 summarizes some important differences between the two analysis steps.

Step 1 established a point-estimate value of dose and risks for each receptor. This was accomplished by assigning a single representative value for each variable used in the dose assessment; for this study hundreds of variables were specified after research and evaluation. These representative values were chosen to be realistic (i.e., not intentionally overestimating or underestimating the doses). Perhaps more important than establishing a point-estimate of dose, these modeling results were used to understand the relative importance of radionuclides, transport pathways, exposure pathways, and other factors. This information, presented in Chapter 11, was used as input for conducting the second step.

Although a single representative value was used for each input variable in Step 1, every variable is uncertain to one degree or another. Two major types of uncertainty are variability and lack of knowledge. Variability comes from parameter values that change in time or over the geographical region modeled. For example, consumption rates by receptors for various foodstuffs changed with nutritional habits over time, but were assumed constant, because these data were not available on a site-specific basis. Because there is not a single value, there is uncertainty as to which one to choose. An example of lack of knowledge is a parameter value not measured for the SRS, but measured elsewhere. There may be a value, but it cannot be applied without uncertainty. Both types of uncertainty were encountered in this

study. This uncertainty in input variables is usually represented by a probability distribution that describes the likelihood that a variable will have a particular value.

Table 4-1 Comparison of Steps 1 and 2

Attribute	Step 1	Step 2
Analysis Type	Deterministic.	Probabilistic.
Variables	All have a fixed value.	Most have a fixed value; 14 uncertain.
End Point	Dose and risks.	Dose.
Subcategories of Dose and Risk	All (organs, radionuclides, exposure pathways, release mode).	Only total dose.
Radionuclides	All (result of Level 1 screening in Phase II).	Minor contributors to dose screened out.
Exposure Pathways	All (all potential contributors).	Minor contributors to dose screened out.
Primary Goal	Understand how doses arise; screening for Step 2.	Establish confidence intervals around mean estimated dose.
Result	Single estimate of dose for each receptor.	Multiple estimates of dose for each receptor.

Step 2 of the analysis evaluated the effect of input variable uncertainty on dose estimates. This probabilistic analysis was simplified by 1) eliminating radionuclides and exposure pathways that were clearly minor contributors to dose and 2) eliminating from the set of uncertain input variables those variables estimated to be minor contributors to the uncertainty in dose. These simplifications helped to focus the analysis and eliminated some extensive computations likely to yield little benefit. By considering input variables with a strong influence on the uncertainty in dose as uncertain, Step 2 provided average values (mean and median) of the dose for each receptor as well as confidence intervals around those values. Although the probability distributions describing the input variables were anchored by the point estimate values for those variables, the mean and median doses calculated in Step 2 were generally higher than the point-estimates of dose calculated in Step 1. In addition, Step 2 included some sensitivity and uncertainty analyses. These analyses developed quantitative measures that indicated which input variables had the largest effect on dose and which variables contributed most to the uncertainty in dose.

4.3 Assessment of Radionuclide Release, Transport, Exposure, and Consequence

The modeling process for this study has four major components:

1. Release of radionuclides into the air and to surface water.
2. Transport of radionuclides through the air, surface water, and food chain (soil, plants, and animals) to exposure locations.
3. Exposure of receptors to contaminated media (air, water, soil, foodstuffs).
4. Dose and risk assessment.

Each of these components is described more fully below. Note that, because calculation of dose is performed in the fourth, rather than the third component, this is a slightly different breakdown than is shown in Figure 4-1. This change, which is explained more fully in Section 4.3.3, is made for convenience and has no substantive effect.

4.3.1 Release of Radionuclides

Chapters 5, 6, and 7 discuss the release and transport of radionuclides into the air and surface water. Because it was difficult to cleanly separate the analysis of release and transport, Chapters 6 and 7, although nominally treating transport, also treat certain aspects of the release. The goal of the release assessment was to develop a time history of radionuclide release on a yearly basis. Although information was available for some facilities and some radionuclides on a much shorter time interval, annual average releases were considered suitable for this intermediate-phase dose reconstruction.

Using information from the Phase II study and from other sources, a compilation of data was created that listed the quantities of radionuclides released for each year into the air and water by each major SRS facility. Data were compiled for 15 individual facilities, including 5 reactors, 2 separations facilities, and 1 tritium recovery and purification facility. These data were used as input to the transport assessments performed for this study. For example, facility-specific atmospheric releases were coalesced into four groups that were then represented in the transport calculation by four virtual sources.

In compiling these data, careful checking and evaluation was performed to ensure that the detailed source terms compiled for this phase were consistent with the summary releases stated in the Phase II report. Because the summary releases incorporated certain correction factors that could depend on a particular radionuclide, facility, and year, ensuring consistency required significant care and effort. For the probabilistic analysis, the same single factor was applied to all radionuclides, from all facilities, for all years; this factor raised or lowered all releases to account for the uncertainty in knowing precisely the quantities that were released.

4.3.2 Air, Water, and Food Chain Transport Assessment

Radionuclides migrate from the point of release through the environment and end up in one of five environmental compartments or media: air, water, soil, plants, or animals. The transport assessments estimate the concentrations of radionuclides in these various media. As described in Section 4.3.3, a receptor may come into contact with these contaminated media in a variety of ways that can result in a dose to the receptor. For convenience, this report has partitioned the discussion of transport into three parts: 1) Chapter 6, Transport of Radionuclides through the Air to an Exposure Location; 2) Chapter 7, Release of Radionuclides to Water and Transport to an Exposure Location; and 3) Chapter 8, Food Chain Transport.

As discussed in Chapter 6 and Appendix D, the transport of radionuclides released to the air from onsite facilities to exposure locations is estimated by an extension of the Gaussian plume model. This extended model, the sector-averaged model, sums up contributions over a range of wind speeds and stability classes characteristic of the site. The result of this calculation is an annual concentration of each radionuclide in air at the specified exposure location, which depends only on the release for that year.

In the absence of detailed information about meteorological conditions during the early days of the SRS operation, data averaged over 20 years of SRS operation (the Joint Frequency Distribution data) was applied to each of the entire 39 years considered in the study. Modeling the changes in annual average meteorology did not seem appropriate at this phase because other, more significant uncertainties would not have been addressed. For example, acute releases occurring over a few hours or days contributed

substantially to the release quantities in early years. These releases, if modeled more precisely as acute events with weather conditions specific to the release time, may have produced substantially different dose estimates. Considering weather conditions on an annual basis would not address these uncertainties. During transport of radionuclides from the release point to the exposure location, the model considered loss of radioactive material resulting from radioactive decay and deposition. Release and exposure locations were modeled as points. Transport of radionuclides from 4 virtual sources to 10 exposure locations was analyzed. For the uncertainty analysis, the Joint Frequency Distribution data obtained for the SRS were considered to be fixed. However, parameter variable distributions for certain other parameters related to air transport, such as the radii of radioactive particles, were considered uncertain.

The water transport was addressed by estimating the concentration of radionuclides in water at two exposure locations: 1) a point near the town of Martin on Lower Three Runs Creek and 2) a point on the Savannah River just below its confluence with Lower Three Runs Creek. The exposure location on the Savannah River was used to represent potential exposure locations elsewhere on the river because there was no strong basis for the estimation elsewhere and, at this point, all the liquid releases from the site were diluted by the smallest quantity of river water containing the entire release.

The simplest approach to modeling water concentrations is to divide the annual quantity of radionuclides released by the annual flow. This simple model was unsuccessful because 1) the concentrations estimated this way did not match the measured concentrations for key radionuclides and 2) significant processes for storage and release of radionuclides by sediment and biota on the SRS were not addressed.

Two different modeling approaches were used to calculate concentrations in the Savannah River and Lower Three Runs Creek. For concentrations in the Savannah River, a model used in Chapter 5 of the Phase II report for three radionuclides was adapted and extended to additional radionuclides included in this study. This model had taken into account the storage and release of radionuclides in bodies of water on the SRS site. For Lower Three Runs Creek, actual measured concentrations at Martin were used whenever possible; however, only data for Cs-137, Sr-90, and tritium concentrations were available. For early years, when concentrations were likely high, direct measurements were not available; however, concentrations were estimated based on annual releases and flowrates by extrapolating from years with concentration data. Chapter 7 describes more fully these models and extrapolation methods. For the uncertainty analysis, liquid transport variables were considered to be fixed; however, the radionuclide concentrations were varied by the adjustment factor described for releases.

Soil concentration was determined by considering deposition from the air, mixing in the soil layer, and removal by radioactive decay, leaching, and weathering. Many of the variables in this model (e.g., particle diameter and weathering rates) were considered candidates for treatment in the probabilistic analysis. The process of deposition at exposure locations was the same as those used to assess depletion of the plume during transport of radionuclides from the release point to the exposure location. Similar models are used to estimate deposition on plant surfaces. A simpler model was used to estimate deposition of radionuclides from water into sediments on the side of streams. Chapter 8 describes these models and variables in more detail.

A standard but complex model was used to estimate the concentration of radionuclides in plants. The model considers uptake from deposition on leaves, uptake by roots from contaminated soil, migration to edible parts by the plant, and removal by weathering and other processes. Numerous plant-specific and radionuclide-specific uptake factors were researched for inclusion in this study (e.g., the growing period and standing biomass for forage was researched). Many of these food-chain input variables were considered as candidates for treatment in the probabilistic analysis. Chapter 8 describes these plant food-chain models and variables in more detail.

A relatively simple, standard model was used to estimate the concentration of radionuclides in animals. This model considers the daily ingestion rate of the radionuclide and the fraction of the amount ingested that is retained in a particular tissue such as meat (muscle), milk, or eggs. These variables (i.e., the consumption rates for particular animals and uptake rates for particular radionuclides and animals) were researched. Many of these variables were considered candidates for treatment in the probabilistic analysis. Chapter 8 describes these animal food-chain models and variables in more detail.

4.3.3 Exposure Assessment

To produce a dose estimate, an exposure assessment usually combines information about radionuclide concentrations in contaminated media with information about how receptors come in contact with the contamination. However, as explained in Section 4.3.4, it is more convenient to combine the dose and risk considerations together. The exposure assessment then calculates intake for radionuclides inhaled or ingested, or calculates exposure for external radiation. These outputs of the exposure assessment are readily converted to dose (and risks) by multiplying an appropriate dose conversion factor that is age dependent.

Dose to a receptor is produced when contaminated media contact the body through one of three exposure routes: external exposure, ingestion, or inhalation. A fourth exposure route, dermal contact, is not considered important in this study. Eighteen different exposure pathways were selected as appropriate to characterize the doses produced at the SRS through these three exposure routes. The following exposure pathways are associated with each exposure route:

- External radiation:
  - Immersion in a plume of air.
  - Exposure to contaminated soil.
  - Exposure to a contaminated shoreline.
  - Exposure to contaminated water while swimming.
  - Exposure to contaminated water while boating.

- Ingestion:
  - Leafy vegetable consumption.
  - Root vegetable consumption.
  - Fruit consumption.
  - Grain consumption.
  - Beef consumption.
  - Poultry consumption.
  - Milk consumption.
  - Egg consumption.
  - Inadvertent soil consumption.
  - Fish consumption.
  - Inadvertent ingestion of water while swimming.

- Inhalation:
  - Inhalation of contamination in the air.
  - Inhalation of contamination resuspended from soil.

The models used for each of these exposure pathways are similar and involve multiplication of the following factors:

- Medium concentration.
- Intake/contact rate.
- Exposure duration.
- Daily activity factor.
- Annual activity factor.

An example of an intake rate is the quantity of beef consumed per year. A contact rate could be the amount of air breathed per day. Exposure duration measures the amount of time a subject is in contact with contaminated media. The daily exposure factor could be the number of hours spent swimming or boating for each occurrence of such a recreational event. The annual activity factor could be how many days a year was spent swimming or boating. The result of these 18 exposure models are either the amount of radionuclide taken into the body (intake) or the amount of exposure to external radiation.
Although the form of each model is the same, the variable values used in each are selected to represent the characteristics of the receptor as delineated in the scenarios. Appendix E presents the rationales for variable values associated with receptor behavior such as food consumption rates and breathing rates. Generally, U.S. average values (e.g., from U.S. Environmental Protection Agency [EPA] or U.S. Nuclear Regulatory Commission [NRC] guidance) were used. Variable values associated with receptor behavior were not treated as uncertain variables because they described hypothetical scenarios. In addition, overlaying an additional treatment of uncertainty seemed redundant because the specification of these hypothetical scenarios was intended to bracket a wide range of behaviors. Furthermore, other variables associated with the scenarios, such as the location and the age of family members, were fixed by the scenario specifications.

Appendix F addresses variables that are independent of receptor actions but depend on site-specific environmental conditions. Where information was available, values specific to the SRS or the surrounding region were used. Some variables depended on local practices that varied over time. However, SRS-specific data frequently were not available. In those cases, generic data were obtained from other sources, such as the International Atomic Energy Agency's handbook of parameter values (4), if the variable values were available and were appropriate. As a last resort, default variable values associated with the GENII code were used (5).

4.3.4 Dose and Risk Assessment

This assessment calculates dose, cancer incidence, and cancer risk for each receptor. These doses and risks are calculated from the intakes and exposures that are the output of the exposure assessment. The calculation is accomplished by multiplying the intake or exposure by a dose conversion factor or a risk conversion factor. These conversion factors have been developed through over 50 years of scientific research and modeling and are approved by international and national radiation protection organizations. The U.S. Environmental Protection Agency (EPA) issued tables of these coefficients in its April 2002 update to Federal Guidance Report (FGR) No. 13 (6). External exposure doses for all pathways except water immersion were calculated using adult dose coefficients issued by EPA in FGR No.13 (7). Dose coefficients for external exposure from water immersion were those issued by EPA in its FGR No. 12 (8). Similarly, cancer risks (both incidence and fatality) were calculated by using risk coefficients issued by EPA in its April 2002 update to FGR No. 13 (6). External exposure risks for all pathways except water immersion were calculated using adult dose coefficients issued by EPA in FGR No.13 (7). Risk coefficients for external exposure from water were assumed to be 0.05 per Seivert for cancer fatality and 0.06 per Seivert for cancer incidence.

For this study, all risk and dose coefficients were applied to the analysis as point-estimates. Uncertainty in the dose and risk coefficients in the uncertainty analysis was not analyzed. Appendix D of FGR No.13 (7) outlines an approach to derive uncertainty intervals for these dose and risk coefficients. This approach,

however, is complex and lengthy and requires multiple expert elicitations. This was judged to be beyond the scope of this phase, which focused on variables with far more uncertainty.

4.4 Computational Framework – Computer Analysis

To automate the computational process, a combination of existing and custom-designed software was used. The assessments of radionuclide transport, human exposure, dose, and risk were performed using state-of-the-art environmental analysis and risk assessment software (i.e., Version 2 of GENII). The GENII code was linked to a pre-processor and post-processor. The pre-processor was developed to efficiently compile and prepare input data for use by the GENII code. The post-processor was developed to efficiently determine doses and cancer risks for both the point-estimate and probabilistic analyses. For the latter, a generally available computer program, Latin Hypercube Sampling (LHS), was used to provide multiple samples of the input variable values (realizations) to the core computer code (9).

4.4.1 Selection of Environmental Analysis and Risk Assessment Software

At the early stages of the project, it was recognized that the assessments to be performed were computationally demanding. There were three main reasons for this:

1. As explained in Section 4.2, the dose assessment requires the linking of several sub-assessments or calculation modules. Given the 18 different exposure pathways considered and the number of times each chain of modules is activated, the calculation must be automated for the calculation to be feasible. Furthermore, each module requires input variable values, which it may share with other modules. The consistent and accurate transfer of these variable values between modules also must be automated.

2. The dose was calculated by adding up incremental doses from each year, radionuclide, exposure pathway, medium of release, etc. This calculation was done for each of the 28 receptors. Doses and risks were also disaggregated by organ (i.e., a huge amount of data needed to be stored, transferred, and processed).

3. Some variables changed as a function of time. The quantities released of each radionuclide changed annually. The sensitivity of the receptors to radiation dose was modeled as changing with the age of the children in each scenario. Some behavioral characteristics (e.g., the amount of beef consumed) also changed in time. These temporal changes were required to be synchronized.

Three approaches were considered to automate the dose reconstruction calculations: 1) use an existing code, 2) custom-develop a code, and 3) use an existing code but augment it with additional custom software to facilitate the analysis. Approaches 1) or 3) were preferred, assuming an existing computer code could be found that met the analytical requirements of the study.

As addressed in Appendix H, the analytical requirements were compared to the capabilities of existing computer codes. Among these requirements were the ability to simulate the models in each of the four linked assessments described in Section 4.2, the ability to allow desired inputs and provide desired outputs, and the flexibility to adapt to conditions near the SRS. Sixty-six codes were identified based on their general classification as tools for environmental transport, exposure, dose, and risk modeling. After screening these codes, 17 candidate codes were evaluated for their suitability. This evaluation eliminated codes that only addressed a limited number of pathways and exposure scenarios. From this evaluation, two suitable codes emerged: Hanford Environmental Dosimetry System, Generation II, Version 2 (GENII); and Multimedia Environmental Pollutant Assessment System (MEPAS). Additional relevant information about the two codes was collected by obtaining and reviewing available literature and copies of these codes, and discussing various code characteristics with representatives who were responsible for

developing and validating the codes. These codes were then critically compared for each analytical requirement. This evaluation chose Version 2 of GENII.

The GENII computer code was developed at Pacific Northwest National Laboratory (PNNL) to support radiological exposure and risk assessment for 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. Radionuclide transport via air, water, or biological activity may be considered. Details of the GENII code may be found in its software design document (5).

4.4.2 Linkage of GENII Code with Pre- and Post-Processors

To efficiently address the large amount of data that was used for the analysis and the voluminous nature of the calculated results, a pre-processor and post-processor were linked schematically to the GENII code. Figure 4-5 shows the schematic of information flow. Appendix G presents a detailed discussion of the computational process.

The pre-processor warehouses input data (e.g., the quantities of radionuclides annually released into the air and water and the specifications of the seven hypothetical family exposure scenarios) and prepares this data for use by the dose program. After receiving this input data, GENII performs the transport and exposure pathway computations that estimate the dose and risk. These calculations are based on unit values (1 Becquerel (Bq) released, 1 kilogram of beef ingested per year, 1 hour spent at an exposure location). The post-processor then accepts the output from GENII and performs additional calculations to adjust the output from GENII to reflect receptor behaviors and characteristics representative of the assumed age of the receptor (e.g., the annual quantities of a specified food consumed by a teenager). Adjustments are also made for the age-sensitivity of the receptor. The result is radiation doses and cancer risks for each receptor that are appropriate for the age and assumed lifestyle of that receptor. The post-processor is also used to create files for input to the sensitivity and uncertainty analysis.

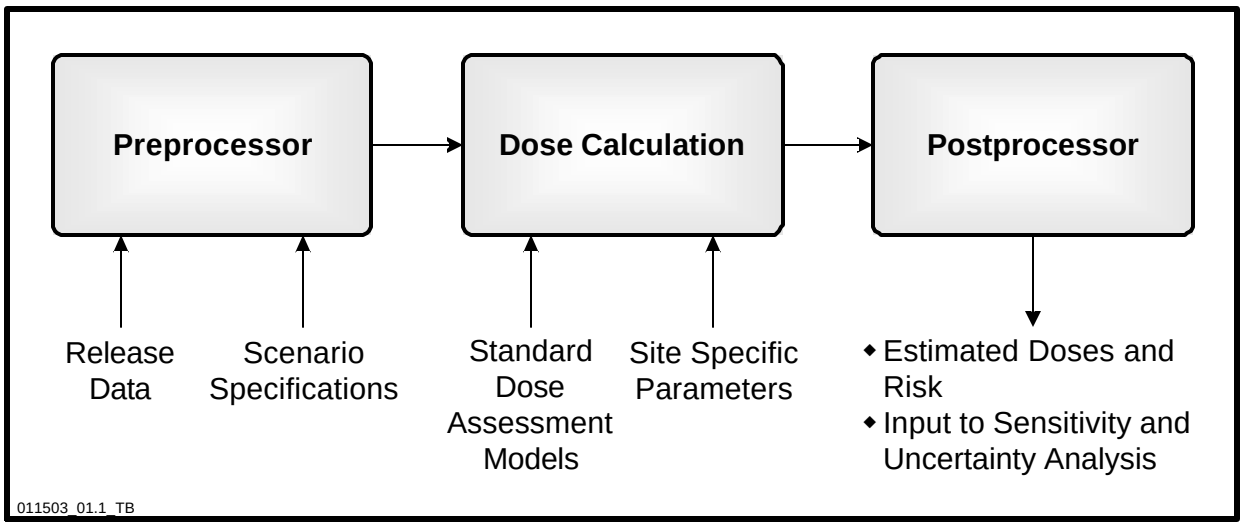

Figure 4-5 Schematic of Information Flow for the Dose Reconstruction Effort

4.4.3 Probabilistic Calculations

The same basic computational approach was used to perform the probabilistic analysis. However, multiple sets of input variable values (realizations) were generated by the generally available LHS computer code (9). The LHS code takes as input the probability distributions describing the uncertainty in selected input variables and provides a set of realizations of those variables. The statistical method encoded in LHS permits efficient estimation of statistics for the dose. Thus, the dose calculation was performed for each realization. The pre-processor was used to sequence through the 40 realizations of uncertain input variables.

4.5 Quality Assurance and Quality Control Procedures

The Quality Assurance Program for this study was designed to provide oversight of all activities and actions performed in support of the development of the point-estimates and the uncertainty analysis. In the initial stages of this study, it was determined that errors could be introduced through calculations and adjustments to existing information and data, through inputting data into electronic spreadsheets and files, through programming of modeling software, and through the interpretation of the modeling results. To address these potential sources of error, Standard Operating Procedures (SOPs) were developed which delineate the protocols for reviewing data management activities, data input, software development, and technical and editorial review of the study report.

The SOPs developed for use on this study include:

- Work Process Controls for the Savannah River Dose Assessment.
- Quality Assurance Training.
- Technical Review and Approval of Task Products for the Savannah River Dose Assessment.
- Records Management for the Savannah River Dose Assessment.
- Quality Assurance Review of Scanned Documents.
- Production of Electronic Records from Hardcopy Documents.
- Computer Software Design for the Savannah River Dose Assessment.
- Quality Assurance of Computer Codes Used for the Savannah River Dose Assessment.
- Quality Assurance (QA) for Testing and Accessing Computer Codes Used for the Savannah River Dose Assessment.
- Information Control.

These SOPS were prepared by the Project Quality Assurance Manager, approved by the Project Director, and the project staff was trained to the requirements of the SOPs.

The basic requirements of the Quality Assurance program for this study as delineated in the SOPs include:

- All project staff must be knowledgeable of the requirements of the applicable SOPs.

- All work products developed in support of this study must be technically or editorially reviewed by a qualified independent reviewer for calculational or input errors and approved for use on the study by the Project Director. A qualified independent reviewer is someone who has the appropriate background through education or experience and was not responsible for the development of the work product.

- All calculations or modifications to data must be reviewed to determine 1) if the calculation was appropriate, i.e. was the right mathematical formula used for the calculation, and 2) was the calculation executed correctly.

- All software developed for this study must be supported by an approved design document and the software must be verified and validated as correct. Verification and validation of all the calculations to be performed by the software is to be done by another method - either electronic spreadsheet or manually.

- All documentation relating to the development and review of work products, such as technical review forms, drafts of report sections, decision documents, project staff communications, and original data sources, are considered Quality Assurance Records and must be maintained in accordance with the Records Management and Information Control SOPs.

4.6 References

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5 RELEASE OF RADIONUCLIDES TO AIR

This chapter summarizes the Phase III effort to derive a detailed source term for radionuclides released into the air from Savannah River Site (SRS) facilities. These radionuclides and the annual quantities released are listed in Appendix B.

CDC previously sponsored Phase I and II of the SRS Dose Reconstruction Project. During Phase I, records necessary for the project were assembled, including facility release records, monthly and weekly reports, laboratory notes, research papers, and personnel interviews. During Phase II, radionuclide and chemical releases were estimated using the records obtained during Phase I. The Phase II study considered uncertainties in the SRS reports of historical radionuclide release. For some isotopes of concern, particularly I-131, the Phase II study provided estimates of release that are notably larger than those historically reported by SRS (Phase II).

The Phase II study was used as the primary basis for the Phase III source term. The Phase II estimates were refined for use in Phase III to achieve greater source term resolution in time and space: i.e., releases by year and location. This greater resolution was mandated by geographically distributed scenarios and the concern with temporal changes expressed in the scenario specifications. Other refinements related to isotopic composition and chemical form provided for more precise modeling of health effects.

5.1 Development of Study Source Term

5.1.1 Approach to Development of Study Source Term

As discussed in Chapter 1, the scope of this Phase III dose reconstruction study was intended to move beyond a screening analysis to identify biologically significant radionuclides and dose pathways. In order to produce a dose assessment with the desired level of detail and confidence, a more refined source term than was available from Phase II was sought. This refined source term for air releases addressed specific requirements of the analysis, which included the following broad themes.

1. To use the results of Phase II, including the identification of significant radionuclides by a screening analysis and modification of historical release data to account for instrumentation deficiencies;
2. To provide enough spatial definition to the source term so that the geographical characteristics of the various scenarios (and their proximity to particular sources on site) would be adequately represented;
3. To provide enough temporal definition to the source term so that the age-related characteristics of scenario members (as they interacted with the time-varying releases from the SRS) would be adequately represented;
4. To provide enough detail about the chemical and isotopic characteristics of the releases so that the dose and risk modeling (treatment of health effects) would be more precise.
5. To enhance the completeness and/or accuracy of the source term.

Starting with the Phase II results, a sequence of steps was followed to obtain as source term for Phase III with the desired qualities. Figure 5-1 outlines this sequence and briefly describes for each step the requirement or need addressed, the additional input information used, and the status of the data set representing the source term after each modification. Each step is described in more detail in the following sections.

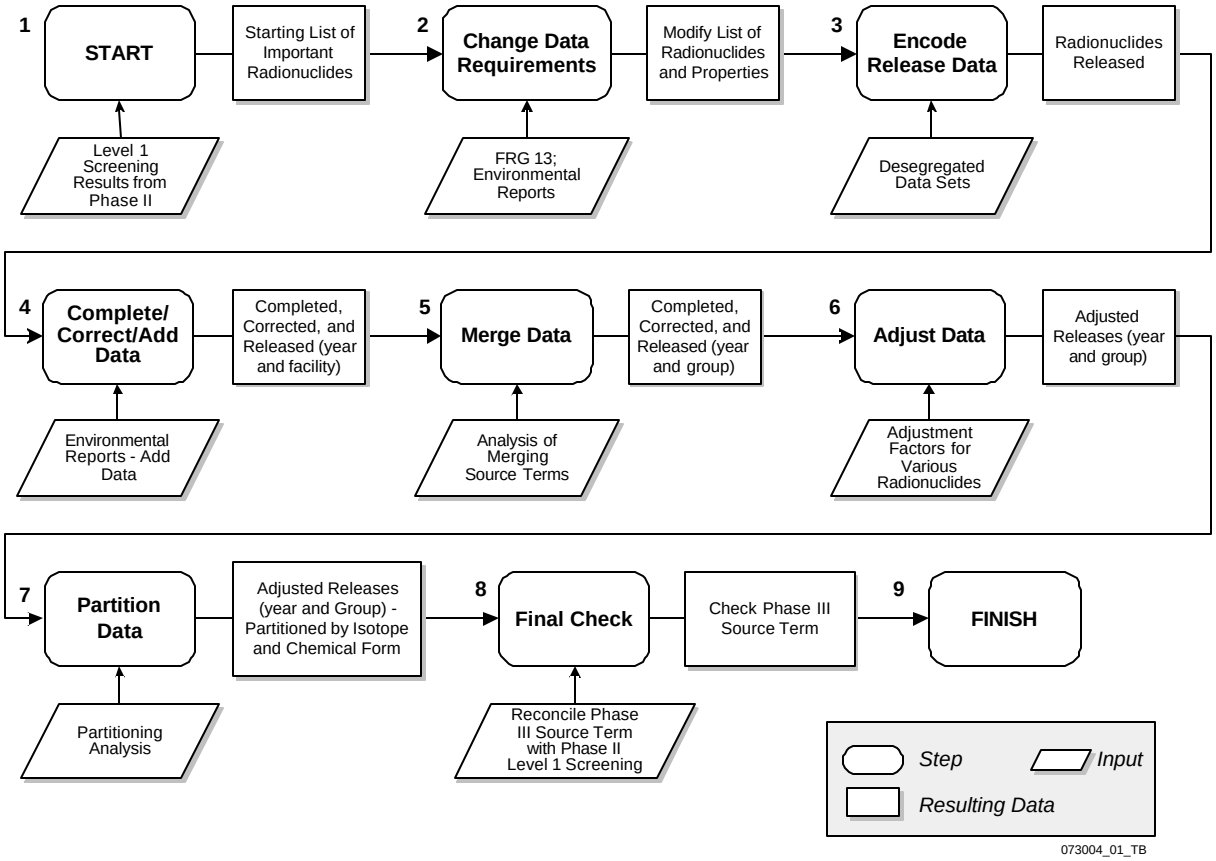

Figure 5-1 Development of Study Source Tem

5.1.2 Identify Important Radionuclides based on Phase II

Phase II provided a number of results that became starting points for Phase III, including: (1) Two screening analyses that established a reduced set of radionuclides to consider in the dose reconstruction; and (2) Detailed source terms for these radionuclides, with varying degrees of spatial definition. These two aspects are summarized in the following sections.

5.1.2.1 Use Phase II Results (Step 1)

Phase II, Screening Level 1, identified twelve groups of key radionuclides released to air; Screening Level 2 further refined the list to include only six radionuclides. To avoid possibly overlooking an important contributor to the Phase III radiological assessment, all twelve groups of key radionuclides identified in the Level 1 screening were modeled in Phase III.

The Phase II screening assessment started with a master list of radionuclides that had been released into the air from SRS facilities. Preliminary estimates of their annual average release rates were also made. But because this list was too large for efficient analysis, a screening assessment was performed to identify a smaller list of key radionuclides that were the dominant contributors to radiation dose and risk (Phase II). This screening assessment was performed using a two-step method recommended by the National Council on Radiation Protection and Measurements (NCRP) for prospective evaluation of a new facility. The method featured (1) a screening considering the summation of six possible exposure pathways, and (2) a screening considering each of the exposure pathways plus the sum total of all six pathways (NCRP 1989, NCRP 1991).

In both screening steps significant simplifications included:

- 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; and
- adult rather than age-dependent dose conversion factors were used (Phase II).

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]

For Level 1, a total screening value was calculated representing the sum of all screening values calculated for each radionuclide. Then those radionuclides were identified that had screening values contributing at least 0.1% of the total screening value. Using a cut-off of 0.1% of the total estimated dose, the initial list of radionuclides was reduced to twelve. These twelve key radionuclides together accounted for more than 99% of the total screening value (Phase II). The radionuclides thus identified in the Level 1 of the screening assessments for air release are listed in Table 5-2. Many of the radionuclides are actually groups of aggregated isotopes such as combined Pu-239 and Pu-240.

Table 5-2 Radionuclide Rank from Phase II Level 1 Screening

Radionuclide	Percent of Total Screening Value (%)
I-131	50.6
H-3	33.7
Ar-41	7.0
Pu-239,240	2.6
I-129	2.3
Ru-103,106	1.1
Pu-238	0.7
C-14	0.6
Cs-137	0.6
Uranium[§]	0.3
Sr-89,90	0.2
Am-241	0.1
Total	99.8

[§]Screened in Phase II as combined U-235 and U-238.

[1]A report describing the NCRP screening method notes, on page 4: "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].

This is the starting list of important radionuclides for Phase III.

5.1.2.2 Phase II Estimates of Radionuclide Release

Phase II provided estimates as annual averages over 36 years of site operation for all twelve groups of key radionuclides identified in Level 1 of the screening analysis (see Table 5-3). These averages spanned a period from 1954 through 1989. Annual release estimates were provided for all twelve radionuclide groups except C-14 and Am-241 for which 36-year averages were provided. More detailed estimates were provided on an annual basis for tritium; Sr-89,90; I-129; I-131; Cs-137; uranium; Pu-238; and Pu-239,40. The level of detail varied depending on the isotope. In some cases, for example, releases from specific SRS facilities (such as specific nuclear reactors) were identified, and in other cases, releases from SRS Areas or groups of facilities (such as groups of seepage basins) were identified.

Table 5-3 Radionuclides Reported in Phase II Study by Facility and Year

Radionuclide Group	Annual Estimates Provided for a Specific Facility or a Group of Facilities?	Estimates Provided as a 36-Year Average Yearly Release from the Entire Site?
H-3	Annual	Yes
C-14	Not available	Yes
Ar-41	Annual	Yes
Sr-89,90	Annual	Yes
Ru-103,106	Annual	Yes
I-129	Annual	Yes
I-131	Annual	Yes
Cs-137	Annual	Yes
Uranium	Annual	Yes (reported as U-235,238)
Pu-238	Annual	Yes
Pu-239	Annual	Yes (reported as Pu-239,40)
Am-241	Not available	Yes

5.1.3 Change Data Requirements to Better Model Health Effects (Step 2)

The initial list of important radionuclides resulting from the Phase II Level 1 screening analysis was modified in three ways for use in Phase III:

1. Some groups of radionuclides were partitioned into separate isotopes. This was done to provide a more refined treatment of dose modeling. By treating isotopes individually, health effects coefficients specific to those isotopes could be used in the dose modeling; if isotopes were aggregated by element, as in the Phase II screening analyses, a single coefficient (related to the isotope with the greatest health effects) would characterize all the isotopes of the element, possibly greatly overestimating doses and risks. Table 5-4 shows 16 isotopes modeled.
2. Because the releases of Ruthenium were relatively small, all releases were modeled as Ru-106.

3. Uranium isotope U-234 and U-236 were added to account for production of these isotopes in the nuclear reactors.
4. One radionuclide, Pu-240 was dropped from consideration. The data upon which the Phase II estimates of releases were based did not list Pu-240 releases separately, but always combined with other isotopes. Furthermore, the health effects coefficients for Pu-239 and Pu-240 are very close, so modeling Pu-240 as Pu-239 will have little effect on the dose estimates. Since there appeared to be no basis and no motivation for differentiating these two isotopes, separate consideration of Pu-240 was dropped.
5. It was considered appropriate to include as releases radioactivity measured as unidentified alpha or unidentified beta-gamma activity. Although the SRS had recorded releases of such material over the years of site operation, an explicit treatment in Phase II was not apparent. Therefore two additional categories were added for these types of releases. However, to provide bounding estimates of their health effects, the unidentified alpha activity was added to the releases for Pu-239 and the unidentified beta-gamma activity was added to the releases for Sr-90. These two classes are added to Table 5-4 to indicate that these activities were compiled and tracked separately.
6. At this point the need to refine the treatment of certain radionuclides by defining their chemical form was established. Two radionuclides: tritium and I-131 can have substantially different behavior in the environment depending on their chemical form. The methods used to partition these radionuclides into different chemical forms are described in Section 5.1.8.2. Methods used to partition some elements into different isotopes are described in Section 5.1.8.1

Table 5-4 Modified List of Radionuclides Considered for Phase III

Americium-241	Plutonium-238,239†
Argon-41	Strontium-89,90‡
Carbon-14	Uranium-234,235,236,238
Cesium-137	Ruthenium-106
Tritium (H-3)	
Iodine-129,131	

Note: Underlined radionuclides were added.
†Unidentified alpha-emitters were modeled as Pu-239
‡Unidentified beta-gamma emitters were modeled as Sr-90

5.1.4 Encode Release Data from Cummins Report (Step 3)

The Phase III source term needed definition in space and time so the assessment of radiation doses and cancer risks would be able to reflect differences associated with the seven hypothetical exposure scenarios considered in Phase III. Enhanced spatial definition of the source term allowed the radiological assessment to model and to evaluate the importance of several facets of the Phase SRS dose reconstruction, including:

1. Different mixtures of radionuclides dominated the releases from the major SRS discharge locations, and these locations are often separated by several miles.

2. Radiation doses at different exposure locations specified by the scenarios depended on: (1) the quantities of particular radionuclides released into the air at the various SRS location and (2) direction-related meteorological conditions, such as the frequency that the wind blew in the

direction of a particular exposure location. Several exposure locations are close to the release points, relative to the distances between some release points.

A more refined definition of the spatial distribution of releases allows for a more precise estimate of doses compared to a source term with a single assumed release point to represent all SRS release points.

Enhanced temporal definition of the source term -- that is, specifying the amount of release for each radionuclide for each year -- allowed the radiological assessment to model and to evaluate the importance of several facets of the Phase III SRS dose reconstruction:

- The behavior of the children in each hypothetical scenario changed significantly during their childhood; this included breathing rates, food ingestion rates, time spent indoors and outdoor;
- The dose and risk factors for children were adjusted until they became adults;
- The annual release rates of many key radionuclides changed considerably over 39 years; of special note were the early years of large releases (e.g., 1956).

The source term, the behaviors of the hypothetical receptors, and their dose and risk characteristics all varied in time; by considering the annual variation of the source term, the interaction of all these time variations was considered. A source term that was expressed in terms of an average over 39 years would not have allowed these important variations to be adequately considered.

To provide the desired level of spatial and temporal definition in the source term, historical release data (Cummins 1991a and Cummins 1991b) was keyed into an electronic data base. This data base described radionuclide releases by isotope, facility, and year. All the data were fully cross-checked and was subject to a thorough quality assurance program.

5.1.5 Complete and Correct Data Set (Step 4)

In the initial stages of the Phase III source term data compilation, it was observed that data were not available for annual release estimates for some radionuclides for the years 1954 through 1989 and for most radionuclides for the years 1990 through 1992. For Phase III, refinements to the Phase II release estimates were made to obtain a source term for all radionuclides: (1) on an annual basis; (2) for all 39 years of the study; and (3) on the basis of major SRS facilities.

For the years 1954 through 1989, when annual release estimates were given in the Phase II report in sufficient detail, Phase II was used to determine annual facility-group release rates. Otherwise, data gathered from SRS references was used. For example, for C-14 and Am-241, the Phase II report only provided estimates for the entire site as averaged over 36 years. For Ru-103,106, the electronic version of Phase II provided a supplemental Excel file that listed annual release estimates for the F- and H-Separations Areas, but not for reactors. Phase II provided annual release data for Ar-41, but the data was not proportioned among the five reactors that released this isotope.

To apportion release data among the different SRS facilities releasing radionuclides into the air, the primary reference was (Cummins 1991a). In some cases, information in (Cummins 1991a) and other references were given as combined values for a group of facilities (e.g., reactors). For these cases, SRS site release history was reviewed and the combined values were apportioned among facilities in accordance with the processes in the facilities that resulted in the airborne releases. See Section 5.1.8.1 and Appendix R for further information on how the release data was partitioned.

For the years 1990 through 1992, release estimates were not provided in Phase II for most radionuclides Therefore, SRS environmental reports and other environmental data (Arnett, 1992; Arnett, 1993a; Arnett, 1993b; Cummins, 1991a; Cummins. 1991b; Evans, 1992) were reviewed for these three years, and the missing source terms were added when information was available.

5.1.6 Merge Data from Fifteen Facilities into One of Four Groups (Step 5)

Section 5.1.4 describes the motivation for refining the spatial definition of the source term. At this point in the analysis, the source term was defined in a data base by each radionuclide, year, and facility. Fifteen separate facilities were considered to be independent sources of air releases. The types of radionuclide releases from each of these fifteen facilities are shown in Table 5-5.

Table 5-5 Main Sources of 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§	

*Releases for these three facilities are combined in available literature for security purposes.
†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 centroid 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-Areas are only about one mile apart.
§Releases from the SRL may have been included in the A-Area releases for at least some years.

Although greater spatial definition was desired, these 15 major sources, as well as several minor sources were too numerous for efficient analysis considering the number of radionuclides, exposure scenarios, and exposure pathways to be addressed and the sensitivity and uncertainty analyses to be performed.

Although spatial simplification of the source term was desirable, any such simplification needed to preserve the inherent geographical variation of the air source term and a suitable level of precision in the dose calculations. Therefore, a two part analysis was performed:

1. Different combinations of individual sources into groups (virtual sources) were evaluated to determine a representative set of "virtual" sources. Different numbers of virtual sources were evaluated, ultimately settling on four groups of sources (as shown in Table 5-6).

2. A careful evaluation was performed to assure that representation of a group of sources by a single virtual source preserved a suitable precision in estimating concentrations; as discussed in more detail below, the representation of a group of sources by these virtual sources was deemed to be sufficiently precise.

Consider a single real source on the SRS, e.g., Reactor L. Since a static, 20-year average meteorology was assumed, a given release from this single source will produce a certain concentration at each of the nine offsite exposure locations of interest, e.g., Girard, GA. First, a unit release rate (e.g., one Ci/y) was assumed for each of the 15 real sources in turn; the concentrations that the GENII code estimated were produced by these unit releases were considered to be the "correct" value. Second, a unit release rate was assumed for each of the 4 virtual sources in turn; the concentrations that the GENII code estimated were produced by these releases were considered to be the "approximate" value for the sources in each group. Third, the "correct" and "approximate" releases were compared; the result was an agreement within 18% between the "correct" and "approximate" values for all sources except one, which was within 27%. This is considered to be excellent agreement for a very stringent comparison, given that for most groups the individual sources do not operate alone. Also recall that the "correct" value is based on modeling that incorporates many assumptions and uncertainties. For example, release rates were assumed to be constant over any given year, when in actuality acute releases caused substantial deviations from this assumption. When the concentrations induced by the virtual sources were compared to the concentration induced by a group of sources of equal strength (e.g., for Group 1 each of the three real sources was assumed to have a release rate of 1/3 Ci/y, while the virtual source had a release rate of 1 Ci/y), the comparisons were even closer; the results agreed within 11%.

This simplification of sources is summarized in Chapter 6 and addressed in detail in Appendix A. The source groupings developed as a result of this analysis are shown in Table 5-6 and Figure 5-2..

Table 5-6 Groupings for Four Virtual Sources

Groups	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 Phase III source term for releases to air, compiled up to this point for each facility by year and radionuclide, was aggregated based on these four virtual release points.

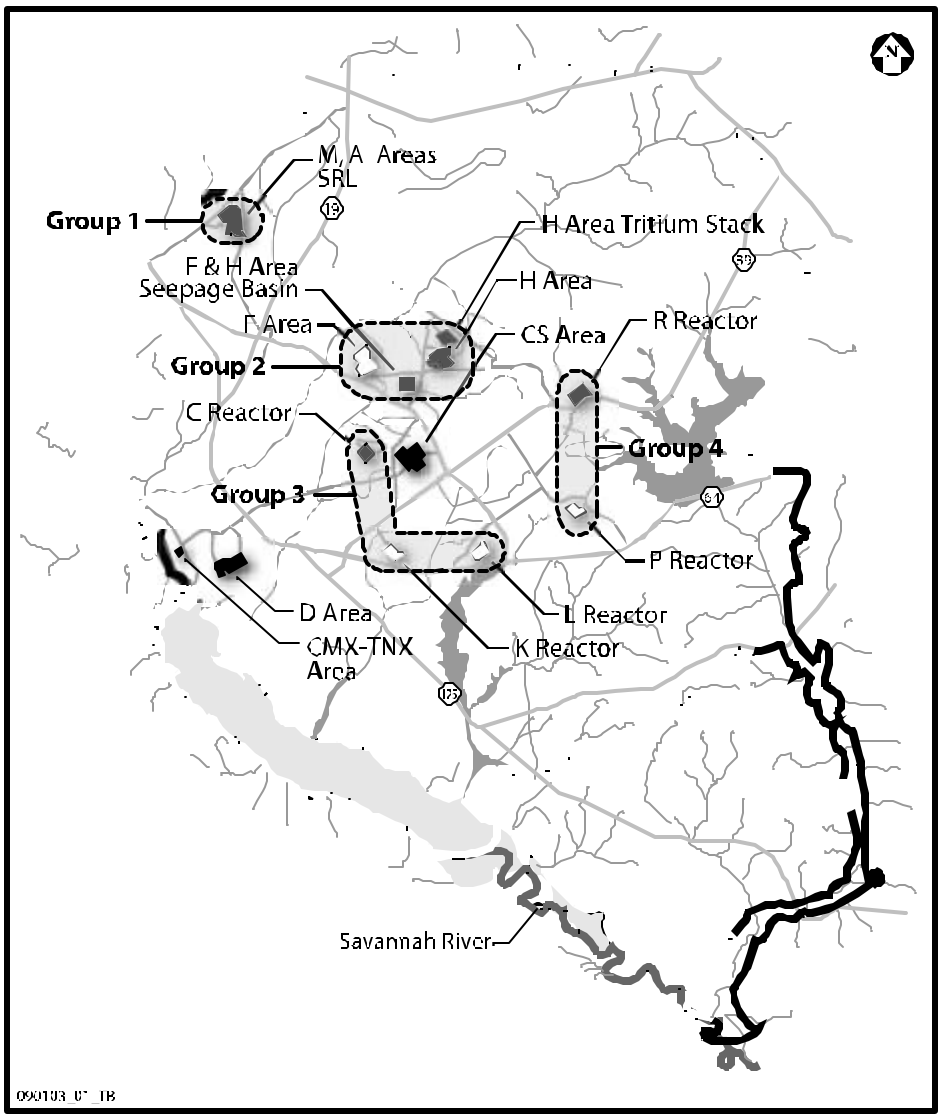

Figure 5-2 Virtual Source Locations

5.1.7 Adjust Data in Accordance With Modifications Made Phase II (Step 6)

Particularly for I-131, uranium, plutonium, and tritium the Phase II estimates of radionuclide release were larger than those historically reported by SRS (Cummins, 1991a & b). Phase II increased the released quantities to account for deficiencies in instrumentation and recording releases. Since historical data was used to provide a greater degree of spatial and temporal definition to the source term, these historical data needed to be modified for use in Phase III to account for these adjustments introduced in the Phase II report.

In Phase II, additional detailed analyses of historical estimates of release were performed for iodine, plutonium, uranium and tritium. These Phase II analyses compensated for several factors that may have caused the reported site releases to be smaller than the releases that actually occurred, including the use of different samplers over time, sampler collection efficiencies, errors associated with counting equipment, and the chemical forms of the released radionuclides. Based on a model of the transmission of effluents in sampling lines and Monte Carlo analyses, Phase II provided revised estimates for iodine, uranium, and plutonium that were generally larger from those reported over the years by SRS (Phase II). Of particular

note was I-131: The Phase II estimates were significantly larger than releases historically reported by SRS.[2] Phase II also observed that releases for the early years of operation (through about 1961) were more uncertain than later releases. Phase II developed probability distributions describing the releases for key radionuclides for each year modeled in Phase II. These probability distributions showed more spread (larger ratios of standard deviations to the mean value) in earlier years than in later years.

In order to incorporate the release values adjusted for uncertainties that were developed in Phase II, the adjusted values of release by year and by facility were imported from spreadsheets attached to the Phase II report (Phase 2, Directory titled Supporting_Files). Adjusted data were used for plutonium, uranium, and iodine releases. Adjusted data were not used for tritium releases in Phase III.

5.1.8 Partition Data to Account for the Mix of Isotope and Chemical Form (Step 7)

In some cases, the radionuclide releases studied in Phase II were compiled on a combined basis, e.g. all isotopes of uranium, all chemical forms of tritium. In order to enhance modeling of the health effects of air releases from the SRS in Phase III, some of these combined releases were partitioned further into specific isotopes or chemical forms. The following sections describe how certain combined releases were separated further into specific isotopes or specific chemical forms.

5.1.8.1 Isotopic Partitioning

Several radioactive constituents that were reported in the Phase II study and in SRS environmental reports were apportioned from the combined activities stated by these sources into release estimates for individual isotopes. For example, the release estimates provided in the Phase II study for Sr-89 and Sr-90 combined, were partitioned into release estimates for each of these isotopes by considering the nuclear processes occurring at the facilities that generated these isotopes. These constituents included:

- Sr-89, Sr-90
- Cs-134, Cs-137
- Uranium
- Plutonium
- Unidentified alpha
- Unidentified beta + gamma

Table 5-7 summarizes the sixteen radionuclides that were determined from this partitioning process for release to air. Source terms for Phase III were developed for each of these sixteen radionuclides. Table 5-8 summarizes how the total activity of each constituent was partitioned into constituent isotopes for each SRS site area. Additional technical information and general assumptions for the partitioning process are in Appendix C.

[2] SRS revised its iodine monitoring and sampling systems and procedures over time. According to the Phase II report, about 99% of the ^{131}I released into the air came from the separations areas. Until September 1961, only elemental ^{131}I was measured at the separations areas. SRS estimated organic iodide activity from elemental ^{131}I release, assuming that organic forms represented 70-90% of all iodine released from separations. The Phase II report addressed measurement uncertainties such as sample collection efficiency, and measurement biases resulting from deposition of elemental iodine in sampling lines, and concluded that SRS underestimated the release of ^{131}I to air during early years (1950s and early 1960s). For example, for each year from 1955 through 1960, the Phase II report estimated that the annual total iodine released to the air was at least 20 times larger than was reported in Cummins 1991. For the year 1961 the total iodine released to air was 12 times larger. SRS staff (Heffner 1999) have criticized these Phase II estimates. After 1961, however, the Phase II estimates of ^{131}I release more closely correspond to those reported by SRS (with few exceptions). Annual ^{131}I releases after 1961 were much smaller than in earlier years (Phase II).

Table 5-7 Radionuclides Considered in Phase III Compared to Those Cited in Phase II

Radionuclides Identified in Step 1 of Phase II Screening	Radionuclides Considered in Phase III Air Release Assessments
H-3	H-3
C-14	C-14
Ar-41	Ar-41
Sr-89, 90	Sr-89 & Sr-90
Ru-103,106	Ru-106
I-129	I-129
I-131	I-131
Cs-134,137	Cs-137
Uranium	U-234, U-235, U-236, & U-238
Pu-238	Pu-238
Pu-239,40	Pu-239
Am-241	Am-241

Radionuclides identified as Sr-89,90 in the Phase II report were apportioned into Sr-89 and Sr-90. For most facilities, the activity was assumed to be Sr-90. For the separations area, the activity was apportioned into 75% Sr-89 and 25% Sr-90 based on Cummins et al (Cummins 1991a).

Radionuclides identified as Cs-134,137 in the Phase II report were assumed to all be Cs-137 because the fission-yield of Cs-134 in nuclear reactors was determined to be very small in comparison with Cs-137 (see Appendix C).

Radionuclides identified as Ru-103,106 in the Phase II report were assumed to all be Ru-106. This assumption was consistent with the screening analysis used in the Phase II report to identify key radionuclides.[3] This assumption will conservatively estimate doses from ingestion and inhalation.

Table 5-8 Summary of Assumed Isotopic Distributions for Air Release

Constituent	SRS Area	Isotopic Distribution by Activity
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
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

[3] In the supplemental files provided as part of Chapter 3 of Phase II, the following notation was made: "We combined all estimates of reported releases of Ru-103 (0.2 Ci), Ru-106 (0.5 Ci), and Ru-103,106 (~1 Ci), and then used the screening factor for Ru-106 to ensure a conservative approach" (Phase II).

Constituent	SRS Area	Isotopic Distribution by Activity
	H Area	91.73% U-234; 1.79% U-235; 6.45% U-236; 0.03% U-238
	M Area	49.49% U-234; 2.25% U-235; 48.26% 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

Radionuclides identified as uranium in Phase II were apportioned into four uranium isotopes: U-234, U-235, U-236, and U-238. The Phase II report only considered the uranium isotopes U-235 and U-238 when it performed its screening analysis. For Phase III, however, U-234 and U-236 were included. U-234 contributes much of the activity of natural or slightly enriched uranium. U-236 is produced from neutron bombardment in nuclear reactors, and would have been present in uranium released from the separations areas, among other areas at SRS.

Radionuclides identified as Pu-239,240 in the Phase II report were assumed to all be Pu-239. The fractional activity of Pu-240 for weapons grade plutonium was determined to be small compared to that for Pu-239 (see Appendix C). Radioactive releases at SRS were often reported as unidentified alpha activity, unidentified beta-gamma activity, or undifferentiated plutonium activity. In most cases, the unidentified constituents would have been a combination of several isotopes. The fractions of total activity that individual isotopes represented probably varied from one release event to another. For simplicity, unidentified alpha activity was conservatively assumed to be Pu-239 because it was one of the more prevalent isotopes created at SRS, and because it is more radiotoxic than uranium isotopes for many of the exposure pathways. Other transuranic isotopes that have been produced and used at the SRS (such as Neptunium-237, Curium-244 and Californium-252) may have contributed to unidentified alpha activity, but these isotopes were produced primarily during brief periods.

Unidentified beta-gamma activity was modeled as Sr-90, which was commonly reported in environmental release reports at SRS. Strontium-90 has a half-life that is sufficiently long (28 years) that it may persist in the environment for many years after release. On the other hand, the health effects of Sr-90 will exceed those of other radionuclides for important dose pathways (e.g., doses per unit of activity from inhalation and ingestion will be greater for Sr-90 than for Co-60).

Undifferentiated plutonium (occasionally found in SRS reports) was assumed to be Pu-239 as this was the main plutonium isotope produced at the site.

5.1.8.2 Chemical Forms of Radionuclides

For the Phase III study two types of releases were partitioned according to their chemical form: tritium and iodine. Section 5.1.8.2.1 discusses Phase III assumptions about the chemical forms of tritium

released to air. Section 5.1.8.2.2 discusses Phase III assumptions about chemical forms of iodine isotopes released to air.[4]

5.1.8.2.1 Tritium

Tritium was one of the major nuclear materials produced at SRS. The Phase II report identified two chemical forms of release: an elemental form and an oxide form. Gaseous tritium (T_2) at room temperature can react with gaseous hydrogen to form elemental tritium (HT). Tritium can also react with oxygen to form an oxide, particularly tritiated water (HTO). Tritium poses a greater radiological risk in the oxide form than in the elemental form because water or water vapor can be easily taken into the body.

From the Phase II data, it was assumed for Phase III that all tritium released into the air from SRS was either in an elemental (HT) or oxide (HTO) form. Most tritium releases occurred from the reactor areas and from the tritium facilities located in the separation areas. Smaller quantities of tritium were released from other areas such as D-Area.

Reactor areas. In other SRS reports and studies, tritium losses from reactor areas were estimated to be 100% in the oxide form (Miller and Patterson 1956; Longtin 1973; Jacober 1973). Westinghouse (1991) has indicated that releases from reactors were due to evaporation of tritiated water and virtually all evaporated waste was released into the air through the reactor facility stacks. Balancing this with other information,[5] it was assumed that all tritium released from the five reactors was in the oxide form.

Tritium was also released into the air from evaporation of water from the reactor seepage basins. Tritium released from the reactor seepage basins was assumed to be in the oxide form.

Separations facilities. In the SRS separations facilities, the chemical form of the released tritium depended on the nature of the work performed at the facilities. The chemical form of the released tritium was determined by using information from (Murphy 1991) and the inadvertent release and incident histories summarized in the Phase II report. Specific information on the tritium release form was often provided for acute and unplanned accidental releases, especially for incidents of tritium release exceeding 700 curies. Each year, the activity from all acute or unplanned releases having known chemical forms was subtracted from the total tritium activity released for that year. The remaining activity was assumed to be split evenly between elemental and oxide forms, based on data from Murphy 1991 suggesting that about 50% of the tritium release was in an oxide form. Then the activity whose chemical form was known from the acute or unplanned releases for that year was appropriately added to the activity in each of the above splits.[6]

Similar to the reactor area seepage basins, small quantities of tritium were released into the air from evaporation of the separation area seepage basins. The evaporated tritium was assumed to be in the oxide form.

[4] Other radionuclides were not partitioned by chemical form. Although health effects may depend upon "the lung clearance class" for other radionuclides, only a single class was considered for each of these other radionuclides. In addition, the model for uptake of tritium by biota depends on the chemical form.

[5] For example, in 1992, 65.90 curies of tritium were released from K reactor in elemental form compared with 39,200 curies in oxide form. The elemental form release accounts for less than 0.2 % of the total tritium release

[6] As an example, assume that the total tritium release from the separations facilities in a given year was 1000 Ci, and this release was in an unspecified elemental and oxide form combination, although there was reason to believe that about half was either form. That year, 200 Ci of tritium was known to have been inadvertently released in an elemental form and 300 Ci of tritium was released in an oxide form. The 1000 Ci of tritium released that year was assumed to consist of 200 + (1000 – 200 – 300)/2 = 450 Ci of tritium in an elemental form and 300 + (1000 – 200 – 300)/2 = 550 Ci in an oxide form.

Other SRS areas. Small tritium releases have been documented in Cummins et al from A Area, D Area, M Area, and CMX-TNX (Cummins 1991a). These releases were assumed to have been all in oxide forms.

5.1.8.2.2 Iodine

The fission and activation processes in nuclear reactors were the primary sources of radioiodine production at SRS. The chemistry of iodine in nuclear facilities and the environment is complicated. The most reactive form of iodine is elemental iodine (I_2). This form of iodine has a relatively high deposition rate. It is important for assessing exposures to the thyroid through the food chain. Under favorable situations (e.g. the existence of other reactive elements, and the presence of catalysts), elemental iodine can combine with other elements and form less reactive gases such as HI, HOI and IO_3, or react with organic compounds forming even less reactive organic iodides like methyl iodide (CH_3I). Iodine existing as an organic molecule contributes to exposure by inhalation but is relatively unimportant for food chain pathways. Radioiodine can also associate with particles that can lower its reactivity. The gaseous radioiodine compound can be absorbed by non-radioactive particulate matter as well.

Two isotopes of iodine were considered in Phase III: I-131 and I-129. Annual I-131 releases were monitored for the H- and F-Area separations facilities, reactors, and other facilities, mainly SRL. Annual I-129 releases were monitored for only the separations areas.

The Phase II report addressed the chemical form of the released iodine. Phase II release estimates for I-131 from the F- and H-Separations areas were apportioned between elemental iodine (I_2) and organic iodine (Phase II). Phase II did not similarly partition release estimates for I-129 from the separations areas, although one might expect a similar distribution. For reactors, Phase II cited measurements of iodine released at commercial pressurized water nuclear reactors by Pelletier et al (Pelletier 1978). From this reference, Phase II estimated that "about 30% of the total would be elemental iodine and that the remainder would be divided between less reactive inorganic forms (~40% of total) and organic iodides (~30% of total)."[7] For I-131 releases from SRL, it was suggested in Phase II (p. 4.2-27) that "most of the radioiodine released from the shielded cells was probably in an elemental form" (Phase II).

For Phase III, the released quantities of iodine into the air were split between elemental and organic iodine in a manner consistent with the information in Phase II and summarized in Appendix B. However, data indicate that the chemical forms of released iodine change as the iodine is transported through the air (Ramsdell 1994). Therefore, the computations in Phase III for transport, dispersion, and deposition of iodine were performed assuming that the iodine was a mixture of chemical forms – i.e., 40% particulate, 30% reactive gas (elemental), and 30% nonreactive gas (organic).[8] These fractions were built into the GENII code by its creators based on their experience with modeling iodine releases (Napier, 2002). The manual for the RATCHET[9] computer code, which was used for the thyroid dose reconstruction work for the Hanford Reservation, observes the following regarding the transport and mid-air partitioning of elemental iodine (Ramsdell 1994):

> *In the time that it took the iodine to travel 3200 meters (2 miles), about two-thirds of the iodine had changed form. Approximately one-third of the iodine was in organic species and the*

[7] Essentially, the Pelletier data indicated that iodine was released in a highly reactive form, a moderately reactive form, and a less reactive form. For the sake of conservatism, the moderately reactive and highly reactive forms could be grouped rather than the moderately reactive and the less reactive forms, leading to a split of about 70% elemental and 30% organic.

[8] Data files containing annual releases of elemental and organic forms of I-131 were input into the pre-processor and added. The total I-131 was then split between chemical forms in the ratios of 40% particulate, 30% elemental, and 30% organic. The revised files from the preprocessor were then input to GENII for the air transport, deposition, and radiation exposure computations. See Appendix G for details.

[9] RATCHET: Regional Atmospheric Transport Code for Hanford Emission Tracking (Ramsdell 1994).

remaining third was associated with particulate material. The partitioning of iodine at 3200 in Ludwick's experiments is consistent with the results of the measurement of iodine in plumes from the stacks at the Hanford Site…with the partitioning of iodine in the plume following the Chernobyl reactor accident.

5.1.9 Compare Final Source Term to Phase II Level 1 (Step 8)

To assure consistency between the Phase II release estimates and the Phase III source term, the total release of each radionuclide over 39 years, as determined in Phase III, was compared with the 36-year total release estimate used in Phase II for the screening assessment. This comparison is shown in Table 5-7. The information herein cited for Phase II was obtained from the Excel spreadsheets included with the Phase II report. As discussed in greater detail in Appendix C.4, the source term used for Phase III is generally consistent with Phase II. Some groups of isotopes, however, deserve comment:

Table 5-7 Comparison of 39-Year Phase III Total Releases (Ci) to 36-Year Phase II Releases Used for Phase II Screening Assessment (Ci)

Radio-nuclide	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
Am-241	$5.88x10^{-3}$	0	$+ 5.88x10^{-3}$	+ 100	X
Ar-41	$6.36x10^{+6}$	$6.40x10^{+6}$	$- 4.00x10^{+4}$	- 0.638	
C-14	$2.97x10^{+3}$	$3.00x10^{+3}$	$- 3.00x10^{+1}$	- 0.901	
Cs-137	3.51	3.50	$+ 1.00x10^{-2}$	+ 0.316	
H-3	$2.51x10^{+7}$	$2.45x10^{+7}$	$+ 6.00x10^{+5}$	+ 2.44	
I-129	5.67	5.70	$- 3.00x10^{-2}$	- 0.448	
I-131	$4.91x10^{+4}$	$2.50x10^{+3}$	$+ 4.66x10^{+4}$	+ 94.9	X
Pu-238	2.08	1.00	+ 1.08	+ 51.8	X
Pu-239	$1.32x10^{+1}$	3.5	+ 9.70	+ 73.6	X
Ru-103,106*	1.58x10+2	1.70	$+ 1.56x10^{+2}$	+ 98.9	X
Sr-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, Ru-103,106 was screened assuming that all activity was Ru-106, Sr-89,90 activity was screened assuming that all activity was Sr-90, and uranium activity was screened assuming that all activity was U-235. For Phase III, activity reported as uranium was apportioned among the uranium isotopes U-234, U-235, U-236, and U-238.

Am-241: The citation of zero for Phase II in Table 5-7 reflects the fact that a 36-year screening total was not provided in the Phase II Excel spreadsheets for Am-241. However, other entries in this table suggest that the value used in Phase II may well have been $5.60x10^{-03}$ Ci over 36 years, which is only slightly smaller than the 39-year total for Phase III of $5.88x10^{-03}$ Ci.

I-131: The Phase III value is about 20 times larger for I-131 than the Phase II screening assessment value. After performing the screening assessment, the Phase II study further investigated releases of I-

131 from SRS facilities. For Phase III, annual I-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.

Plutonium isotopes: The Phase III source term is slightly larger than the Phase II release estimates because unidentified alpha activity was assumed to be Pu-239. Because the unidentified alpha activity only summed to 0.08 curies, this adjustment to Pu-239 was not a significant change to the Phase II release estimate.

Ru-103,106: The total release over 36 years as apparently used for Ru-103,106 was different for Levels One and Two of the Phase II screening assessment. For Level One of the screening assessment, release over 36 years is given as 1.7 Ci. But for Level Two of the screening assessment, one can calculate a 36-year release of 155.7 Ci. Also, another Phase II Excel spreadsheet estimates a total 36-year release of Ru-103,106 from the F- and H-Canyons of 158 Ci. 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, it was concluded that a value of 158 Ci is more reasonable for Phase III than the value cited in Phase II for Step 1 of the screening assessment

Sr-89,90: The Phase III source term for Sr-89,90 increased by 45 curies over the Phase II estimates because unidentified beta-gamma activity was assumed to be Sr-90.

Uranium: The 39-year total uranium value used for Phase III is larger than the 36-year Phase II screening value. After performing the screening assessment, the Phase II study increased the estimated releases of uranium from SRS over that reported by SRS to account for sampling and measurement inefficiencies (see Chapter 4.4 of the Phase II report). The Phase III source term reflects these increased Phase II estimates as well as releases during the years 1990 through 1992.

5.2 Phase III Source Term by Groups of Radionuclides

This section contains summaries of the assumptions and procedures used to develop the source term for each radionuclide released into the air and listed in Table 5-7.

Tables of the annual quantities of these radionuclides released from each of the four virtual sources identified in Section 5.3.2 are provided in Appendix B. Uncertainties associated with these release estimates are addressed in Chapter 12.

5.2.1 Tritium

The main sources of tritium release to the air from SRS were the reactors and the separations areas. Phase II provided tritium release estimates for reactors and the separations areas for 39 years. There is good agreement between the Phase II release estimates and SRS data for the reactor and the separations areas (Phase II.). For Phase III, however, sources were added that were not addressed in detail in Phase II. These sources included tritium that evaporated annually from the reactor and separations areas seepage basins, as well as annual releases from the A-, M- and D-Areas, SRL, CMX-TNX. The information on annual release of tritium from these additional areas, facilities, and seepage basins was obtained from Cummins et al (Cummins 1991a).

Seepage basin evaporation data in Cummins et al were presented as totals for all reactor and separations areas seepage basins (Cummins 1991a). Annual quantities of tritium evaporated from the reactor seepage basins had to be apportioned into two virtual groups of reactor facilities consistent with Table 5-6. It was assumed for Phase III that evaporation from the seepage basins was linked to the tritium inventories that

were discharged to the reactor seepage basins in liquid form. For each year, the total tritium inventory that was released into all reactor seepage basins was determined. The fractions of this total tritium inventory that were released into each of two groups of reactor seepage basins was also determined (C-, K-, and L-seepage basins in one group and P- and R-seepage basins in another). Then these fractions were assumed for the annual release of evaporated tritium into the air from each group of reactor seepage basins. These two fractions were multiplied by the total annual amount of tritium evaporated from reactor seepage basins to arrive at annual releases from both virtual groups of reactor facilities.

In addition, for Phase III, environmental report data for 1990 through 1992 was used rather than the reactor estimates for these years from Phase II. The combined totals from these environmental reports are somewhat larger than those listed in Phase II. This may be due to limited data in early studies. For these years, tritium release data were reported in the SRS environmental reports as combined releases from all reactors (Cummins 1991b, Arnett 1992, Arnett 1993). Information from Phase II was used to group the tritium released from all reactors into two virtual groups of reactor facilities.

5.2.2 I-131

As noted in Section 5.3.6.2, annual I-131 releases were determined in this Phase III study for the H- and F-Area separations facilities, reactors, and for SRL, and were grouped into the four virtual sources summarized in Table 5-6. Annual release information for the years 1954 through 1989 was obtained for these facilities from Phase II. For the separations areas and reactors, the median values from the Excel spreadsheets published with the electronic version of Phase II were used. Annual release information for the years 1990 through 1992 was obtained from environmental reports (Cummins 1991b, Arnett 1992, Arnett 1993). Information from (Cummins 1991a) was used to partition the I-131 estimates from Phase II, which are given for all reactors, into two virtual sources consistent with the reactor groupings in Table 5-6.

5.2.3 Ar-41

Argon-41 is an activation product that was created in large quantities during reactor operations. It is a noble gas having a short (1.83 hours) half life.

For Phase III, as in Phase II, all Ar-41 released into the air was assumed to come from the SRS reactors. Information from Phase II, from Cummins et al (Cummins 1991a), and from Savannah River environmental reports (Cummins 1991b, Arnett 1992, Arnett 1993) for the years 1990 through 1992 was used to partition Ar-41 release from the five reactors into the two reactor virtual source groupings listed in Table 5-6.

5.2.4 Americium-241

For Phase III, annual Am-241 release data was obtained for the years 1977 through 1989 from Cummins et al (Cummins 1991a). This reference identified Am-241 only for the F- and H-Separations Areas. For the years 1999 through 1992, additional data were available from SRS environmental reports (Cummins 1991b, Arnett 1992, Arnett 1993) and from (Carlton 1997b).

5.2.5 C-14

For Phase III, estimates of C-14 released into the air were made for the separations areas and for the reactors. For the separations areas, data was available from Cummins et al. for the years 1955 to 1989 (Cummins 1991a). Data from SRS environmental reports were used for 1990 through 1992 (Cummins 1991b, Arnett 1992, Arnett 1993).

For the reactors, data was available from Cummins et al for the following time frames (Cummins 1991a):[10]

- C-Reactor: 1955 through 1985.
- K-Reactor: 1955 through 1988.
- L-Reactor: 1955 through 1968, 1987, and 1988.
- P-Reactor: 1955 through 1988.
- R-Reactor: 1955 through 1964.

After 1988, information on C-14 release from nuclear reactors was available in the SRS Environmental Report for 1992 as summed over all reactors (Arnett 1993). For 1992, the carbon-14 released from the reactors was apportioned the C-, K-, L-, and P-Reactors in equal fractions.[11]

5.2.6 Cs-137

For Phase III, annual releases of Cs-137 were estimated for all years from the separations areas and for a few years from the reactors.

Most of the SRS atmospheric release of Cs-137 occurred from the F- and H-separations Areas (Phase II, Cummins 1991a). To develop source terms for Cs-137 release from the separations areas, information from these references was used for the years 1954 through 1989, and data from SRS environmental reports was used for the years 1990 through 1992 (Cummins 1991b, Arnett 1992, Arnett 1993).

For reactors, Cs-137 release was not reported for the years 1954 through 1989 (Cummins 1991a). Cs-137 releases from reactors were reported, however, in SRS environmental reports for the years 1990 and 1992 (Cummins 1991b, Arnett 1993). These releases were small (on the order of 0.00002 Ci in 1990 and 0.00003 Ci in 1992), but were added to the source term for completeness. For 1990, the released activity was apportioned equally among C-, K-, L-, and P-Reactors. For 1992, the activity was all released from L- and K-Reactors. This was done because for 1992, data was available that apportioned the total released Cs-137 activity (3.05×10^{-5} Ci) between these two reactors (Arnett 1993b).

5.2.7 I-129

For Phase III, consistent with the information in the Phase II study and in Cummins et al., it was assumed that all release of I-129 to the air came from the separations areas (Phase II, Cummins 1991a). For Phase III, the annual I-129 release estimates from the Phase II study were compared with the smaller annual release estimates provided in Cummins et al. (Cummins 1991a). For the Phase III study, the Phase II estimates were used rather than the Cummins et al estimates. As discussed in Chapter 4 of the Phase II report, the historical SRS reports may have underestimated the true release because of sampling line loss, sampler collection efficiency, and counting errors (Phase II).

For 1990 through 1992, annual release estimates from SRS environmental reports were used for the separations areas (Cummins 1991b, Arnett 1992, Arnett 1993).

[10] Recall that R-Reactor shut down in 1964, C-Reactor shut down in 1985, P-Reactors shut down in 1988, and that L-Reactor was shut down in 1968, but was restarted in 1985 and shut down again in 1988. K-Reactor was shut down in 1988 but briefly operated in 1992 (Phase II).

[11] Release from R-Reactor was assumed to have been much smaller for the years 1990-1992, compared with other reactors, because it had permanently shut down much earlier (at least 21 years) than did the other reactors. Because of uncertainty about the fraction of the total release that should have been allotted to each of the other four reactors, the 1992 C-14 release (0.183 Ci) was apportioned equally among the four reactors. Hence, 75% of the C-14 was released from the C-, K-, and L-Reactor group, and 25% was released from the P- and R-Reactor group.

5.2.8 Ruthenium-103, 106

For Phase III, annual release estimates for Ru-106 were made for the F- and H-Separations Areas. For the years 1955 through 1989, release data were obtained from an Excel worksheet linked to the electronic version of Phase II (Phase II). For the years 1955 through 1968, data were provided as combined Ru-103,106 for both the F- and H-Areas. For the years 1969 through 1989, data was separately provided for Ru-103 and Ru-106 (Phase II).

For Phase III, releases documented in Phase II for the years 1955 through 1989 of Ru-103, Ru-106, and combined Ru-103,106 were assumed to be entirely Ru-106. This assumption was consistent with that used in the Phase II screening analysis (Phase II) and provides conservative estimates of dose by inhalation and ingestion. Releases of Ru-106 for the years 1990 through 1992 from the separations areas were obtained from SRS environmental reports (Cummins 1991b, Arnett 1992, Arnett 1993).

The Phase III source term also includes Ru-106 release from the reactor areas for the year 1990. This release was documented in the SRS Environmental Report for 1990 (Cummins 1991b). Although the release was small (about 0.00003 Ci), it was included for completeness. This release was apportioned among the reactors.

5.2.9 Strontium-89 and Strontium-90 with Unidentified Beta-Gamma

For the Phase III study, Sr-89 and Sr-90 were anticipated to have been released into the air from the separations areas. Sr-90 was anticipated to have been released into the air from the reactors and from the A-Area.

Separations areas. Annual release data for combined Sr-89,90 from the F- and H-Separations Areas were provided in the Phase II report for 1954 – 1989 (Phase II). In Phase III, the combined Sr-89,90 activity was apportioned into 75% Sr-89 and 25% Sr-90 (see Section 5.1.8.1). To this activity was added the activity that was reported through 1989 in Cummins et al as unidentified beta-gamma activity (Cummins 1991a). All this unidentified activity was assumed to be Sr-90 (see Section 5.1.8.1).

Sr-89 and Sr-90 activity was assigned to the years 1990 and 1991 using information from SRS environmental reports (Cummins 1991a, Arnett 1992). For these two years, data were reported in these two references as combined Sr-89,90, including unidentified beta-gamma. This combined activity was assumed to be all Sr-90. For 1992, Arnett et al reported 1.62×10^{-3} Ci of combined Sr-89, 90 with unidentified beta-gamma activity (Arnett 1993). A second reference reported 2.75×10^{-4} Ci of combined Sr-89,90 activity without referencing unidentified beta-gamma activity (Arnett 1993a). The difference was 1.35×10^{-3} Ci. The activity (1.62×10^{-3} Ci) reported by (Arnett 1993a) was partitioned between Sr-89 and Sr-90 in a 75%-25% ratio. The difference (1.35×10^{-3} Ci) was assumed to be Sr-90.

Reactors. For reactors, Sr-90 release data were not provided in the Phase II report (Phase II). However, for the years 1954 through 1989, annual unidentified beta-gamma activity was released from reactors and reported in Cummins et al (Cummins 1991). This activity was assumed for Phase III to be Sr-90. Reactor-specific annual Sr-90 estimates were apportioned using Cummins (1991a) data into two virtual source groups consistent with Table 5-6. For the years 1990 through 1992, the release data obtained from environmental reports for the reactor areas were equally apportioned into C-, K-, L- and P-Reactors.

A-Area. For the years 1954 through 1989, annual releases from A-Area that were identified in Cummins et al as unidentified beta-gamma activity (Cummins 1991a) were assumed to be Sr-90. For the years 1990 through 1992, SRS environmental reports were used to develop Sr-90 release estimates from A-Area (Cummins 1991b, Arnett 1992, Arnett 1993).

5.2.10 Uranium and Plutonium with Unidentified Alpha

For Phase III, annual estimates of uranium released into the air were made for the F- and H-Separations Areas and for M-Area. Annual estimates of plutonium released into the air were made for the separations areas, the reactors, and for A-Area.

Separations Areas. The Phase II release estimates were based on information from Cummins et al (Cummins 1991a). However, the Phase II estimates were increased in earlier years, compared with that reported by Cummins et al (Cummins 1991a), because of concerns about sampling uncertainties. For Phase III, the Phase II estimates of release of uranium and plutonium from the separations areas were enhanced using additional data from environmental reports.

For Phase III, uranium activity was apportioned into four uranium isotopes based on the isotopic partition assumptions summarized in Section 5.1.8.1 and Table 5-8. Note that uranium isotopic composition varied in the F- and H- Separations Areas, because the processes conducted in each area differed. Uranium data for Phase III were available for 36 years from Phase II (Phase II) and for three years from SRS environmental reports (Cummins 1991b, Arnett 1992, Arnett 1993).

For the years 1954 through 1989, uranium released from the F-Separations Area was reported separately in Phase II from uranium released from the H-Separations Area. This information was sufficient to partition the uranium released from both the separations areas. But for 1990 through 1992, information about uranium released from the separations areas was provided in SRS environmental reports (Cummins 1991b, Arnett 1992, Arnett 1993) only as combined releases from both areas. Isotopic partitioning of uranium was performed for these years using an SRS report for the year 1992 that provided uranium release data separately for F- and H-Areas (Arnett 1993a). This reference indicated that 95% of the uranium in 1992 was released from the F-Area and 5% from the H-Area (Arnett 1993). It was assumed that this 95%-5% uranium split between F- and H-Areas was also applicable to 1990 and 1991. The total uranium released from each separations area for these years was apportioned into isotopic distributions consistent with Table 5-8. Then the total release of each uranium isotope from both separations areas was determined for purposes of the virtual source grouping. Finally, release data for each uranium isotope in F- and H-Area were increased for Phase III using the same method described in Chapter 4 of Phase II to compensate for sampling line loss.

For plutonium, Phase II increased its estimates of plutonium released into the air, relative to that reported by SRS, to compensate for sampling line loss. The source term adjustment in Phase II for plutonium air release was done for Pu-238 and for Pu-239,240 together. Because sampling line loss should have been the same for any plutonium isotope, for Phase III the procedure cited in Phase II to compensate for sampling loss was applied to both Pu-238 and Pu-239. The total plutonium activity reported in Phase II before adjustment matched the calculated plutonium term in Cummins et al (Cummins 1991a). Using the isotopic information provided in (Cummins 199a), plutonium reported as total plutonium in Phase II was apportioned for Phase III into Pu-238 and Pu-239.

Cummins et al reported unidentified alpha activity released from the F- and H-Separations Areas (Cummins 1991a). For Phase III, this unidentified activity was included as Pu-239. The activity was increased in Phase III, relative to that reported in Cummins 1991), to compensate for sampling line loss. As discussed earlier, the inclusion of this unidentified activity as Pu-239 did not significantly change the plutonium source term.

Reactors. Annual estimates of Pu-239 released from the nuclear reactors were made for Phase III using information from Cummins et al for the years 1973 through 1989 (Cummins 1991a). In this case, starting in 1973, Cummins 1991 provided air release data for unidentified alpha activity for the reactor areas. For

Phase III it was assumed that this alpha activity was Pu-239 consistent with Section 3.5.4. For 1990 through 1992, information from SRS environmental reports was used (Cummins 1991b, Arnett 1992, Arnett 1993). No estimates were made for uranium release from reactors, because such releases were not identified in Phase II, Cummins 1991, or other documents.

M-Area. Annual estimates of uranium isotope releases from M-Area were made in Phase III using information from (Cummins 1991a). This reference listed annual uranium releases (as U-Nat – i.e., natural uranium) from 1975 through 1989, except that no releases were listed for 1981 and 1984. This activity was apportioned among the isotopes U-234, U-235, and U-238. Releases for the years 1990 through 1992 were estimated using information from SRS environmental reports (Cummins 1991b, Arnett 1992, Arnett 1993).

A-Area. Cummins et al reported annual release of unidentified alpha activity from A-Area for most of the years from 1961 through 1992 (Cummins 1991a). No release information was provided for 1964-1967, 1972, 1979, 1981, 1982, 1984, and 1985. This unidentified alpha activity was assumed to be Pu-239 for Phase III. Information from environmental reports was used to complete the estimates for 1990 through 1992 (Cummins 1991b, Arnett 1992, Arnett 1993).

5.3 Annual Release of Tritium, Iodine-131, and Argon-41

As will be seen in Chapter 11, radiation doses calculated from the air pathway are dominated by tritium, I-131, and Ar-41. To help shed light on these calculated doses, the source term assumed in Phase III for these radionuclides is graphically depicted in the Figures below. The annual release of tritium to air from the SRS reactors and separations facilities is shown in Figure 5-1. Clearly, the bulk of the tritium released over the 39 years of nuclear materials production came from the F-and H-Separations Areas rather than from the reactor areas. Annual releases of iodine-131 from all reactors and from the separations areas at SRS are shown in Figure 5-2. Note again that the bulk of the I-131 was released from the separations areas, and that the largest I-131 release from the separations areas occurred in 1956. (Also note that the y-axis of this graph (Curies of I-131 released) is in a logarithmic scale.) Annual releases of Ar-41 from the five SRS reactors are shown in Figure 5-3. Although Ar-41 releases rise and fall over the years, one can see a succession of peaks that gradually diminish in height. The largest peak occurred over roughly a five-year period between 1958 and 1963. Successively smaller peaks occurred in the years 1967 and 1968, in 1973, and in 1986.

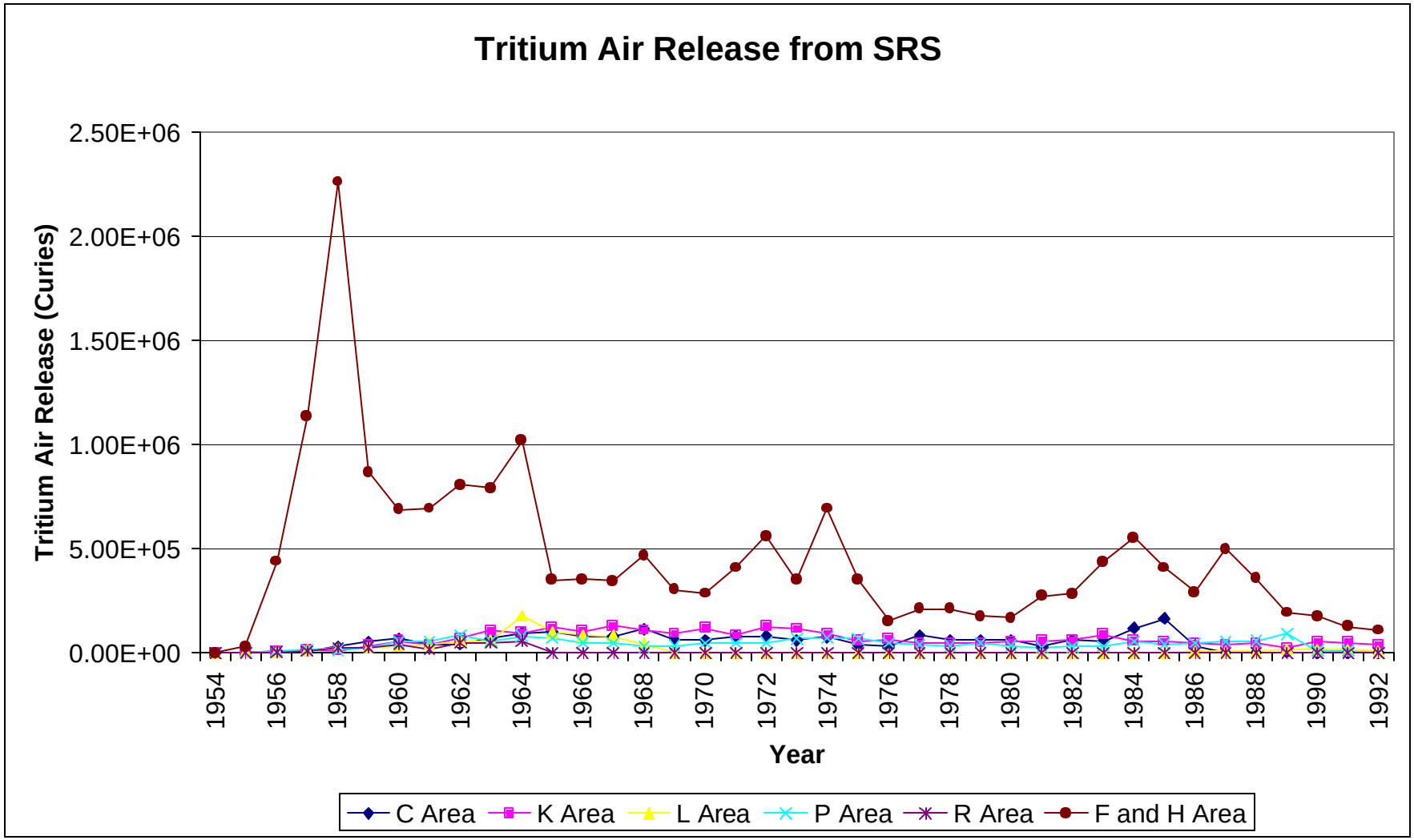

Figure 5-1 Tritium Release to Air from SRS

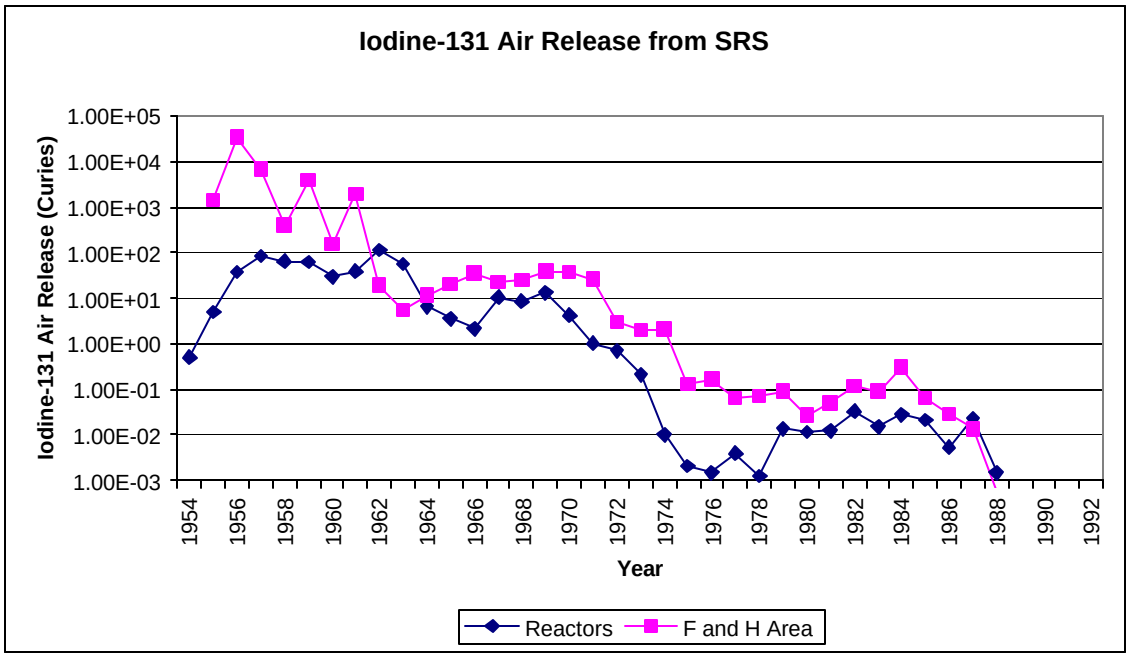

Figure 5-2 Release of I-131 to Air from SRS

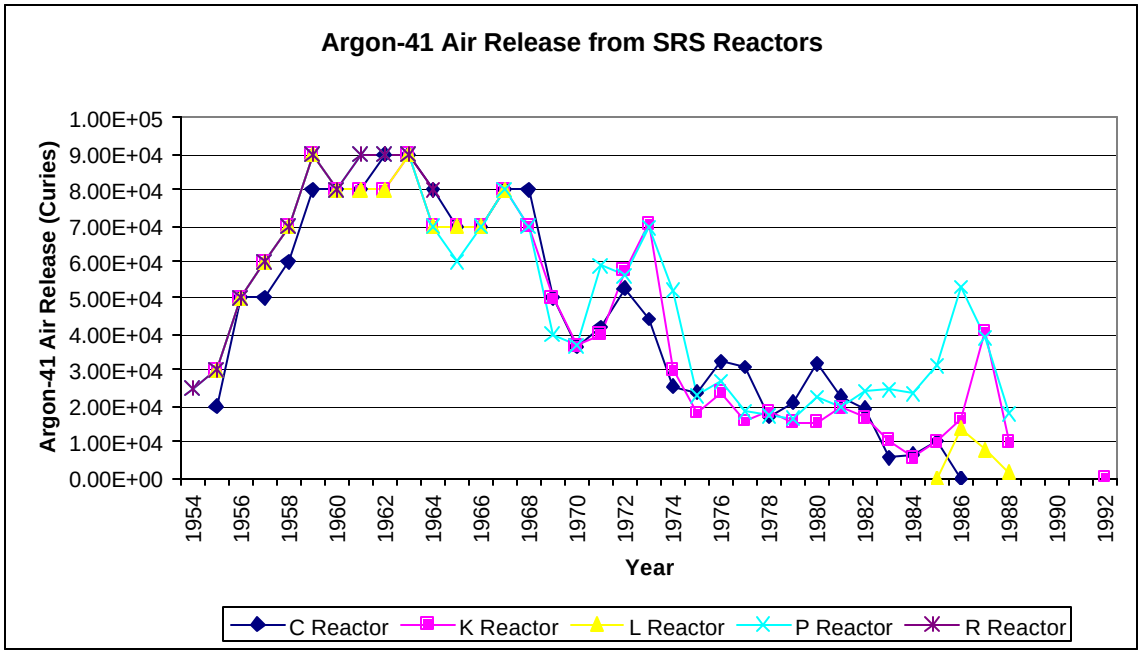

Figure 5-3 Release of Ar-41 to Air from SRS Reactors

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6 TRANSPORT OF RADIONUCLIDES THROUGH THE AIR TO AN EXPOSURE LOCATION

Radioactive materials in the form of gases and particulates may be released into the air and transported by the wind to an exposure location. The radionuclide concentrations in air and deposited on ground surfaces at this exposure location depend on atmospheric transport, diffusion, and deposition processes that affect the transport of radionuclides from the point of release to the exposure location (Figure 6-1).

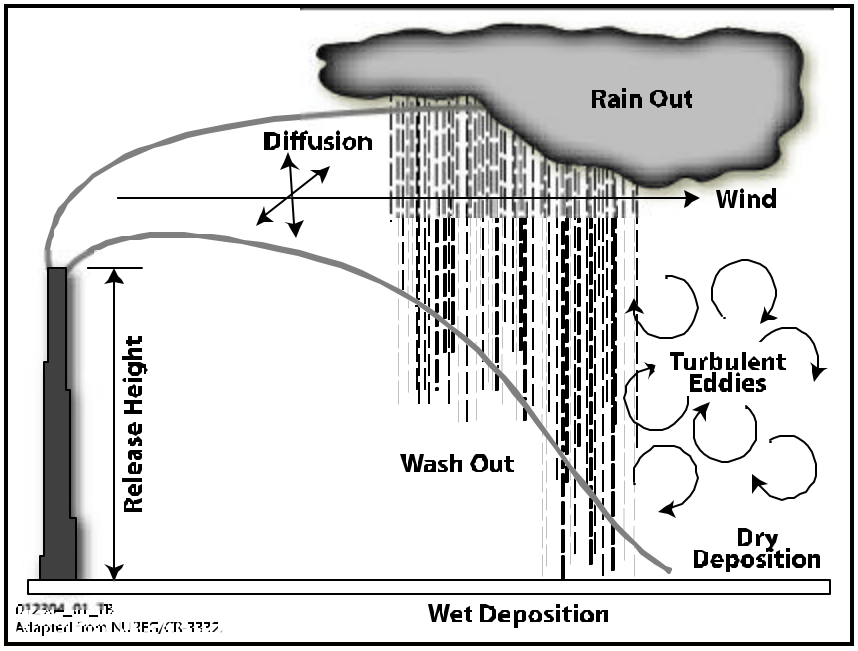

Figure 6-1 Atmospheric Dispersion and Removal Processes

Adapted from NUREG/CR-3332 (Till and Meyer, 1983)

6.1 Description of Atmospheric Processes

Some of the atmospheric processes that are important for Phase III of the SRS Dose Reconstruction Project include: dispersion, depletion, and release height.

Dispersion. As the effluent plume is transported from the source, turbulent eddies within the plume diffuse the effluent. The combined influences of diffusion and transport are generally called dispersion (Till and Meyer, 1983). 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.

As the plume moves with the wind, diffusion continues in the upward vertical direction to the mixing height, generally ranging from about 200 to 2,000 meters above the surface of the earth (Till and Meyer, 1983). Within this atmospheric mixing layer,[1] turbulence is generated that mixes the effluent. But the top of the mixing layer is marked by a decrease in turbulence. Above this "boundary," further vertical diffusion can be significantly reduced (Till and Meyer, 1983).

[1] Another name for the mixing layer is the planetary boundary layer (Till and Meyer, 1983).

There are two main types of turbulence within the mixing layer: mechanical turbulence caused by ground surface effects, and thermal turbulence caused by heating and cooling of the earth's surface.

Mechanical turbulence results from the frictional drag of the earth's surface. Turbulence increases in proportion to the wind speed and the roughness of the underlying surface. Within the mixing layer, wind speed tends to increase with height because of reduced friction between the air and the earth's surface. In heavily built up areas, such as urban areas, wind speed increases with height at a slower rate than in areas where the terrain is less rough, such as the suburbs, or in level country.

Thermal turbulence depends on the stability of the atmosphere within the mixing layer. Atmospheric conditions within the mixing layer are unstable, stable, or neutral depending on conditions that promote, retard, or have no effect the movement of air particles from one location to another. Assuming that a parcel of air (and the particles within it) is set in motion so that it either rises or falls, further movement depends on the temperature of the parcel of air relative to that of the surrounding atmosphere into which it moves (Till and Meyer, 1983):

- *Unstable conditions*. If an initially rising parcel of air is warmer than the surrounding atmosphere, it is more buoyant than the surrounding atmosphere and continues to rise. But if an initially falling parcel of air is cooler than the surrounding atmosphere, it becomes denser than the surrounding atmosphere, and therefore less buoyant. It continues to sink. In either case, air particle movement is promoted.
- *Stable conditions*. If an initially rising parcel of air is cooler than the surrounding atmosphere, it becomes denser than the surrounding atmosphere, and sinks. But if an initially falling parcel of air is warmer than the surrounding atmosphere, it becomes more buoyant than the surrounding atmosphere, and rises. In either case, air particle movement is retarded.
- *Neutral conditions*. If a rising or falling parcel of air is at the same temperature as the surrounding atmosphere, then movement of air particles is neither promoted nor retarded by buoyancy forces.

Different atmospheric stability conditions can strongly affect the dispersion of effluents. For example, under stable conditions and when winds are strong and in a constant direction, a plume of effluent from a stack can retain a narrow shape in the vertical direction for a long distance downwind. On the other hand unstable conditions can result in a looping plume, and the effluent released from a stack can contact the ground relatively close to the release point (Liu and Lipták , 2000).

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

Wet deposition processes include rainout and washout. Rainout is a process that occurs within clouds. Effluents interact with precipitation formation processes and are removed from the clouds by rain. Washout occurs below the cloud layer. Falling rain contacts the effluent, carrying it to earth. Dry deposition processes include removal of effluent due to gravitational settling, or from contact with the ground, vegetation, or buildings.

Radioactive isotopes decay during transport to a downwind receptor. The significance of this removal process depends on the radionuclide half-life and the transport time.

The chemical forms of the radioactive isotopes affect their deposition rates and therefore their depletion from the plume. Factors to be considered include whether a radioactive isotope is being transported as a gas or a particle, and if the latter, its diameter and density.

Release Height. Almost all the radionuclide activity that was released into the air from SRS was released from stacks rather than from ground level. Concentrations are essentially zero near the base of the stack, but rise quickly to a peak value at some distance downwind, and then decrease regularly thereafter. Concentrations are larger along the centerline of the plume than on the ground on either side (Slade, 1968). The higher the effluent release point, the farther the effluent usually travels before significant concentrations of effluent reach ground level.

6.2 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 (Till and Meyer, 1983). Figure 6-2 shows a simplified depiction of a Gaussian plume model, depicting contaminants released from a stack. The model accounts for the downward movement as well as the vertical and horizontal dispersion of the released contaminants, and predicts contaminant concentrations on the ground and in the air. The figure depicts Gaussian (normal) distributions in the vertical and crosswind directions. Near the point of release, the concentration is high near the centerline and falls off rapidly toward the edges. But further downstream, the distribution of concentration spreads from the centerline (Cummins and Todd, 1991).

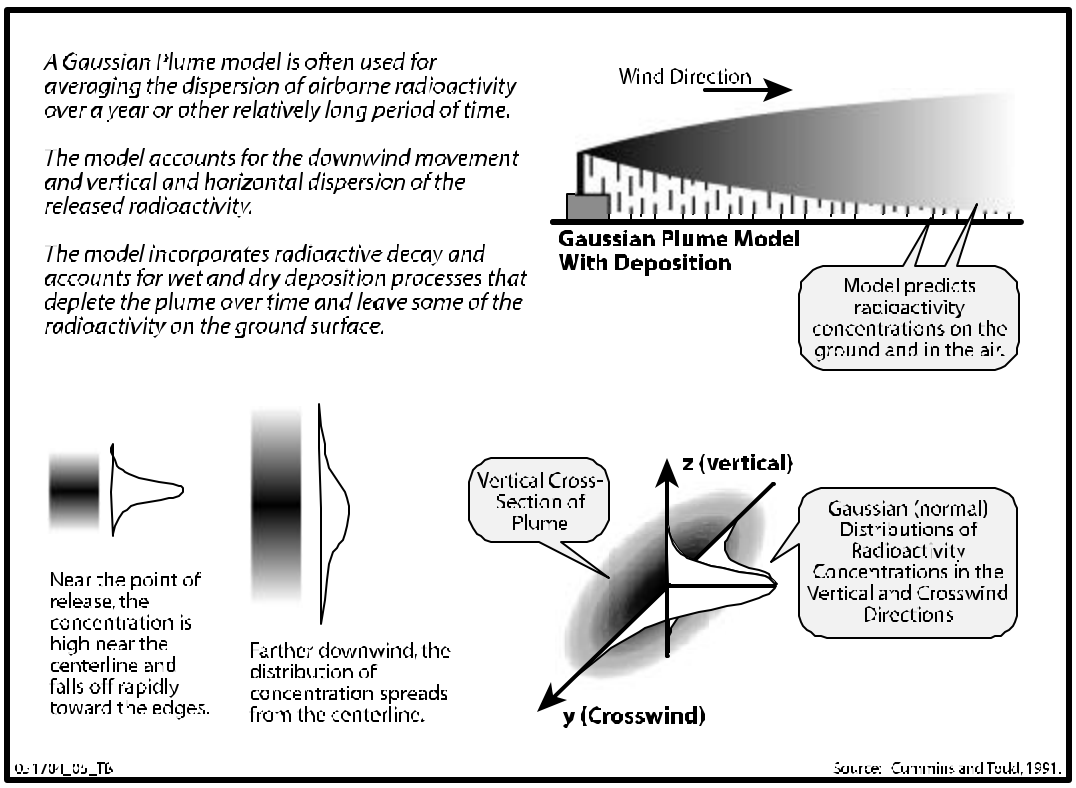

Figure 6-2 Illustration of Straight-Line Gaussian Plume Model (Cummins and Todd, 1991)

The shapes of the concentration distributions are described in the Gaussian plume model by parameters known as diffusion coefficients.[2] Assuming that diffusion along the direction of the wind is small compared to transport by wind, the Gaussian plume model incorporates two diffusion coefficients, s_y and

[2] Some references refer to s_y and s_z as diffusion coefficients; others as dispersion coefficients.

s_z, that are the standard deviations of the Gaussian distributions in the crosswind (horizontal) (s_y) and vertical (s_z) directions.[3]

Many systems have been used to estimate diffusion coefficients. Most of the systems have been based on atmospheric stability classes and the distance from the source. These atmospheric classes are linked to the three atmospheric stability conditions (neutral, stable, and unstable) described in Section 6.1. A commonly used system is the Pasquill-Gifford system (Till and Meyer, 1983). It uses a set of equations that approximate a corresponding set of empirically-determined curves. The curves provide s_y and s_z values as a function of the distance from a source for six stability classes.[4] This system was used for the Phase III study because it is well established and compatible with the data that was obtained for the SRS.

6.3 Sector Average Modification to Gaussian Plume Model

Wind normally does not blow from the same direction for prolonged periods. For chronic or long-duration releases, the basic Gaussian plume model is modified using a sector-average approximation:

- An imaginary circle is drawn around the effluent release point, and the circle is divided into a series of pie-shaped wedges, called sectors.
- The quantity of effluent discharged into each sector is determined by considering the frequency that the wind blows in the direction of the sector.
- In each sector, the average effluent concentrations are determined as a function of distance from the release point by considering the wind speed and stability class, weighted by the frequency that these conditions occur in each sector.

Historically, the circumference around the release point has been divided into sixteen sectors corresponding to the sixteen major compass directions: N, NE, NNE, E, and so forth. Each sector is a pie-shaped wedge describing a 22.5^o arc (360° /16 sectors). Radionuclide concentrations and deposition rates were calculated in each sector. At a given distance from the release point, the model considers the concentration to be constant across the sector. The actual concentration, in fact, would not be discontinuous, as this suggests, but because the model considers only sixteen directions, the numerical result is coarser. If smaller and smaller sectors were chosen for the analysis (i.e., one degree), then the magnitude of any discontinuities would become extremely small.

Appendix A has a more detailed description of the sector average modification and how is was employed on this study.

6.4 Use of Joint Frequency Distribution Data

6.4.1 Definition

The joint frequency distribution (JFD) 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 appropriate time interval and computing the frequency of occurrence of each joint frequency category. Each joint frequency category represents a band (range) of wind speeds, directions, and stability conditions.

[3] By convention, the coordinate system used in Gaussian plume models defines the x-axis as the direction downwind of the source, the y-axis as the cross wind direction (lateral to the source), and the z-axis as the vertical direction.
[4] The six stability classes are: (A) extremely unstable, (B) moderately unstable, (C) slightly unstable, (D) neutral, (E) slightly stable, and (F) moderately stable (Liu and Lipták , 2000).

6.4.2 Data Available from SRS

To estimate airborne radionuclide transport from release points to exposure locations, a set of meteorological data was needed that reflected the conditions that existed between 1954 and 1992. The data was needed to establish the joint frequency distributions for input to the computer model.

The preference was to use SRS-specific meteorological data that spanned all 39 years of nuclear material production. Unfortunately, the onsite SRS meteorological program was established in the early 1970's, leaving a data gap of about 20 years. To approximate meteorological data for all 39 years, consideration was given to using data from the National Weather Stations (NWSs) located near Columbia, South Carolina, and near Augusta, Georgia. Even though these two NWSs were only about 90 km apart and reasonably close to SRS,[5] there were differences in topography and weather patterns, as well as limitations in the available meteorological data (Weber, et al., 2001). A comparison of wind roses for the years 1992 -1996 between these NWSs and the SRS meteorological station showed clear differences in wind patterns (Weber, et al., 2001). The data from these NWSs was considered not sufficiently representative of SRS meteorological conditions to warrant using these data for Phase III.

Therefore, the limited available data from the SRS meteorological station was used to represent all 39 years of nuclear material production. Because joint frequency distribution data from the SRS meteorological station was available for Phase III as five-year averages, four five-year JFD averages were combined to arrive at a twenty-year average. This assumption appeared to be reasonable in light of the general practice used by the SRS for estimating environmental consequences. For example, the SRS Environmental Report for 1991 states that SRS used the meteorological measurements made over a five year period (1982-1986) and that other time periods "show very little change in dispersion conditions" (Arnett, et al., 1992).

6.5 Source and Exposure Locations

Figure 6-3 shows the locations of the four virtual sources considered for Phase III for release of radionuclides into the air. Also shown are the ten exposure locations where members of the hypothetical exposure scenarios were exposed to radionculides that had been transported from the four virtual sources.

[5] The Augusta NWS station is about 30 km west-northwest of the SRS meteorological station, while the Columbia NWS station is about 80 km northeast of the SRS meteorological station (Weber, et al., 2001).

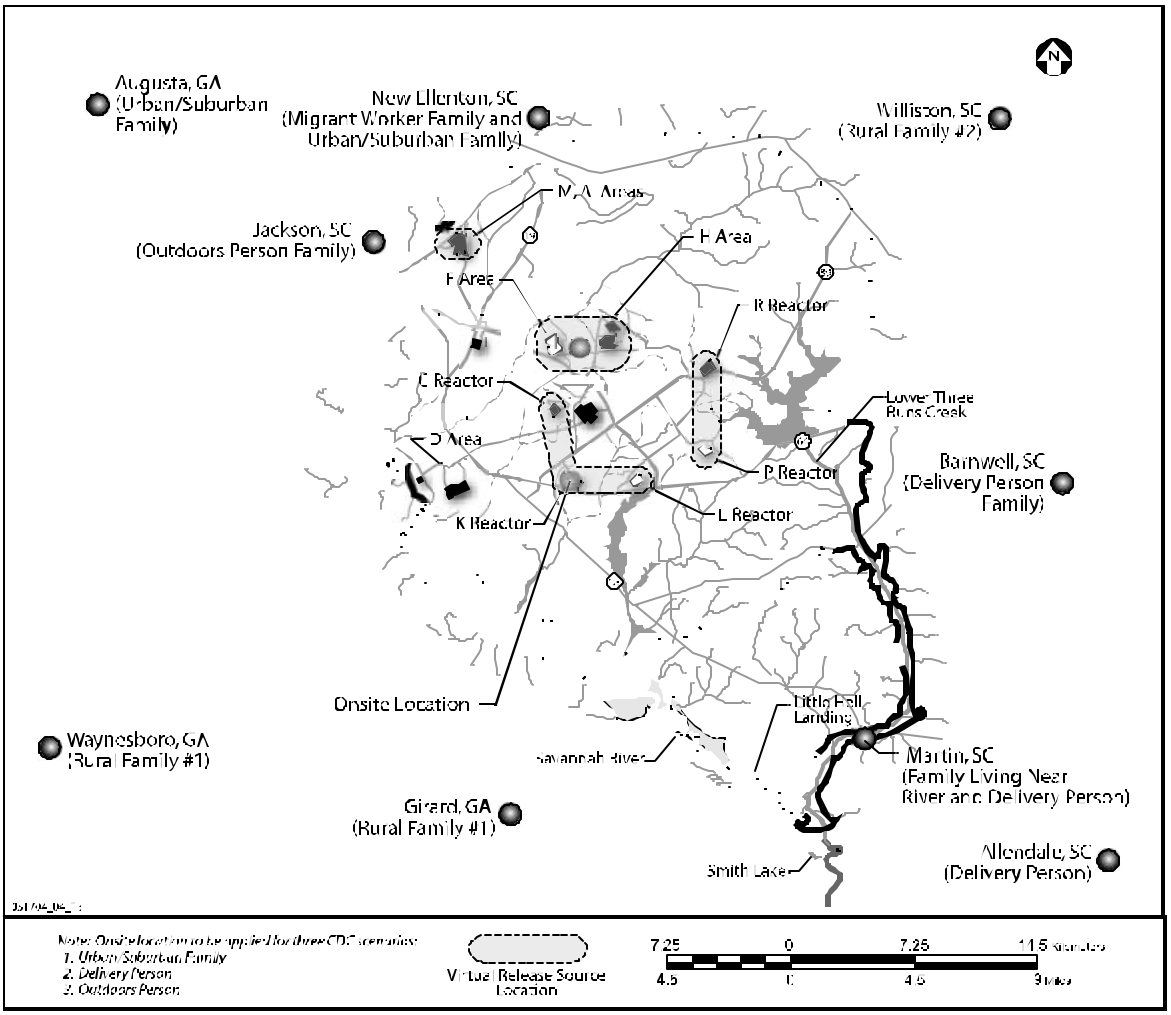

Figure 6-3 Virtual sources and Air Pathways Exposure Locations

Exposure locations and the exposure scenarios are listed in Table 6-1. Members of some exposure scenarios (e.g., Migrant Worker Family) were exposed to radionuclides in air and deposited on the ground at only one exposure location, while members of other exposure scenarios (e.g., Delivery Person Family) were exposed to radionuclides in air and deposited on the ground at more than one exposure location.

Table 6-1 Exposure Locations and Exposure Scenarios

This Exposure Location	Is Considered for These Exposure Scenarios
1. Girard, GA	Rural Family One
2. Waynesboro, GA	Rural Family One
3. Augusta, GA	Urban/Suburban Family
4. Jackson, SC	Outdoors Person Family
5. New Ellenton, SC	Urban/Suburban Family, Migrant Worker Family
6. Barnwell, SC	Delivery Person Family
7. Martin, SC	Delivery Person Family, Near River Family
8. Allendale, SC	Delivery Person Family

9. Williston, SC	Rural Family Two
10. SRS near K-Reactor	Urban/Suburban Family, Delivery Person Family, Outdoors Person Family

The distances from each virtual source to each of the ten exposure locations are presented in Table 6-2 in order of increasing distances from each source.

Table 6-2 Distances (m) from Virtual Sources to Exposure Locations

A-Area, M-Area, SRL		F- and H-Area*		C-, K-, & L-Reactors, D-Area, CMX-TNX*		P- & R-Reactors*	
Distance	Exposure Location	Distance	Exposure Location	Distance	Exposure Location	Distance	Exposure Location
4,824	Jackson	8,666	On site	1,889	On site	8,881	On site
9,266	New Ellenton	12,392	Jackson	16,582	Jackson	20,648	Barnwell
16,226	On site	14,205	New Ellenton	21,092	New Ellenton	20,666	New Ellenton
24,196	Augusta	25,657	Williston	23,149	Girard	20,961	Jackson
30,065	Williston	28,585	Barnwell	23,629	Martin	21,880	Martin
36,789	Barnwell	29,293	Martin	27,743	Barnwell	22,354	Williston
37,477	Girard	30,033	Girard	29,256	Williston	25,800	Girard
38,309	Martin	33,397	Augusta	36,775	Waynesboro	36,775	Allendale
38,710	Waynesboro	39,858	Waynesboro	38,318	Augusta	41,940	Augusta
54,256	Allendale	45,038	Allendale	40,178	Allendale	44,286	Waynesboro

*Includes tritium evaporation from seepage basins.

6.6 Additional Parameters Used for Transport Analysis

In addition to basic meteorological data, values for several additional model parameters were specified. All four virtual sources are modeled as point sources having elevated release heights as listed in Table 6-3.

Table 6-3 Heights of Virtual Sources

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), D-Area, CMX-TNX.
4	61	P- and R-Reactors (includes stacks and basin evaporation)

Values for other parameters used for the air transport assessment are provided in Appendix F.

6.7 References

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7 RELEASE OF RADIONUCLIDES TO WATER AND TRANSPORT TO AN EXPOSURE LOCATION

This chapter summarizes the Phase III work to estimate the release of radionuclides from the Savannah River Site (SRS) facilities to surface water and their transport by water to locations where hypothetical receptors could be exposed. This work resulted in estimates of the annual concentrations of twenty-two radionuclides at two exposure locations: one in the Savannah River and one in Lower Three Runs Creek. Appendix B lists these annual estimated radionuclide concentrations. This analysis provides the starting point for estimating dose resulting from liquid releases of radionuclides from the SRS. The concentrations of radionuclides in water developed by the methods discussed here are used as input to aquatic food chain transport modeling described in Chapter 8, and external and internal exposure models discussed in Chapter 9.[1]

7.1 Overview of the Problem and Solution

The required end points for considering water releases of radionuclides from SRS facilities are the annual concentrations produced by those releases at locations where receptors might be exposed. These annual concentrations depended on three factors: (1) the exposure locations; (2) the annual radionuclide releases to water from the SRS facilities; and (3) the physical and chemical processes affecting the migration of the radionuclides from the points of release to the exposure locations.

In order to estimate doses from radionuclide releases to water, the GENII[2] code allows the user the flexibility to: (1) specify radionuclide releases to water and the water flow rate for the receiving body of water or (2) specify the radionuclide concentrations. The second option was selected for this study because, as discussed in the following, the estimation of radionuclide concentrations is too complex to perform except external to the GENII code.

7.1.1 Exposure Locations

The scenarios (Chapter 3) outline exposure to radionuclides through various activities, including fishing, hunting, and boating in the SRS vicinity. In order to assess dose from these exposures, it is essential to know the concentrations of radionuclides at the exposure locations. The two locations chosen to represent exposure to water releases from the SRS are:

- The Savannah River below the point of confluence with Lower Three Runs Creek and
- Lower Three Runs Creek at Martin, S.C.

These locations are shown in Figure 7-1.

For this study, the radionuclide concentrations in surface waters are considered to be dependent on liquid releases of radionuclides from SRS facilities to on-site streams and seepage basins. In fact, some radionuclide concentrations in surface waters may have resulted from the deposition of air borne radionuclides onto the surface waters or the land surfaces they drained. These concentrations (and the doses that result from them) are expected to be small compared to the concentrations induced by water releases from SRS facilities. Consequently, exposures of receptors to bodies of water not hydrologically

[1] For Phase III the exposure pathways dependent on water releases of radionuclides include: 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

[2] All references to GENII in this chapter refer to version 2 of GENII.

downstream of the SRS were assumed to have negligible radionuclide concentrations and were not modeled.

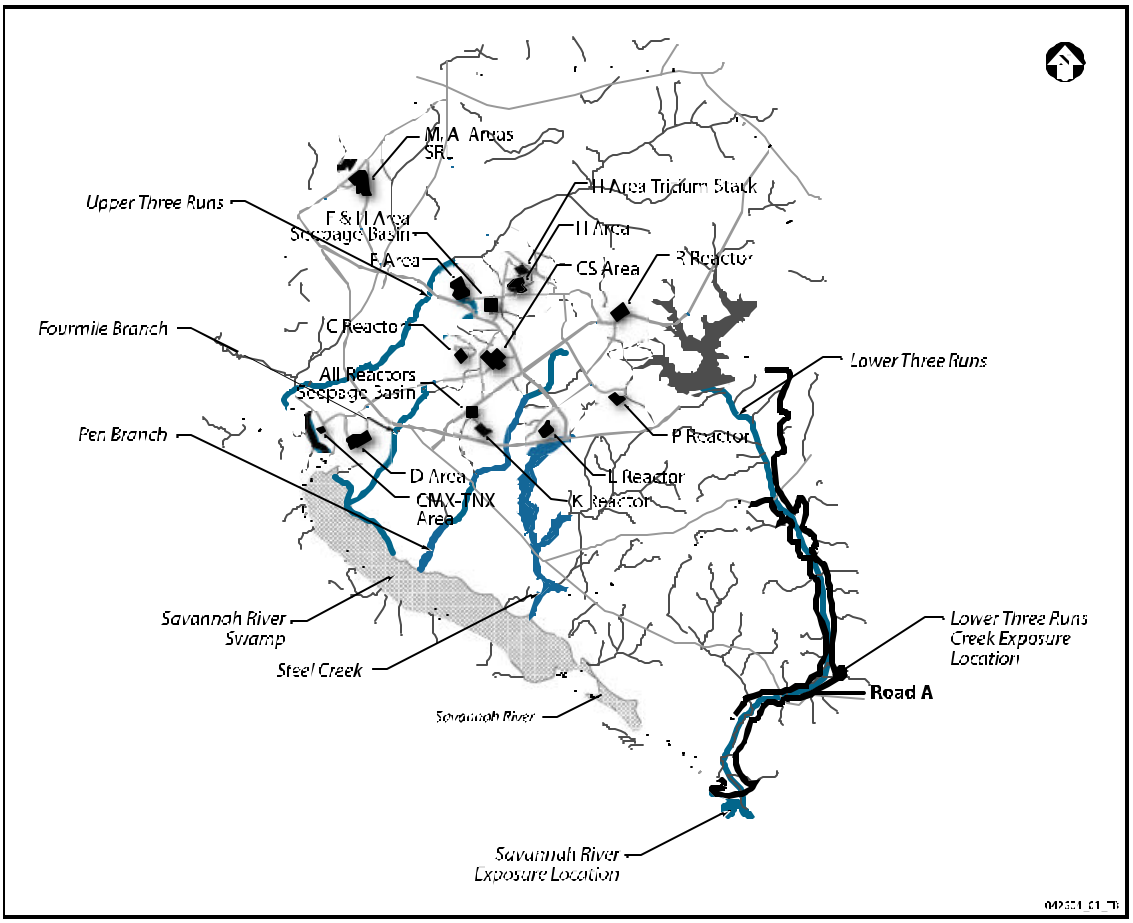

Figure 7-1 Major SRS Sources of Release to Surface Water

7.1.2 Sources of Release to SRS Surface Waters

Figure 7-1 depicts the major facilities releasing radionuclides to surface water bodies on the SRS site:

- 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 radionuclides discharged into seepage basins located in reactor and separations areas. Radionuclides released into seepage basins could leak to underlying sediments and then be carried by groundwater to onsite streams. Surface water releases of radionuclides were highest in the early to middle 1960s and decreased into the 1980s.

7.1.3 Migration of Radionuclides in SRS Surface Waters

As shown in Figure 7-1, there are five major onsite streams that received radionuclides from SRS facilities. Waters from Upper Three Runs Creek, Fourmile Branch, Pen Branch, and Steel Creek pass through a low-lying wetland area adjacent to the Savannah River and the SRS, the Savannah River Swamp, before they discharge into the Savannah River. Water from Lower Three Runs Creek does not pass through the swamp. Figure 7-1 also 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 these 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 7-1 illustrates some of the geographic features of the SRS that require consideration while deriving radionuclide concentrations for human contact from surface water. For example:

- Releases to surface water were channeled by way of drainage to one or more of the streams that flowed into the Savannah River. Because of this, radiation exposures could only occur in well-defined geographic locations – i.e., at accessible locations below site discharge points in the Savannah River or along Lower Three Runs Creek.
- Each stream flowing offsite contained the contribution of more than one SRS facility or Area.
- Much liquid effluent was discharged over the years to seepage basins rather than directly to onsite streams. A portion of the radionuclides was eliminated by radioactive decay, which was a major purpose of the seepage basins. Some portion of the volatile and gaseous radionuclides discharged into seepage basins entered the atmosphere, essentially becoming part of the air source term. A portion of the radionuclides in the seepage basins seeped into the soil and entered the groundwater system. Some of this material then seeped into surface streams, where their transportation characteristics were affected by other processes, such as sorption on sediments or migration.
- Some of the radionuclides discharged to onsite streams were not immediately transported to locations where the radionuclides could have been contacted by members of the public. (Except for Lower Three Runs Creek, it was assumed that contamination in SRS streams was not accessible by members of the public.) Streams containing radionuclides had to flow for several miles before being discharged to the Savannah River. Through this process many radionuclides may have been sorbed onto stream and swamp sediments, reducing the inventory eventually released offsite.
- All but one of the major onsite streams discharging radionuclides to the Savannah River passed through the Savannah River Swamp. Because of sedimentation processes characteristic of wetlands, radionuclides were likely deposited into swamp sediments. The swamp, however, historically flooded about 20% of the time. Flooding would tend to resuspend contaminated sediments and redissolve sorbed radionuclides; in this way radionuclides released at earlier times could increase radionuclide content in the Savannah River above that attributed to the site radionuclide releases during a given year.

7.1.4 Summary of Approaches to Estimating Concentrations

Because of these considerations, annual radionuclide concentrations in water at the two exposure locations specified by the Phase III scenarios were estimated by modeling performed outside the GENII computer code. These concentration estimates needed to reflect the complex processes governing radionuclide migration from the release facility to the exposure location; these processes include radioactive decay, surface water transport, sorption on sediments, groundwater transport, sorption on soil, and uptake by biota

Different approaches were used in developing concentration estimates for the Savannah River exposure location and the Lower Three Runs Creek exposure location, because the physical situations for release and transport to these exposure locations were different and the information available to make estimates was different.

As shown in Figure 7-2, the procedure for developing concentration estimates began with the initial, common starting point: those radionuclides identified in Phase II as important for estimating doses. However, as described in the following, different modeling approaches were used for concentration estimates in the Savannah River and those in Lower Three Runs Creek at Martin.

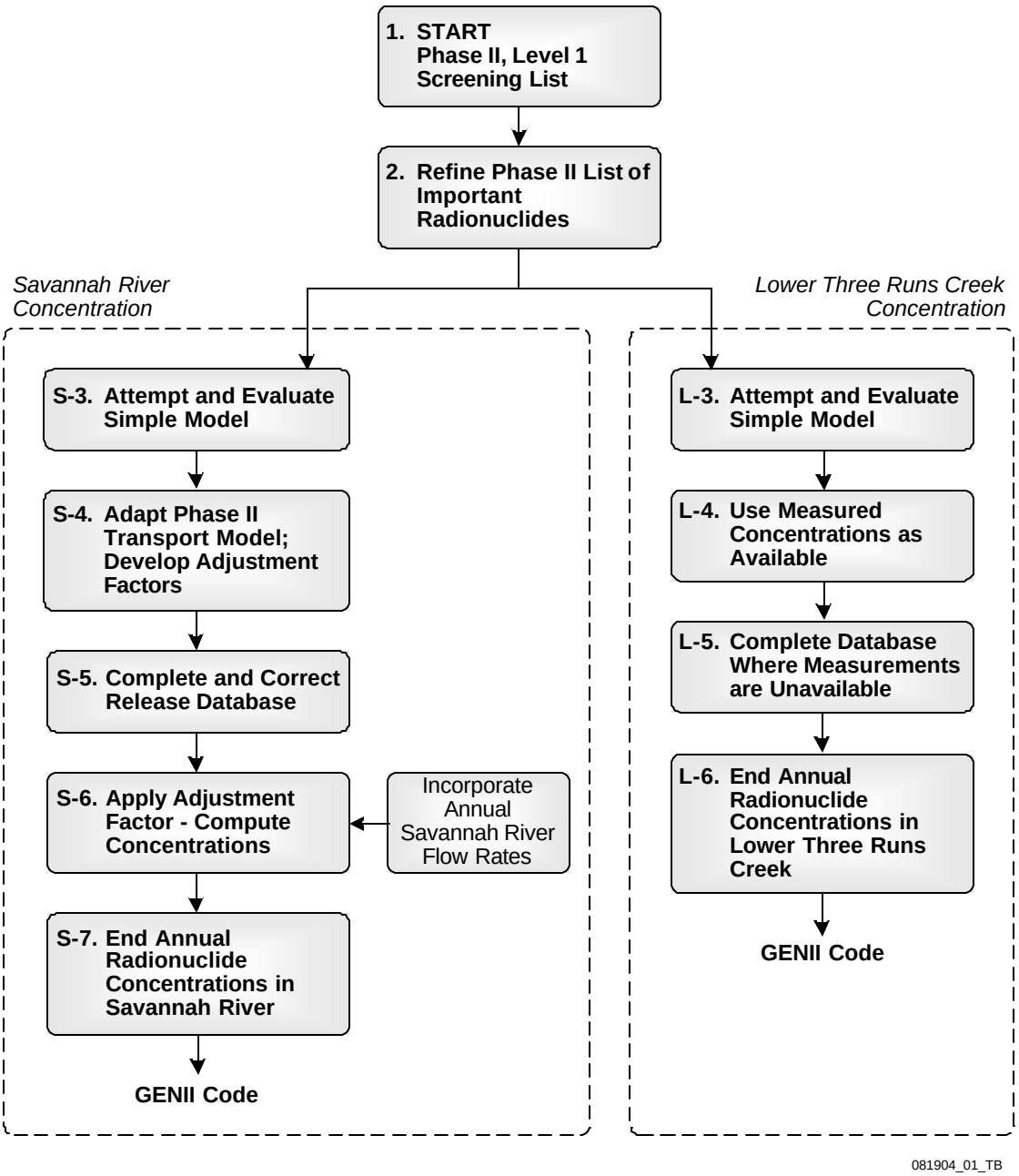

Figure 7-2 Approaches to Estimating Radionuclide Concentrations in Water at Exposure Locations

These procedural steps for developing the source term are briefly described in the following list. Then each subsection that follows discusses these steps in more detail.

Common Steps :

1. START: List of important radionuclides from Phase II, Level 1 screening analysis;
2. Refine list of radionuclides. Two isotopes of uranium were added to refine the treatment of health effects. Y-91 was deleted because it fell below the requirement for inclusion.

Savannah River Steps :

S-3. Attempt a simple model: estimate annual concentrations in the Savannah River by dividing annual release rate by the annual flow rate. This did not provide acceptable results when compared to measured concentrations in the river.

S-4. .Phase the II model; develop scaling factors for all radionuclides based on K_D. Phase II modeled radionuclide releases to the Savannah River for three important radionuclides based on several factors influencing transport from the point of release to the river. Adjustment factors were derived based on these modeled releases and tabulations of annual amounts of radionuclides released at the point-of-release. These adjustment factors were to be applied to each remaining radionuclide not modeled in Phase II, depending on its geochemical K_D.

S-5. Complete and correct the release data base; release data for some years not compiled in the Phase II report and files were supplied from other sources. Corrections for unidentified alpha emitters and unidentified beta-gamma emitters were added. Other minor anomalies were corrected.

S-6. Apply adjustment factors; the adjustment factors based on the Phase II modeling were used to estimate annual concentrations from the tabulated values of annual releases. In order to calculate concentrations, incorporate data on annual flow rates in the Savannah River.

S-7. END: Concentrations by year and radionuclide in the Savannah River.

Lower Three Runs Creek Steps:

L-3. START: Attempt a simple model; estimate annual concentrations in Lower Three Runs Creek by dividing annual release rate by the annual flow rate. This did not provide acceptable results when compared to measured concentrations in the river.

L-4. Use measured concentrations for three radionuclides, Cs-137, Sr-90, H-3; there were in adequate or no measurements for the remaining nuclides of interest;

L-5. Complete the concentration data base for Cs-137, Sr-90, and H-3, for instances where measured concentration data was unavailable.

L-6. END: Concentrations for Cs-137, Sr-90, and H-3 by year and radionuclide in Lower Three Runs Creek.

7.2 Identify Important Radionuclides Based on Phase II

Phase II of the SRS Dose Reconstruction Project identified the radionuclides that were released to the surface water from SRS, performed a screening assessment to identify a smaller group of radionuclides to be addressed in more detail, and estimated radionuclide quantities released into water over much of the time period of nuclear material production. This information was used as the starting point for estimating the water concentrations of radionuclides at the exposure locations of interest.

7.2.1 Phase II Screening Assessment

The Phase II screening assessment started with a master list of radionuclides that had been reported as released into surface water from SRS facilities. Preliminary estimates of their yearly average release rates were made for a 36-year period. A screening assessment was performed to identify a smaller list of key radionuclides that were the dominant contributors to radiation dose and cancer risk (Phase II). This screening assessment was performed using a two-step method recommended by the National Council on Radiation Protection and Measurements (NCRP).

The initial screening analysis conservatively assumed that all radionuclides were discharged into a single body of surface water with a fixed flow rate. Using the NCRP methodology referenced above, estimated 36-year average releases (representing 1954-1989), and an average dilution flow rate of 7.7 x 109 m^3/y of water, the total effective doses were estimated for each radionuclide. A total dose was estimated by summing the incremental doses from each radionuclide. A screening factor was computed for each radionuclide equal to the ratio of the incremental dose from each radionuclide to the total dose. Those radionuclides that contributed at least 0.1% to the screening factor were given further consideration in estimation of the source term. The radionuclides that Phase II identified as meeting this criterion were Cs-137, Co-60, H-3. I-131, P-32, Pu-238, Pu-239,240, Sr-89,90, S-35, Tc-99, uranium, Y-91, Zn-65, and Zr/Nb-95. A summary of the Level 1, Phase II screening results is presented in Table 7-1. A second, Level -2 screening, which ranked radionuclides according to their relative importance by exposure pathway, was also performed. Seven radionuclides identified in this fashion were: H-3, Cs-137, Sr-90, Co-60, P-32, I-131, and uranium.

Table 7-1 Radionuclides Identified as Significant in the Level 1 Screening Analysis in Phase II

Radionuclide	Percent of Total Screening Value
Ce-141,144*	0.91
Cs-134	0.52
Cs-137	75.23
Co-60	1.80
H-3	0.74
I-131	0.91
P-32	5.64
Pu-239,40*	0.48
Pu-238	0.21
Ru-103,106*	1.39
Sr-89,90*	9.35
S-35	0.68
Tc-99	0.13
Uranium*	0.57
Zn-65	0.68
Zr,Nb-95*	0.38
Total	**99.6**

*Ba,La-140 were screened as Ba-140; Ce-141,144 as Ce-144; Pu-239,40 as Pu-239; Ru-103,106 as Ru-106; Sb-124,125 as Sb-125; Sr-89,90 as Sr-90; uranium as U-235 and U-238; and Zr,Nb-95 as Zr-95.
Source: Phase II Rad-Screening.xls Excel spreadsheet (Phase II).

Note that although Y-91 was included as significant based on the Level 1 Phase II screening analysis, the numerical analysis in Phase II does not appear to support its inclusion based either on the Level 1 or Level 2 screening criteria; its screening value was only 0.0345% of the total screening value, which is below the 0.1% screening value criterion for Level 1 screening. Neither did it rank among the top three radionuclides for any exposure scenario considered in the Level 2 screening analysis.

7.2.2 Modify List of Radionuclides and Properties

As shown in Figure 7-2, the second generic step in defining the source term for liquid releases was to modify the list of radionuclides identified as important in Phase II. The initial list of important radionuclides resulting from the Phase II Level 1 screening analysis was modified in several ways:

1. Some groups of radionuclides were partitioned into separate isotopes. This was done to provide a more refined treatment of dose modeling. By treating isotopes individually, health effects coefficients specific to those isotopes could be used in the dose modeling. If isotopes were aggregated by element, as in the Phase II screening analyses, a single coefficient (related to the isotope with the greatest health effects) would characterize all the isotopes of the element, possibly greatly overestimating doses and risks. **Table 7-2** shows the 22 isotopes modeled for liquid releases in Phase III.

   a. Each member of the mother-daughter pair, Nb-95 and Zr-95, was modeled as a separate isotope to account for the slight differences in health effects.

   b. Cs-134 and Cs-137 were modeled as separate isotopes; furthermore the Level 1 screening value for Cs-134, 0.52%, exceeded the criterion for retention.

   c. Sr -89 and Sr-90 were modeled separately.

2. Because the releases of Ruthenium were relatively small, all releases were modeled as Ru-106.

3. I-129 was included for Phase III even though, like Y-91, its screening value did not meet the 0.1% criterion (its screening value was 0.06%). I-129 was included for three reasons: (a) it has similar chemical and physical properties as I-131, which was identified as a key radionuclide; (b) there were concerns about possible health effect after it concentrates in the thyroid; and (c) although the liquid release of I-129 is not as well monitored as I-131 (Kantelo 1993), its long half-life (~1.7x10+07 years) is orders of magnitude longer than that of I-131 (~8.04 days), thus making it much longer lasting in the environment. This long half-life could be a differential factor for some scenarios and exposure pathways.

4. One radionuclide, Pu-240 was dropped from consideration. The data upon which the Phase II estimates of releases were based did not list Pu-240 releases separately, but always combined with other isotopes. Furthermore, the health effects coefficients for Pu-239 and Pu-240 are very close, so modeling Pu-240 as Pu-239 will have little effect on the dose estimates. Since there appeared to be no basis and no motivation for differentiating these two isotopes, separate consideration of Pu-240 was dropped.

5. It was considered appropriate to include as releases radioactivity measured as unidentified alpha or unidentified beta-gamma activity. Although the SRS had recorded releases of such material over the years of site operation, an explicit treatment in Phase II was not apparent. Therefore two additional categories were added for these types of releases. However, to provide bounding estimates of their health effects, the unidentified alpha activity was added to the releases for Pu-239 and the unidentified beta-gamma activity was added to the releases for Sr-90. These two classes are indicated in **Table 7-2** to indicate that these activities were compiled and tracked separately.

Table 7-2 Modified List of Radionuclides Considered for Water Concentrations in Phase III

Ce-144	Ru-106
Cs-134	Sr-89[b]
Cs-137	Sr-90[‡b]
Co-60	S-35
H-3	Tc-99
I-129	U-234
I-131	U-235[c]
Nb-95[a]	U-236
P-32	U-238[c]
Pu-238	Zn-65
Pu-239[†]	Zr-95[a]

[†]Unidentified alpha-emitters were modeled as Pu-239
[‡]Unidentified beta-gamma emitters were modeled as Sr-90
[a, b, c] These radionuclides were paired in the Phase II, Level 1 screening analysis.
Note: Underlined radionuclides were added.

The general approach for partitioning aggregate quantities of radionuclides is summarized in Table 7-3. (See Appendix C for details.) Unlike the analysis of releases to air, there was no need to refine the treatment of certain radionuclides by defining their chemical form; this is because all radionuclides were either dissolved or suspended in water, which dominated the chemistry. For example, tritium would be present as tritiated water.

Table 7-3 Partitioning Assumptions for Radionuclides Released to Surface Water

Constituent	SRS Area	Isotopic Distribution by Activity
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
Nb,Zr-95	All areas	65% Nb-95; 35% Zr-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	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

7.3 Modeling Releases and Concentrations for the Savannah River

7.3.1 A Simple Model (Step S-3)

As a first step in estimating radionuclide concentrations in the Savannah River, a simple model based on conservation of mass was evaluated (Step 3 in Figure 7-2). Recall that the point of interest on the Savannah River was located below the confluence with Lower Three Runs Creek; actually, the point of interest is very close to the USGS flow monitoring station at river mile 120 (RM-118.8 in later years) at highway 301 (also designated in various SRS reports as station 10A or R-10). Because the location of interest is downriver from the points where site streams drain into the Savannah River, one can reasonably assume that all liquid releases exiting the site boundary must pass through this point. Since the river flow is measured very close to this point, one can construct a simple mathematical model based on conservation of mass for the average radionuclide concentration at this location:

$$C_{ij} = R_{ij}/Q_j \qquad (7\text{-}1)$$

Where,

C_{ij} is the concentration of radionuclide i in year j (Bq/m^3);
R_{ij} is the quantity of radionuclide i released from the SRS to water in year j (Bq/y);
Q_j is the flow rate of water past the location for year j (m^3/y)

However, as described in Section 7.1.3, the migration of radionuclides from their point of release on the SRS to this location of interest in the Savannah River is not direct or simple. Nevertheless, to test a simple approximation, the quantities of radionuclides released from the facility were assumed to be equal to the quantities ending up in the river, for any given year. Figure 7-3 and Figure 7-4 compare radionuclide concentrations computed according to this simple model to measured concentrations at this location. Comparisons are shown for tritium in Figure 7-3 and cesium-137 in Figure 7-4. Measured concentrations at this location were not apparent for years prior to 1960. Two different estimates of flow rate were used to compute the calculated concentrations. In one case the "USGS Actual Flow Rate" was used for each year of the calculation, in full accord with equation (7-1). In the other case, the "39-year Average Flow Rate" was used; i.e., the flow rate was a fixed value (9.49 billion cubic meters) for all years. Note that the measured and calculated concentrations do not agree very well. For tritium, measured values in early years are higher than calculated values; in later years, the peaks and dips do not correspond in time very well. For cesium, early measured values are higher than calculated concentrations, but in middle years calculated values are higher than measured values.

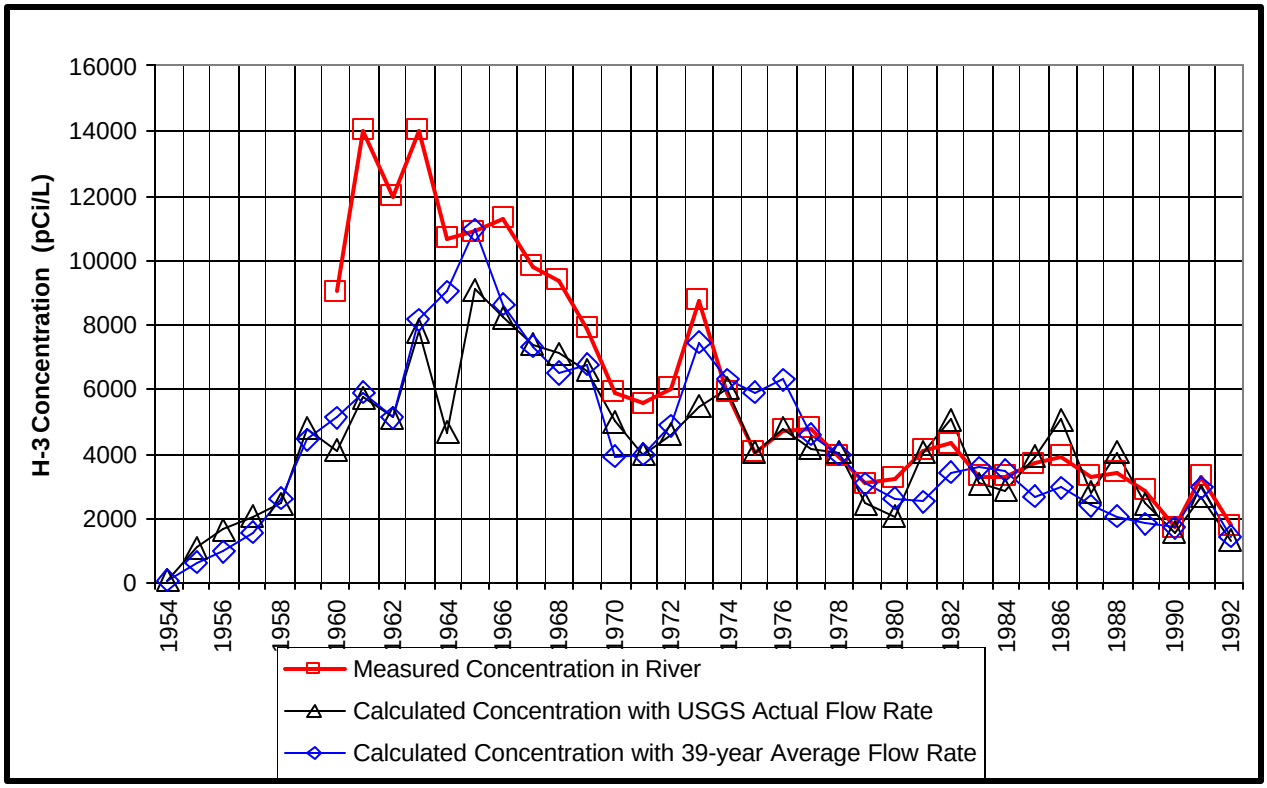

Figure 7-3 H-3 Concentration in Savannah River (pCi/L)

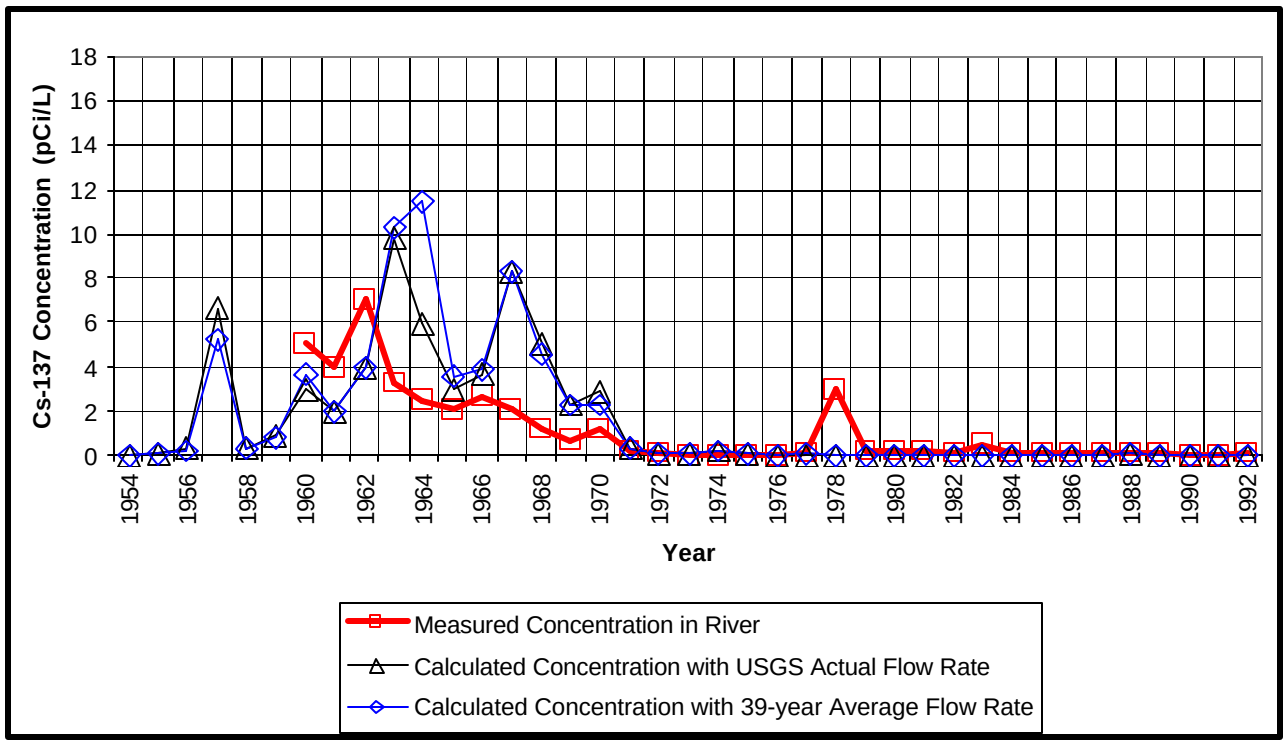

Figure 7-4 Cs-137 Concentration in Savannah River Water (pCi/L)

Because of this lack of agreement with measured concentrations, use of this simple modeling approach was abandoned. However, this presented the problem of exactly how this necessary input for the dose reconstruction (i.e., radionuclide concentrations in the Savannah River) would be obtained. Although there were measured concentrations for a few radionuclides (H-3, Cs-137, I-131, Sr-90, and others), this was not a suitable solution because:

- The goal of the dose reconstruction was to represent doses from the set of 22 radionuclides selected (**Table 7-2**) and there were no measured values for most of these;
- The measured concentrations were frequently near detection limits for the instruments used, so the accuracy of the measurements was questionable; in some cases, the detection limit (or half the detection limit) was listed as the measured value;
- Consistent measurements of concentrations were not available during some of the important early years of site operation, when releases were known to be large;
- The estimates of average annual measured concentrations were based on periodic samples that were subject to substantial uncertainties:
  - the possibility that major releases were not effectively or consistently sampled and
  - the possibility that the turbulent, unsteady flow in the river steered contaminated water toward or away from the sampling locations.

7.3.2 Adapt the Phase II Water Transport Model for Savannah River Concentrations (Step S-4)

In order to overcome the difficulties encountered with a simple model of radionuclide concentrations in the Savannah River, the model developed in Phase II for a few radionuclides was adapted and extended for Phase III. This is shown as Step 4 in Figure 7-2.

7.3.2.1 Phase II Water Transport Model

Section 7.1.3 of this report and Chapter 5 of Phase II discuss why 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. Chapter 5 of the Phase II report describes how a relatively simple model was used to estimate the release to the Savannah River of H-3, Sr-90, and Cs-137, based on concentrations of these constituents measured at the sampling stations along Road A, the sampling point closest to the river (Phase II). 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:

1. Transport of radionuclides through surface water as dissolved and suspended constituents.
2. Release of previously retained radionuclides by periodic flooding of the Savannah River Swamp.
3. 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, many of the radionuclide measurement uncertainties, when incorporated into the Phase II model, increased the modeled quantities discharged to the Savannah River.

The SRS Swamp was observed to flood about 20% of the time (74 days per year on the average) from 1958 to 1967. It was assumed that additional releases to the Savannah River from the swamp occurred when there was flooding. This uncertainty was considered a source of bias that increased releases of radionuclides such as cesium and strontium that were retained in the swamp. For most years, releases were increased for cesium and strontium by 20% (with a range of 10%-30%). For years with very high rainfall amounts like 1964 and 1971, a value of 40% (with a range of 25%- 60%) was assumed. For years with low rainfall, it was assumed that the swamp flooded only about 10% of the time (with a range of 5%-15%) (Phase II). (Detailed records existed for annual rainfall) (Reference).

Uncertainties associated with the release estimates were considered to originate from analytical errors in measurement of flow and in sampling and analysis of radionuclide concentrations in the water. Because tritium was not impacted heavily by flow through the SRS 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 Site and the USGS (Phase II). Estimates of error for the routine concentration measurements varied with the radionuclide, the sample preparation and with the counting procedure (Phase II).

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

7.3.2.2 Adaptation of Phase II Model for Savannah River Concentrations

A mathematical model of the transport of individual radionuclides to the Savannah River, similar to that used in Phase II, would require significant resources 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. Because each chemical species has unique aqueous transport properties, developing a model that would accommodate the variations in chemical-physical transport was beyond the scope of Phase III.

However, Phase II had modeled the quantities of three specific radionuclides (H-3, Sr-90, Cs-137) released into the Savannah River, taking into account the complex phenomena and issues governing their migration. The release quantities estimated by the Phase II model are different from the facility releases (point of release quantities) compiled in Phase II and in the SRS historical data. These differences represent the effect of the phenomena causing radionuclide decay, storage, and release, during migration in site streams, from seepage basins, and through the Savannah River swamp and measurement uncertainty. A quantitative measure representing these phenomena is just the ratio of the modeled release activity to the facility release activity:

$$F_{jk} = R_{Mjk}/R_{Fjk} \qquad (7\text{-}2)$$

Where,

F_{jk} is the factor representing the effects of radionuclide migration for year j and modeled radionuclide k;
R_{Mjk} is the modeled release of radionuclide k for year j;
R_{Fjk} is the facility release of radionuclide k for year j tabulated from site data.

Note that the index "k" is used to denote the radionuclide here, rather than the index "i" used in equation (7-1), because "k" refers only to one of the three radionuclides (H-3, Sr-90, Cs-137) modeled in Phase II, while "i" refers to any radionuclide.

The fundamental assumption made to extend these results of Phase II modeling to the analysis in Phase III is that the distribution coefficient (K_D – a measure of the degree to which a particular radionuclide is sorbed to soil, sediment, and some biota) of a radionuclide would be the primary factor affecting the influence of the site, as represented by the factor, F_{jk}. Using this assumption, one could extend the modeling of the three radionuclides performed in Phase II to the entire suite of radionuclides modeled in Phase III. As will be described in more detail, this extension was based on three categories of K_D into which the Phase III radionuclides were binned. A more precise rendering was not considered warranted given the extent of other uncertainties.

As stated in Section 7.3.2.1, other factors incorporated into the Phase II model were periodic flooding of the Savannah River swamp and uncertainties in measuring the quantities of released radionuclides. Clearly, K_D does not encompass these factors. However, the factors representing river flooding were tied to precipitation records and were adjusted from year to year; similarly, the factors representing measurement uncertainty were adjusted annually, with larger uncertainties in earlier years. Thus, the annual variations in the factor defined by equation (7-2) should incorporate these other facets of the Phase II model. However, some of the uncertainties related to measuring tritium in environmental samples are unique to tritium. This may mean that factors developed for tritium, if applied to other radionuclides, may overestimate the degree of measurement uncertainty.

A complication in applying equation (7-2) is that RMjk, the modeled release of radionuclide k for year j, is a random variable, not a single value, because the model used in Phase II was probabilistic. However, the median value of the distribution was chosen as a measure of the central tendency of these quantities.

The remaining steps needed to estimate releases of any radionuclide of interest to the Savannah River, based on the factors defined by equation (7-2) are:

1. Determine the annual radionuclide water releases for each radionuclide from SRS facilities, for the three modeled radionuclides, R_{Fjk}, and for all other radionuclides, RFij ;
2. Compute the ratios, F_{jk}, indicated by equation (7-2);
3. Bin the radionuclides by K_D group;
4. Apply the ratios for each group of radionuclides to annual releases from facilities, thereby obtaining adjusted annual releases by radionuclide. However, the release data base needed to be completed and corrected before applying the adjustment factors (discussed in Section 7.3.3), so this aspect is discussed in Section 7.3.4.

7.3.2.2.1 Annual Radionuclide Release at Points of Release

The principal reference used to develop the annual radionuclide point-of-release data files, (i.e. files containing R_{Fjk}, the facility release of radionuclide k for year j tabulated from site data) was Cummins et al (Cummins 1991a). 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 three categories:

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

Although the total release to site streams could 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. There appear to be at least two reasons for this choice:

> (A) 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
>
> (B) the sum of Categories 1 and 3 should be a conservative estimate of liquid releases to site streams.

Exceptions are H-3 and I-131, where only direct releases to streams (Category 1) were considered for the screening assessment.

For these reasons, the annual sums of releases from Categories 1 and 3 were chosen as representative of SRS releases to site streams. This meant that tritium evaporated from seepage and containment basins was excluded from the point-of-release data file created for tritium. Evaporated tritium was included in the Phase III atmospheric releases (Chapter 5). It also meant that the estimated Cs-137 desorption from the Four Mile Creek bed that was reported by Cummins et al (Cummins 1991a) 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. Including these desorption estimates would have caused double counting.

7.3.2.2.2 Adjustment Factor Development

Adjustment factors were calculated according to equation (7-2) by dividing the median values of radionuclide release computed by the Phase II release model for each of three modeled radionuclides by the radionuclide releases for these radionuclides from all facilities. These modeled and tabulated releases are listed in Table 7-4. The resultant adjustment factors are listed in Table 7-5.

Table 7-4 Tabulated Releases from Facilities and Median Value of Modeled Releases Used for Adjustment Factors (Ci)

	Tabulated Releases from Facilities			Median Value of Modeled Releases		
Year	**H-3**	**Cs-137**	**Sr-90**	**H-3**	**Cs-137**	**Sr-90**
1954	$3.66x10^{+02}$	$1.80x10^{-01}$	$3.90x10^{-02}$	$7.64x10^{+03}$	$1.41x10^{-01}$	$4.13x10^{-02}$
1955	$5.87x10^{+03}$	$1.37x10^{0}$	$8.16x10^{-01}$	$1.32x10^{+04}$	$2.65x10^{-01}$	$1.45x10^{-01}$
1956	$9.39x10^{+03}$	$3.43\ x10^{0}$	$1.04x10^{+01}$	$1.50x10^{+04}$	$1.11\ x10^{0}$	$3.60x10^{-01}$
1957	$2.24x10^{+04}$	$8.40x10^{+02}$	$1.96x10^{+02}$	$2.16x10^{+04}$	$1.16\ x10^{0}$	$1.54\ x10^{0}$
1958	$2.88x10^{+04}$	$1.04x10^{+02}$	$1.58x10^{+01}$	$2.88x10^{+04}$	$9.51\ x10^{0}$	$8.30x10^{-01}$
1959	$5.17x10^{+04}$	$4.14x10^{+01}$	$2.18x10^{+01}$	$6.29x10^{+04}$	$3.59\ x10^{0}$	$1.80\ x10^{0}$
1960	$6.09x10^{+04}$	$4.36x10^{+01}$	$2.36x10^{+01}$	$6.98x10^{+04}$	$7.60\ x10^{0}$	$1.76x10^{+01}$
1961	$8.11x10^{+04}$	$4.06x10^{+01}$	$9.85\ x10^{0}$	$8.28x10^{+04}$	$1.03x10^{+01}$	$4.22\ x10^{0}$
1962	$7.23x10^{+04}$	$1.03x10^{+02}$	$1.04x10^{+01}$	$6.47x10^{+04}$	$1.92x10^{+01}$	$6.78\ x10^{0}$
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	$1.28x10^{+05}$	$5.56x10^{+01}$	$1.17x10^{+01}$	$1.06x10^{+05}$	$2.35x10^{+01}$	$5.22\ x10^{0}$
1966	$1.33x10^{+05}$	$5.36x10^{+01}$	$6.12\ x10^{0}$	$9.56x10^{+04}$	$2.72x10^{+01}$	$4.46\ x10^{0}$
1967	$1.04x10^{+05}$	$6.87x10^{+01}$	$6.72\ x10^{0}$	$8.75x10^{+04}$	$3.80x10^{+01}$	$4.82\ x10^{0}$
1968	$1.07x10^{+05}$	$7.08x10^{+01}$	$9.19\ x10^{0}$	$8.39x10^{+04}$	$2.08x10^{+01}$	$5.46\ x10^{0}$
1969	$7.88x10^{+04}$	$5.14x10^{+01}$	$1.02x10^{+01}$	$7.64x10^{+04}$	$1.04x10^{+01}$	$3.58\ x10^{0}$
1970	$6.61x10^{+04}$	$4.43x10^{+01}$	$7.26\ x10^{0}$	$4.25x10^{+04}$	$1.02x10^{+01}$	$3.89\ x10^{0}$
1971	$4.47x10^{+04}$	$1.05x10^{+01}$	$3.14\ x10^{0}$	$4.44x10^{+04}$	$1.69\ x10^{0}$	$3.81\ x10^{0}$
1972	$6.09x10^{+04}$	$9.14\ x10^{0}$	$1.25\ x10^{0}$	$4.68x10^{+04}$	$6.28x10^{-01}$	$1.92\ x10^{0}$
1973	$8.69x10^{+04}$	$7.48\ x10^{0}$	$9.01x10^{-01}$	$6.10x10^{+04}$	$4.44x10^{-01}$	$2.07\ x10^{0}$
1974	$5.61x10^{+04}$	$8.09\ x10^{0}$	$4.27x10^{-01}$	$5.41x10^{+04}$	$7.01x10^{-01}$	$1.72\ x10^{0}$
1975	$5.15x10^{+04}$	$7.75\ x10^{0}$	$9.12x10^{-01}$	$4.93x10^{+04}$	$3.61x10^{-01}$	$1.46\ x10^{0}$
1976	$7.32x10^{+04}$	$8.94\ x10^{0}$	$4.76x10^{-01}$	$4.64x10^{+04}$	$1.46x10^{-01}$	$1.18\ x10^{0}$
1977	$4.59x10^{+04}$	$6.58\ x10^{0}$	$5.55x10^{-01}$	$4.03x10^{+04}$	$2.45x10^{-01}$	$9.04x10^{-01}$
1978	$3.76x10^{+04}$	$1.04x10^{+01}$	$2.06\ x10^{0}$	$3.55x10^{+04}$	$1.04x10^{-01}$	$6.20x10^{-01}$
1979	$4.52x10^{+04}$	$6.27\ x10^{0}$	$2.68\ x10^{0}$	$2.84x10^{+04}$	$1.04x10^{-01}$	$6.24x10^{-01}$
1980	$3.54x10^{+04}$	$1.83\ x10^{0}$	$1.55x10^{-01}$	$3.00x10^{+04}$	$7.72x10^{-02}$	$5.05x10^{-01}$
1981	$3.94x10^{+04}$	$2.81\ x10^{0}$	$1.04\ x10^{0}$	$2.51x10^{+04}$	$1.16x10^{-01}$	$4.61x10^{-01}$
1982	$3.15x10^{+04}$	$2.85\ x10^{0}$	$6.98x10^{-01}$	$3.08x10^{+04}$	$8.36x10^{-02}$	$3.95x10^{-01}$
1983	$4.06x10^{+04}$	$3.43\ x10^{0}$	$2.35x10^{-01}$	$3.24x10^{+04}$	$7.74x10^{-02}$	$3.84x10^{-01}$
1984	$3.58x10^{+04}$	$6.13\ x10^{0}$	$9.44x10^{-02}$	$3.23x10^{+04}$	$1.22x10^{-01}$	$4.25x10^{-01}$
1985	$3.40x10^{+04}$	$6.23\ x10^{0}$	$1.70x10^{-01}$	$2.21x10^{+04}$	$5.14x10^{-02}$	$2.25x10^{-01}$
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	$1.44x10^{+04}$	$6.39\ x10^{0}$	$4.40x10^{-02}$	$1.82x10^{+04}$	$2.92x10^{-01}$	$2.63x10^{-01}$
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 7-5 Adjustment Factors by Radionuclide Group and Year

Year	Group 1 H-3	Group 2 Sr-90	Group 3 Cs-137	Year	Group 1 H-3	Group 2 Sr-90	Group 3 Cs-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.

Note that the adjustment factor initially calculated for tritium in year 1954 was 20.8814, which is three 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 Phase II, 17,530 curies of tritium from D-Area was assumed to be released surface waters in 1954 (Phase II). This D-Area release, however, is not documented in Cummins et al (Cummins 1991a). For Phase III, it was reasoned that if tritium release from D-Area were the only reason for such a large adjustment factor in 1954, the other radionuclides in this group (i.e. I-129,130, Tc-99, and S-35) should not be similarly adjusted lest the true releases of these radionuclides be significantly overestimated. 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 (Cummins 1991a) does not show iodine, technetium, and sulfur being 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.

7.3.2.2.3 Binning Radionuclides by Distribution Coefficient, K_D

As stated above, the adjustment factors developed in the previous section are to be applied according to the geochemical characteristics of the released radionuclides as indicated by the distribution coefficient. 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 will be 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 is expected to depend on this retardation phenomenon and the radiological half-life of the radionuclide.

The K_D values of the radionuclides considered in this analysis span many orders of magnitude. However, to simplify the analysis, the radionuclides have been divided into only three groups:

(1) $K_D \leq 10$
(2) $10 = K_D = 1000$
(3) $K_D > 1000$

These groups correspond to the nominal K_D values used in the Phase II modeling of water releases: 0, 100, and 10,000, respectively for H-3, Sr-90, and Cs-137. All radionuclides analyzed in Phase III were assigned to a particular group and were assigned the same annual adjustment factor calculated for that group. The group assigned to each radionuclide is stated in Table 7-6. Table 7-6 also provides the K_D value(s) used to determine the group assigned to each radionuclide. Note that the "Adjustment Factor Group" in the last column in Table 7-6 corresponds to the index "k" in equation (7-2).

Table 7-6 Grouping of Radionuclides According to K_D Values

Radionuclide	Soil-to-Water Distribution Coefficient, K_D			Adjustment Factor Group
	Phase II Value	Soil Value*	Swamp Value†	
H-3	**0**	0		H-3
I-129, 131		1.55		H-3
Tc-99		2.49		H-3
S-35		7.5		H-3
Ru-103, 106		55		Sr-90
Co-60		60		Sr-90
Sr-89, 90	**100**	3040	1676	Sr-90
Nb-95		160		Sr-90
P-32		173		Sr-90
Zn-65		200		Sr-90
Ce-141, 144		490	255	Sr-90
Zr-95		600		Sr-90
U		1000	170	Sr-90
Pu		4100		Cs-137
Cs-134, 137	**10,000**	59		Cs-137

*Source: Kaplan et al., 2003.
†Source: Kaplan and Serkiz, 2000.

It should be noted that the K_D's used in Phase II are orders of magnitude different from those reported in recent SRS literature (Kaplan, 2003). In the Phase II modeling, a range of K_D's having a median value of 10,000 were used for Cs, whereas the range of values used for Sr had a median value of 100. Median K_D's reported by Kaplan et al for agricultural soils are 59 for Cs and 3041 for Sr (Kaplan 2003). Another report by Kaplan gives a K_D value of 1676 for Sr-90 in the swampy soils (Kaplan and Serkiz, 2000).

7.3.3 Completion and Correction of the Release Data Base (Step S-5)

The data base describing liquid releases from various SRS facilities was compiled in electronic format largely from SRS tabulations (Cummins, 1991a). This initial set of data was completed and corrected as follows:

1. Data for releases in the years 1990-1992 were added by examining the appropriate Site Environmental Reports (Cummins, 1990; Cummins, 1991b; Arnett, 1992; Arnett, 1993).

2. Releases categorized as unidentified beta-gamma activity were added to the Sr-90 releases on an annual basis.

3. Releases categorized as unidentified alpha activity were added to the Pu-239 releases on an annual basis.

4. Releases of I-131 (half-life of 8.04 days) into seepage basins were not included because it was assumed the activity would substantially decay before the iodine could migrate from the seepage basins to the surface streams; i.e., for I-131 only category 1 releases were included.

5. The Phase II report and SRS reports indicate a total release of 3 Ci of I-129 for the period from 1955-89. This 3 Ci release was apportioned evenly over these years, since no more defined information was available. As with other radionuclides, releases for 1990-1992 were obtained from SRS Environmental Reports.

6. Conflicting values for releases of Sr-90 from the L-reactor were obtained from the Cummins report for 1989, depending upon whether radionuclides were summed by facility or radionuclide indexes. What appear to be two spurious entries for Sr-90 releases from the L-reactor in 1989 were not included.

7.3.4 Apply Adjustment Factors and Compute Concentrations for Savannah River (Step S-6)

The completion and correction of facility release data described in the preceding section resulted in a tabulation of the quantity of contaminants released by year and radionuclide for the 22 radionuclides listed in **Table 7-2**. These corrected facility release quantities are used to derive the estimated releases by year and radionuclide to the Savannah River, as follows:

$$R^{R}_{ij} = R^{CF}_{ij} \cdot F_{jk} \qquad (7\text{-}3)$$

Where,

R^{R}_{ij} is the release to the Savannah River of radionuclide i and year j;
R^{CF}_{ij} is the Corrected Facility releases of radionuclide i and year j estimated according to the procedure in Section 7.3.3
F_{jk} is the adjustment factor computed according to equation (7-2).

Note that the correction factor, F_{jk}, depends upon the both the year j and the radionuclide group k; for each radionuclide i the correction factor group is indicated in Table 7-6. When the radionuclide release being adjusted in equation (7-3) was one of those modeled in Phase II (i.e., Cs-137, Sr-90, or H-3), the computed release to the river, R^R_{ij}, is just the modeled release from Phase II for each year. However, this is not entirely the case for Sr-90. Because the corrected facility release for Sr-90 included unidentified beta-gamma activity, the computed releases to the river, R^R_{ij}, is higher than the releases modeled in Phase II.

Figure 7-5 shows the yearly activity estimated by the procedure described above for release of tritium to the Savannah River from the SRS. This graph is consistent with the median (50th percentile) of the Phase II model discussed in Section 7.2.3 Releases rise to a peak in 1964 and then decrease. Figure 7-6 shows the yearly activity estimated in Phase III for release of Cs-137 and Sr-90 to surface water on the SRS site. Somewhat like tritium, releases of Cs-137 rise to a rough peak in 1964, and then decrease, although a second, smaller peak is seen in 1967. The large peak for Sr-90 in 1967 reflects the release into the K-Area containment basin of over 100 curies of unidentified beta-gamma activity during that year.

Once the radionuclide releases to the Savannah River have been obtained by the procedure described above, the concentrations of the radionuclides in the river can be easily computed by a variant of equation (7-1):

$$C_{ij} = R^R_{ij}/Q_j \qquad (7\text{-}4)$$

These concentrations were computed in this fashion, tabulated in a spreadsheet, and input to the GENII code. Concentrations in the Savannah River for various radionuclides computed in the manner described above are shown in Figure 7-7. Note the peaks in activity seen for P-32, Cs-137, and Sr-90 in the years 1966 and 1967. Chapter 11 discusses how the peaks caused high doses in receptors exposed to the contaminants released to the water through fish ingestion.

In order to compute the concentrations indicated in equation (7-4) the annual flow rates, Q_j, for the Savannah River were required. Annual flow rates for the Savannah River were derived in two ways:

1. For the years 1954 through 1969 and for the years 1983 through 1992, flow rates for the Savannah River as measured at Burtons Ferry Bridge (Highway 301) near Millhaven, Georgia, were obtained from the USGS [USGS 2003c]. This monitoring station is located about 500 feet downstream of the bridge on U.S. Highway 301 linking Screven County, GA, with Allendale County, SC. Hence, it is downstream of all surface water discharge points into the Savannah River from SRS.

2. No information was available from USGS for this monitoring station for the years 1970 through 1982. For these years, flow rates were projected from flow rates measured at Augusta, GA. The projected flow rates were derived using a relationship from [Hayes & Marter]. This reference reports a strong linear relationship (r = 0.98) between the flows at the Burtons Ferry Bridge and Augusta monitoring stations: $Flow_{BFB} = 1.15\ Flow_{AUG} + 202$.

The flow rates derived for this report are listed in Table 7-7 in units of cubic feet per second (cfs). Table 7-7 also presents the Savannah River volumes (liters) calculated for Phase III assuming 365 days per year (except for 366 days per year every leap year).

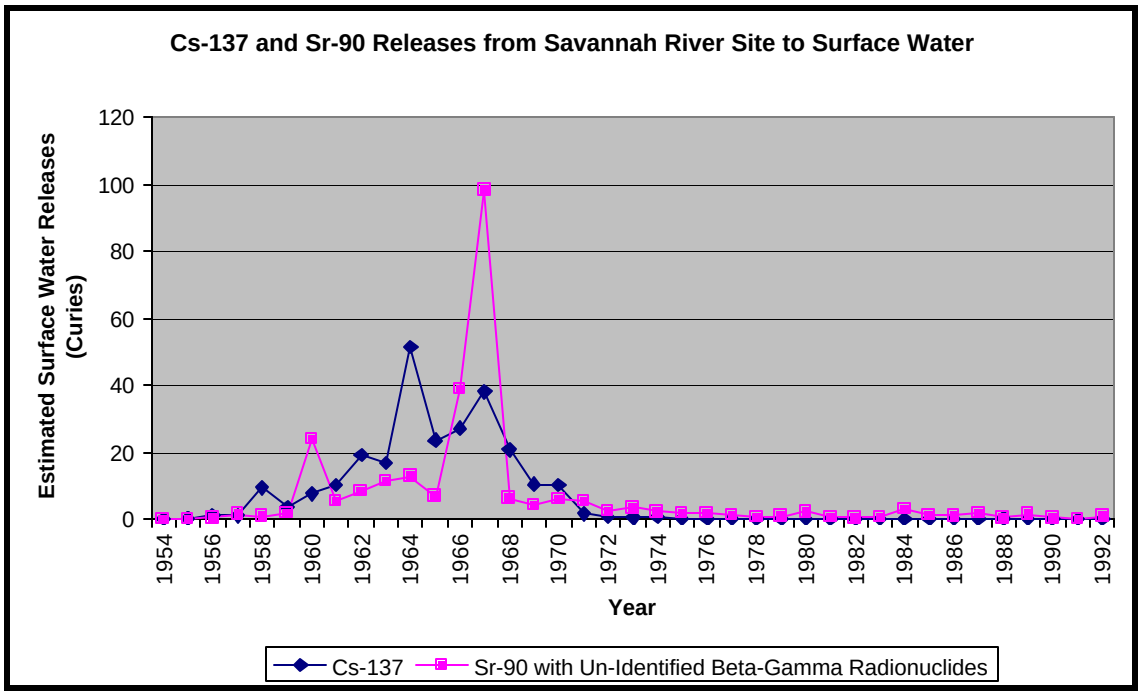

Figure 7-5 Tritium Release to Savannah River (Ci/y)

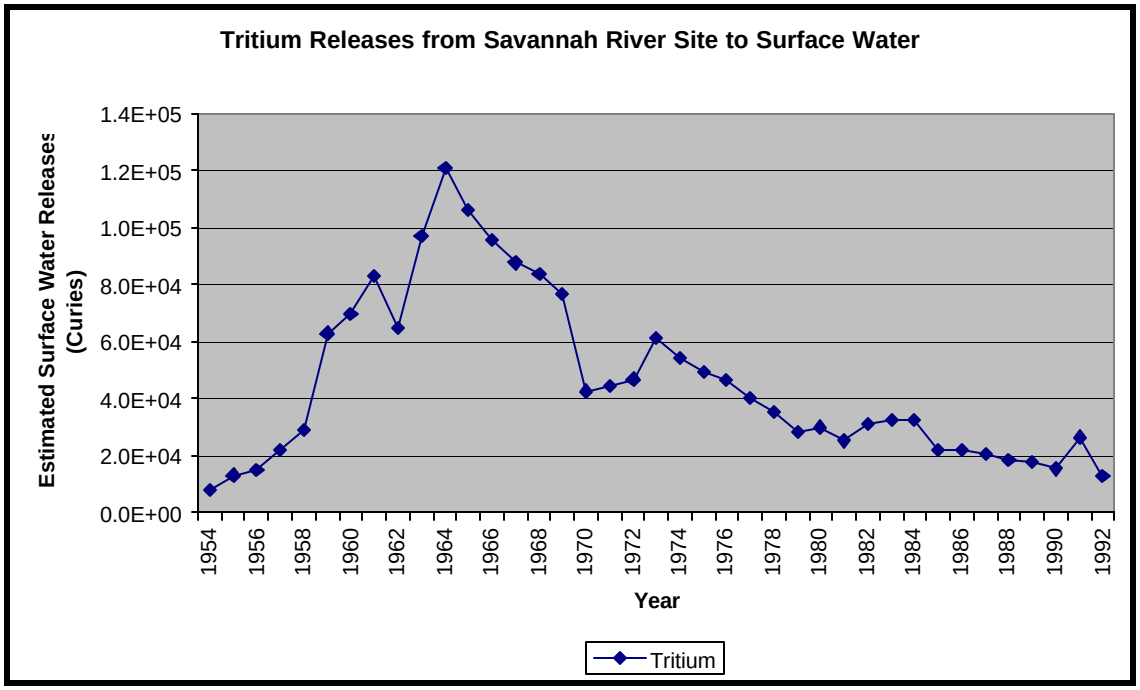

Figure 7-6 Cesium-137 and Strontium-90 Release to Savannah River (Ci/y)

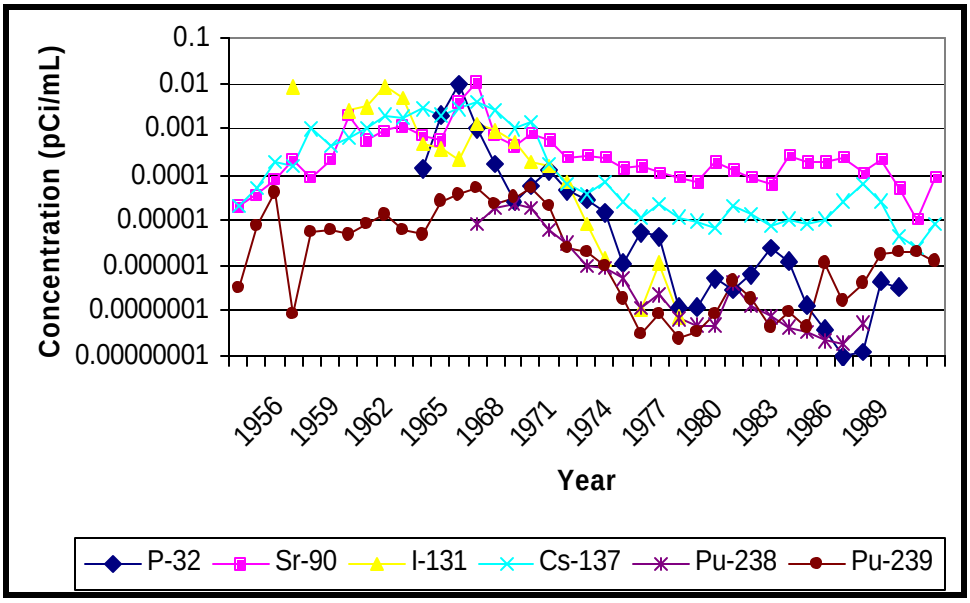

Figure 7-7 Estimated Concentrations of Selected Radionuclides in Savannah River (pCi/mL

Table 7-7 Savannah River Flow Rates and Annual Volumes as Determined for Burtons Ferry Bridge (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

7.3.5 Comparison of Phase II Release Estimates and Phase III Source Terms

Because the estimates for concentrations in the Savannah River were based on water releases from the entire SRS, a comparison of the Phase II and Phase III bases is discussed here. The data used as input to Phase III of the SRS Dose Reconstruction Project were checked as part of a Quality Assurance Program. However, to assure appropriate agreement between the Phase II and Phase III analyses, the total releases for all significant radionuclides were compared.

7.3.5.1 Comparison of Phase II Modeled Release s to SRS Point-of-Release Data

For H-3, Sr-90, and Cs-137, the annual medians (50th percentile) of the Phase II Savannah River release model are compared with the annual point-of-release estimates for these radionuclides as compiled from Category 1 and 3 releases documented in Cummins 1991a. The results of this comparison are summarized in Table 7-8.

Table 7-8 Comparison of Phase II Median Releases to Savannah River with SRS Point-of-Release

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

*This ratio does not include 1954 estimates for H-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 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 7.4.6. The Phase II report stated that releases were adjusted if it was believed that reported releases were too low. This extremely high ratio is probably a reflection of such an adjustment, since reporting of releases in the early years of operations was not as accurate as in later years.

The ratios as a function of time are presented in Figure 7-8. Note that the ratios are dramatically higher during the last years of operations. The late years may reflect that operational releases from facilities in general were reduced, but there were still releases of residual radioactivity from the site. In particular the releases for Sr-90 were elevated because unidentified beta-gamma activity was added to the Sr-90 inventory. Note that the variations in time are significant. This is due, in part, to the model that increased releases in years with large spring floods to account for the remobilization of radionuclides stored in previous years in the sediments and biota of the swamp. For these reasons, annual adjustment factors were used for Phase III rather than an average adjustment factor covering all years.

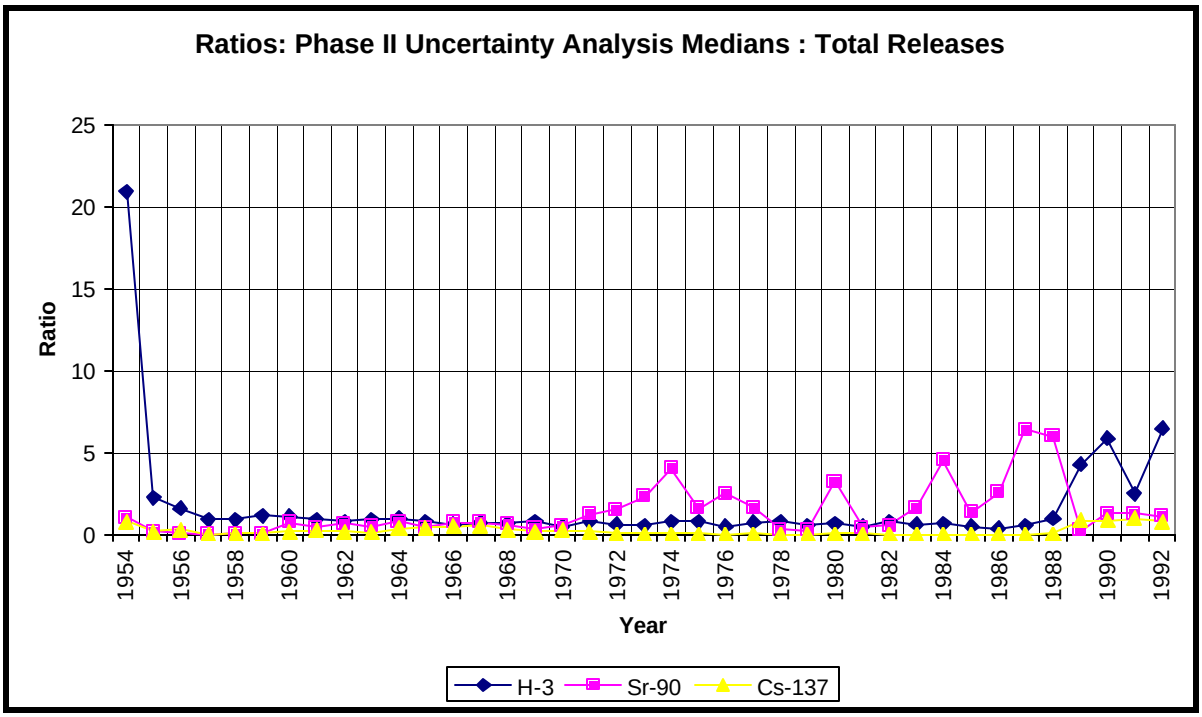

Figure 7-8 Annual Ratios of Phase II Median of Savannah River Release Model to SRS Point-of-Release Data.

7.3.5.2 Comparison of Phase III Releases with Phase II Screening Assumptions

Because of the approach adopted for Phase III, the releases to streams, seepage basins, and containment basins were compiled by radionuclide as point-of-release estimates, as discussed in Section 7.3.2.2.1. There are two comparisons of Phase III release estimates and Phase II release estimates that help to place the Phase III analysis in context:

1. the sum of Phase III releases for each radionuclide and all facilities over 36 years compared to the sum of 36-year, overall site releases for each radionuclide used in the Phase II screening analysis; and

2. the sum (36 years and all facilities) of the extrapolated releases used in Phase III compared to sum of 36-year, overall site releases for each radionuclide used in the Phase II screening analysis.

Table 7-9 shows these comparisons.

Table 7-9 Comparison of Phase III Releases with Phase II Screening Assumptions

Releases from Phase II Water-Level 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	
Radio-nuclide	**Surface Water Release from SRS (Ci/36 yr)**	**Cat. 1+Cat. 3 Unless Otherwise Noted (Ci/36 yr)**	**Ratio, Screening to Phase III Basis**	**Check**	**Phase III Release to River (Ci/36 yr)**	**Ratio, Phase III River Release to Screening**
Am-241	1.00E-02					
Ba, La-140	2.20E+02					
Ce-141,144	$7.00x10^{+02}$	$7.08x10^{+02}$	0.99		$4.58x10^{+02}$	$6.54x10^{-01}$
Cm-244	8.00E-01					
Cs-134	$1.35x10^{+01}$	$1.35x10^{+01}$	1.00		2.87	$2.13x10^{-01}$
Cs-137	$1.95x10^{+03}$	$1.95x10^{+03}$	1.00		$2.57x10^{+02}$	$1.32x10^{-01}$
Co-58	2.73E+00					
Co-60	$8.40x10^{+01}$	$8.42x10^{+01}$	1.00		$5.40x10^{+01}$	$6.43x10^{-01}$
Cr-51	5.00E+03					
H-3	$1.50x10^{+06}$	$1.53x10^{+06}$	0.98	*	$1.73x10^{+06}$	1.16
I-131	$3.03x10^{+02}$	$3.02x10^{+02}$	1.00	*	$2.88x10^{+02}$	$9.50x10^{-01}$
I-129	1.20	3.00	see note	*	2.71	2.26
Np-239	1.44E+03					
P-32	$1.96x10^{+02}$	$1.96x10^{+02}$	1.00		$1.29x10^{+02}$	$6.60x10^{-01}$
Pu-239, 240	8.00	7.9	1.01		2.95	$3.69x10^{-01}$
Pu-238	4.00	4.0	0.98		$7.08x10^{-01}$	$1.77x10^{-01}$
Ru-103,106	$1.80x10^{+03}$	$1.80x10^{+03}$	1.00		$1.30x10^{+03}$	$7.25x10^{-01}$
Sb-124,125	2.40E+01					
Sr-89,90	$6.20x10^{+02}$	$7.11x10^{+02}$	0.87	*	$4.60x10^{+02}$	$7.42x10^{-01}$
S-35	$1.75x10^{+03}$	$1.75x10^{+03}$	1.00		$1.53x10^{+03}$	$8.77x10^{-01}$
Tc-99	$5.30x10^{+01}$	$5.30x10^{+01}$	1.00		$5.47x10^{+01}$	1.03
Th-232	2.00E-01					
U-235,238	$4.20x10^{+01}$	$4.15x10^{+01}$	1.01		$1.19x10^{+01}$	$2.83x10^{-01}$
Y-91	1.20E+02					
Zn-65	$1.50x10^{+02}$	$1.50x10^{+02}$	1.00		$9.64x10^{+01}$	$6.43x10^{-01}$
Zr,Nb-95	$1.45x10^{+02}$	$9.64x10^{+02}$	0.15	*	$8.23x10^{+02}$	5.67
						Average Ratio
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

Comparison 1. The Table 7-9 column headed "Check" compares the unadjusted Phase III values to the Phase II screening values. A star notation indicates that an explanation is warranted. These explanations are provided below.

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

I-131. The entry from the Phase II screening assessment is Category 1 release only; i.e., release to streams only. This appears to be appropriate because of the short, 8-day half-life of I-131. Any substantial holdup duration would cause the seepage basin inventory to decay away. The Phase III point-of-release data file only includes releases to streams.

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

Sr-89,90. Although the Phase II screening value and the Phase III base value are different by about 15%, this appears to be due to an addition problem 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 Sr-89,90 releases are applied in the dose reconstruction, unidentified beta-gamma releases were added to the Sr-90 inventory in the amount of 218.88 Ci (before multiplication by the adjustment factor for Sr-90), this dwarfs any differences between the Phase III basis and screening values.

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

Comparison 2. 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). Average ratios for three groups of radionuclides (H-3, Sr-90, and Cs-137 groups) are given in Table 7-9.

The radionuclides scaled to H-3 have, on average, increased values compared with the screening assessment inventories (+28%). The Sr scaled nuclides have, on average, 62.1% of the screening value. The Cs-scaled nuclides have, on average, about 20% 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. Since 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.

7.4 Modeling Concentrations for Lower Three Runs Creek

Unlike other streams draining the Savannah River Site, Lower Three Runs Creek can be routinely accessed by members of the public. Hence concentrations in the creek needed to be estimated so that potential exposures, in accordance with the scenario specifications, could be assessed.

7.4.1 A Simple Model for Lower Three Runs Creek (Step L-3)

Similar to the approach described in Section 7.3.1 annual concentration estimates of three radionuclides (H-3, Sr-90, and Cs-137) for the exposure location at Martin, SC, were computed by finding the ratio of (1) the annual release of each of these radionuclides into Lower Three Runs Creek and (2) the corresponding annual flow rates of Lower Three Runs Creek as determined from USGS monitoring stations. These calculated concentrations were then compared with concentrations of these nuclides as measured over the years at Martin, SC.

Annual flow rates for Lower Three Runs Creek at Martin, SC, were not available for the years 1954 through 1992, although they were available for the years 1998 through 2001. To estimate the flow rate at Martin for the time period of interest, the flow rate was estimated by ratio from the flow rate at a nearby location on the creek. The process for doing so is described in [ATL 2003].

Calculated Lower Three Runs Creek concentrations of H-3, Sr-90, and Cs-137 are compared with directly measured concentrations in Figure 7-9, Figure 7-10, and Figure 7-11. This comparison shows that concentrations in Lower Three Runs Creek based on release inventories and flow rates disagreed with measured concentrations. This disagreement was particularly evident for the case for H-3 and Cs-137 during the early years of site operation.

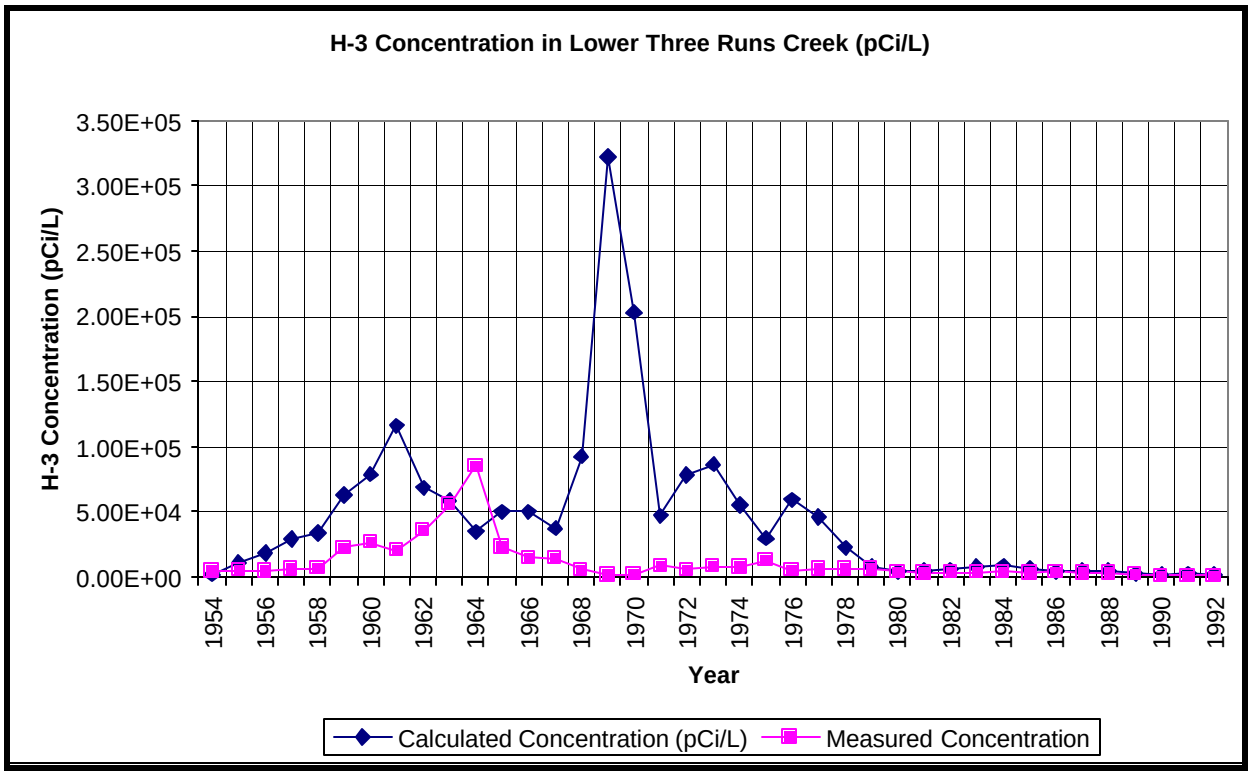

Figure 7-9 Comparison of Calculated to Measured Concentrations of H-3 in Lower Three Runs Creek

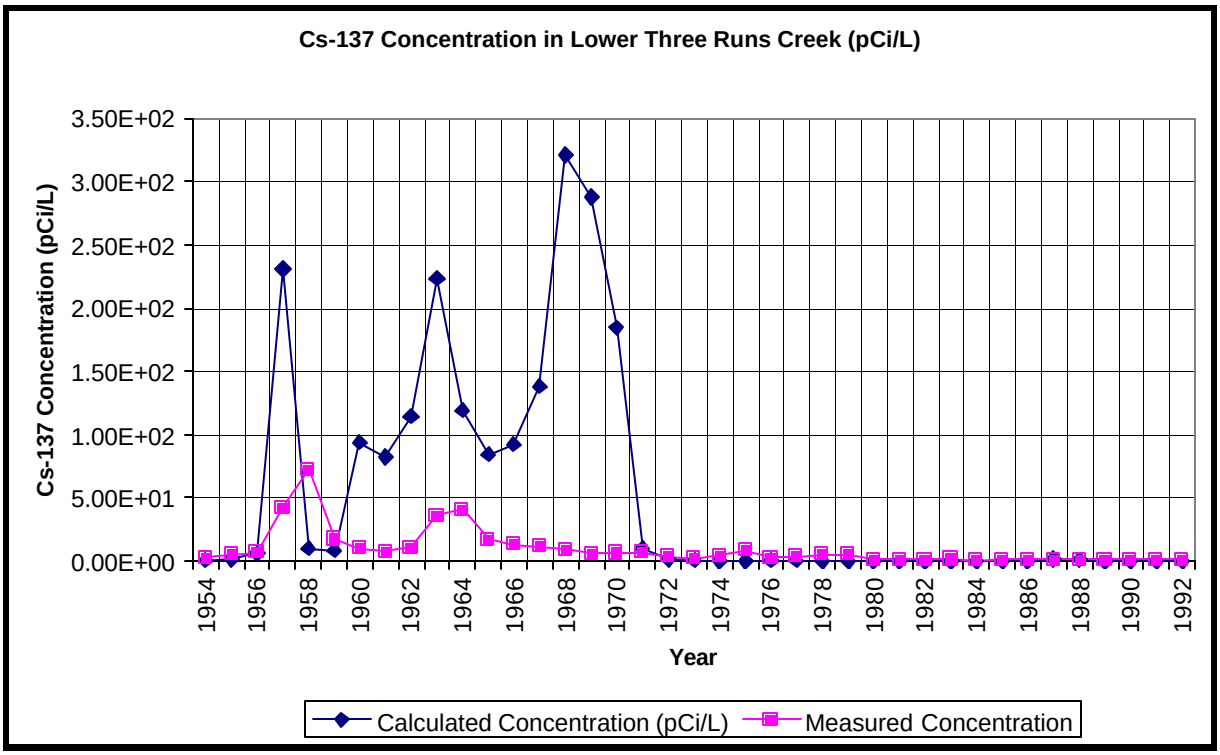

Figure 7-10 Comparison of Calculated to Measured Concentrations of Cs-137 in Lower Three Runs Creek

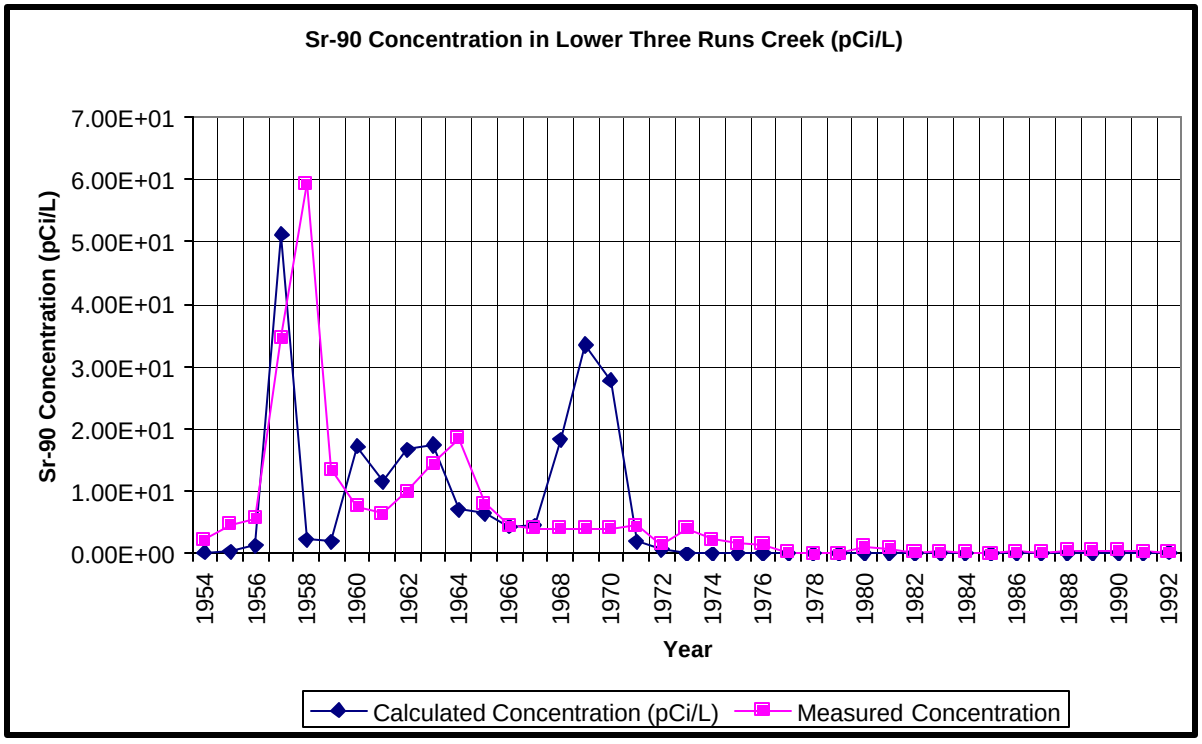

Figure 7-11 Comparison of Calculated to Measured Concentrations of Sr-90 in Lower Three Runs Creek

7.4.2 Use Available Measured Concentrations (Step L-4)

Because the concentrations estimated with a simple model did not agree with measurements, for Phase III the measured concentrations (at Martin, when possible) were used for three critical radionuclides (Cs-137, Sr-90, and H-3) to estimate doses at Martin from releases to Lower Three Runs Creek. This change was especially important for early years when concentrations in the creek were high, but the estimates based on release inventories gave excessively high concentrations.

Short of developing a physically-based model similar to that used in Phase II for releases into the Savannah River, there was no practical alternative to estimating concentrations from SRS releases in Lower Three Runs Creek. Although releases through Lower Three Runs Creek would be expected to experience the same types of loss mechanisms (sedimentation, decay, and sorption or uptake), as other site streams, the influence of these processes was thought to be smaller than for other streams mainly because Lower Three Runs Creek does not pass through the Savannah River Swamp.

The choice of using actual measured concentration in the river had the following advantages:

1. The inventory of radionuclides initially entered into the Lower Three Runs Creek from the site and the annual flow rates in Lower Three Runs Creek became non-important because radionuclide concentrations were obtained directly from the actual measured concentrations in the monitoring reports.

2. The transport mechanisms were reflected in the measured concentrations. Sediment retention, radionuclide decay, biota uptake, periodic flooding, absorption and dilution only influenced how the radionuclides were transported in the creek. The focus in Phase III is to assess the exposures to these radionuclides in the river. Thus the result of radionuclide transport was the most important issue.

3. These three radionuclides (Cs-137, Sr-90, and H-3), identified as important in the Phase II Level 1screening, were measured on a regular basis for most of the operational years.

The disadvantages include:

1. Not all of the radionuclides of interest (radionuclides that passed the Level 1 Screening criteria) were routinely measured.

2. Contributions from runoff of land-deposited SRS radionuclide releases to air and discharges from non-SRS sources, if present in any significant fashion, could not be effectively distinguished or separated from liquid releases to Lower Three Runs Creek from the SRS.

7.4.3 Complete Data Base for Measured Concentrations (Step L-5)

Annual data for H-3, Sr-90, and Cs-137 were compiled from a variety of sources to make the surface water source term for Lower Three Runs Creek.

7.4.3.1 Cesium-137 and Strontium-90

Average annual Lower Three Runs Creek concentrations were determined for Cs-137, and Sr-90 using a variety of references. For the years 1964 through 1992, annual average concentrations were determined using data published in SRS environmental reports [Ashley 1965, Ashley 1966, Ashley 1967, Ashley 1968, Ashley 1969, Ashley 1970, Ashley 1971, Ashley 1972, Ashley and Zeigler 1973, Ashley and Zeigler 1974, Ashley and Zeigler 1975, Ashley and Zeigler 1976, Ashley and Zeigler 1978a, Ashley and

Zeigler 1978b, Ashley and Zeigler 1981, Ashley 1982, Zeigler 1983, Ashley and Zeigler 1984, Ashley 1984, DOE 1985, Zeigler 1986, Zeigler 1987, Zeigler 1988, Davis 1989, Cummins 1990]. For the years 1954 through 1963, no environmental reports were published. For these years, measured water concentrations in Lower Three Run Creek for nonvolatile beta, radiostrontium, and radiocesium were obtained from Health Physics Regional Monitoring Semiannual Reports or Semiannual Progress Reports [Horton 1954, Horton 1955, Alexander and Horton 1956, Horton and Mealing 1956, Horton and Mealing 1957, Mealing 1957, Mealing and Horton 1957, Mealing 1958, Harvey 1959a, Harvey 1959b, Dupont 1959, Dupont 1960a, Dupont 1960b, Dupont 1961, Dupont 1962a, Dupont 1962b, Dupont 1963, Dupont 1964]. In these references, measured nonvolatile beta concentrations are available from 1954 to 1963 while radiostrontium and radiocesium concentrations are only available from the second half year of 1958 through 1963. Measured average concentrations in Lower Three Run Creek at Martin were cited from these semiannual reports except for the first half year of 1954, when no sampling location is specified.

From the second half year of 1958 to 1962, measured nonvolatile beta, radiostrontium, and radiocesium concentrations provided the basis to calculate average values of the ratios of the concentrations of radiostrontium and radiocesium to the concentrations of nonvolatile beta activity in Lower Three Runs Creek at Martin. These average values are presented in Table 7-10. The average value of the ratio of radiostrontium to non-volatile beta over the period 1958 through 1962 is 0.25. The average value of the ratio of radiocesium to non-volatile beta over this time period was 0.30.

Table 7-10 Ratio of Radiostrontium and Radiocesium to Nonvolatile Beta Activity in LTRC at Martin

Date	Location	NVB* (pCi/L)	Radiostrontium (pCi/L)	Strontium-NVB Ratio	Radiocesium (pCi/L)	Cesium-NVB Ratio
Jul-Dec 1958	Martin	130	28	0.22	38	0.29
Jan-Jun 1959	Martin	74	16	0.22	19	0.26
Jul-Dec 1959	Martin	49	11	0.22	16	0.33
Jan-Jun 1960	Martin	20	6	0.30	8	0.40
Jul-Dec 1960	Martin	40	9	0.23	12	0.30
Jan-Jun 1961	Martin	24	8	0.33	8	0.33
Jul-Dec 1961	Martin	27	5	0.19	7	0.26
Jan-Jun 1962	Martin	50	11	0.22	11	0.22
Jul-Dec 1962	Martin	30	9	0.30	10	0.33
Mean	Martin			0.25		0.30
Standard Deviation	Martin			0.05		0.05

*NVB- Non-volatile beta.

These ratios were used to scale average annual concentrations of Sr-90 and Cs-137 from average annual nonvolatile beta concentrations for the years 1954 through 1957 when radiostrontium and radiocesium data were not reported. The ratios were also used for 1958 because Sr-90 and Cs-137 data was not reported for the first half of this year. This scaling approach is the same approach used in Phase II to determine Cs-137 and Sr-90 concentrations for some years in SRS streams (see Chapter 5, p. 5-49, of Phase II).

7.4.3.2 Tritium

Average annual Lower Three Runs Creek concentrations were determined for tritium for the years 1964 through 1992 using data published in SRS environmental reports [Ashley

1965, Ashley 1966, Ashley 1967, Ashley 1968, Ashley 1969, Ashley 1970, Ashley 1971, Ashley 1972, Ashley and Zeigler 1973, Ashley and Zeigler 1974, Ashley and Zeigler 1975, Ashley and Zeigler 1976, Ashley and Zeigler 1978a, Ashley and Zeigler 1978b, Ashley and Zeigler 1981, Ashley 1982, Zeigler 1983, Ashley and Zeigler 1984, Ashley 1984, DOE 1985, Zeigler 1986, Zeigler 1987, Zeigler 1988, Davis 1989, Cummins 1990]. For the second half of 1958 through 1963, measured tritium concentrations in Lower Three Run Creek were obtained from Health Physics Regional Monitoring Semiannual Reports and Semiannual Progress Reports [Horton 1954, Horton 1955, Alexander and Horton 1956, Horton and Mealing 1956, Horton and Mealing 1957, Mealing 1957, Mealing and Horton 1957, Mealing 1958, Harvey 1959a, Harvey 1959b, Dupont 1959, Dupont 1960a, Dupont 1960b, Dupont 1961, Dupont 1962a, Dupont 1962b, Dupont 1963, Dupont 1964]. Measured average concentrations in Lower Three Run Creek at Martin were cited from these semiannual reports except for the first half year of 1954, when no sampling location is specified.

From 1954 to 1957, tritium releases were monitored in facility effluents but not in Lower Three Runs Creek. For these years, tritium concentrations were estimated using information in the Phase II report. The tritium activity discharged to Lower Three Runs Creek accounted for approximately 5% of the total tritium entering on-site streams. This is based on weekly measured values from 1959-1967 in the streams at the last onsite location before the streams emptied into the Savannah River. A documented annual creek flow rate from 1954 to 1958 could not be located. As a result, the flow rates for these years were estimated as discussed in Appendix S.

7.4.3.3 Interpretation of Monitoring Data in Lower Three Runs Creek

Monitoring data were used in the following manner:

If the concentration of a radionuclide of interest (i.e. tritium, cesium, or strontium) was reported, it was included directly. The reported concentration was used directly if the result was reported as an annual average. When concentration data was provided on a semi-annual basis, the average for the first and second half of the year was taken to represent the annual average concentration. The average was used because the environmental monitoring report only shows the average for the monitored period, although sometimes the number of samples taken was also reported as well as maximum and minimum concentrations for the period.

If the environmental report or other reference showed “ND”, “<MDA”, “Below Detection Limit”, or “Below Sensitivity,” one half of the reported detection limit or sensitivity was used for the indicated period of time. Detection limits or sensitivity are generally listed in every year’s environmental report for different analytical instrumentation, analytical parameters, and sample matrices. When a detection limit or sensitivity is referenced for a particular water sample, the detection limit or sensitivity of the corresponding analytical procedure for the particular radionuclide (i.e. tritium, radiocesium, or strontium) was used.

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8 FOOD CHAIN TRANSPORT

This chapter discusses the modeling of radionuclide migration in the food chain. The primary focus is uptake of radionuclides by plants and animals from contaminated environmental media. These contaminated media may include air, water, and soil. For uptake of radionuclides by terrestrial animals, contaminated media may also include plants. The primary reason for considering food chain transport is to estimate radionuclide concentrations in foodstuffs, both plant and animal products, that may be consumed by humans.

The starting point for estimating food chain transport is the radionuclide concentrations in air and water at various exposure locations. Previous chapters have discussed transport of radionuclides through the primary media of air and water; air transport is discussed in Chapter 6 and water transport is discussed in Chapter 7. For this study, food chain transport is simulated by several models that consider a variety of processes that include:

- For radionuclides transported by air:
  - Deposition of radionuclides onto vegetation and soil
  - Uptake of radionuclides by plants from soil and plant surfaces
  - Uptake of radionuclides by animals that consume plant products
- For radionuclides transported by water:
  - Deposition of radionuclides into sediments
  - Uptake of radionuclides by aquatic animals

In general, the radionuclide concentrations in soil used to model food chain transport need not correspond to concentrations used to model direct exposure and inhalation; however, for this study these concentrations generally correspond. Therefore this chapter also discusses contamination of soil, to promote a compact presentation. This chapter qualitatively describes the models used and summarizes the values for many of the variables used to generate point-estimates of radiation dose and risk. All of the variable values may be found in Appendix E and Appendix F.

8.1 Introduction

The complete mathematical formulations of the models used for this study are documented in the GENII Version 2 Software Design Document [GENII SDD] (Napier et al., 2002). These generic models are implemented in the GENII computer code. This chapter discusses the use of these models, as implemented in the GENII computer code, to simulate transport of radionuclides in the food chain in the vicinity of the SRS for the 39-year period studied. The mathematical formulations for most of models discussed in this chapter are documented in Chapter 9 of the GENII SDD.

Transport of radionuclides in the food chain may be viewed as transport into and out of different compartments in the food chain, as shown schematically in Figure 4-2 and 4-3. The food chain compartments considered in this study of the SRS are: soil, plants, terrestrial animals, and aquatic animals. Radionuclides enter these compartments either directly from contaminated air and water or by transfer from another food chain compartment. For example, radionuclides may enter edible plants by direct deposition of radionuclides from contaminated air or by uptake from soil contaminated by airborne radionuclides. The mathematical models use the principle of mass conservation to estimate the concentration in a food chain compartment based on the rates of radionuclide input (e.g., deposition, uptake) and removal (e.g., radioactive decay, weathering).

The generic models implemented in the GENII computer code allow radionuclides to enter soil, plants, and animals from contaminated water; for example, animals may take up radionuclides from contaminated drinking water. However, agricultural practices in the vicinity of the SRS did not include use of the Savannah River or Lower Three Runs Creek for irrigation of crops or watering of farm animals. Other water sources used for agricultural purposes were considered to have low levels of contamination; these other water sources, may have been slightly contaminated by deposition of radionuclides from air, but did not receive liquid releases of radionuclides from the SRS. Therefore, the only instance of contaminated water transferring radionuclides to a food chain compartment that has been modeled is the contamination of shoreline sediments.

The remainder of this chapter is organized according to the four food chain compartments considered in this study of releases from the SRS: soil, plants, terrestrial animals, and aquatic animals; in addition, two special models for tritium and carbon-14 migration in the food chain are discussed in a separate section.

8.2 Soil Concentration

Soil concentrations are calculated differently, depending on the major physical processes involved in a particular situation. As with other concentrations calculated, soil concentrations are based on conservation of mass. However, depending upon the nature of the soil, different radionuclide addition and removal processes may be applicable. Some of the physical processes that might apply to terrestrial soils include:

- deposition from air to surface soil,
- deposition from water to surface soil during irrigation,
- depletion by radioactive decay,
- leaching from surface soil,
- loss from surface soil during harvest of contaminated plants, and
- removal by resuspension of contamination and subsequent transport by wind.

For aquatic sediments the main process is deposition of radionuclides from contaminated water. Because irrigation with water contaminated by liquid releases from SRS facilities was not practiced during the period of time studied, deposition on farm land of radionuclides released to water by the SRS was not modeled. However, contamination of farm land by deposition of airborne radionuclides was modeled. Deposition of radionuclide contamination from water to sediments on the shoreline was modeled as a viable mechanism to contaminate soil.

8.2.1 Radionuclide Deposition from Air

Irrigation with contaminated water is not considered in this study because: (1) water from the Savannah River and Lower Three Runs Creek, which were contaminated by liquid releases from the SRS, was not used for irrigation and (2) contamination of other waters that might have been used for irrigation, such as reservoirs, ponds, and wells was considered to be slight. For this reason, the only source of radionuclide contamination in terrestrial soils is deposition of airborne radionuclides.

Two types of deposition are usually modeled: (1) dry deposition and (2) wet deposition. "*Dry deposition* refers to any physical removal process that does not involve precipitation." "*Wet deposition* refers to processes in which atmospheric chemicals are accumulated in rain, snow, or fog droplets and are subsequently deposited onto Earth's surface." (Hemond and Fechner-Levy, 2000).

Dry deposition may involve several processes including gravitational settling, impaction onto plant and soil surfaces, and absorption by soil and plant surfaces. For small particles and gases, gravitational settling is negligible. The model implemented by the GENII code uses an electrical analogy to calculate a net deposition velocity from three separate "resistances" (s/m): aerodynamic resistance, surface resistance, and transfer resistance and the gravitational settling velocity. The aerodynamic and surface resistances depend upon the wind speed, as detailed in the GENII Software Design Document (Napier et al., 2002). For this study the default values for transfer resistance were used: 10 s/m for gas (iodine) and 100 s/m for particles. To calculate the gravitational settling velocity for particles two key variables were the particle density and diameter; for the point estimates the values for these variables were chosen to be 2.0 g/cm^3 and 0.001 mm, respectively. The deposition velocity is calculated by combining the separate resistances and the gravitational settling velocity, if appropriate (not appropriate for gases and very fine particles). The dry deposition rate is then calculated from the deposition velocity and air concentration of each radionuclide for any given year:

$$R_{ai} = V_d C_{ai} \qquad (8\text{-}1)$$

Where R_{ai} is the rate of deposition from air, a, of radionuclide i (Bq/m^2/s)
V_d is the deposition velocity (m/s)
C_{ai} is the air concentration of radionuclide i in that year.

Clearly the concentration in air varies with the location of the exposure location at which the radionuclide deposition is to be calculated; however, for simplicity an index denoting this variability has not been included in the equation. The air concentrations of the radionuclides studied were obtained by the approach discussed in Chapter 5.

Wet deposition for gases considers that the gas is soluble in water, but partitions the gas between air and water according to Henry's Law. Henry's Law describes the ratio of the concentration of a chemical in air to the concentration in water at equilibrium. Wet deposition for particles uses the concept of a washout coefficient that describes the fraction of the air concentration of particles removed per unit distance of travel of precipitation. Default values build into the GENII code were used for the Henry's Law constants. The washout coefficient is computed based on the precipitation rate during a precipitation event. A key variable for wet deposition is the average daily rain rate, which was taken to be 11.4 mm/d, based on data from 1970-99 (National Climactic Data Center, 2003).

8.2.2 Radionuclide Concentration in Soil – Direct Exposure

To estimate the concentration of radionuclides in soil for determining dose resulting from direct exposure from the ground plane, most removal processes are not considered; the only removal process considered is radioactive decay. Thus a key variable in determining these concentrations is the decay constant for each radionuclide. These are well established and are incorporated into one of the many GENII databases.

For direct exposure calculations, the average concentration in the soil is used, considering the total air deposition rate, at a particular exposure location, and radioactive decay. Every year was considered separately and for this study the radionuclide concentration at the beginning of each year was assumed to be zero. Some long-lived radionuclides may have persisted in the soil from year to year, but the results of this study suggest that dose pathways for these radionuclides were not likely to be significant. The model used to estimate soil concentration assumes that radionuclides deposited from the air onto the soil surface is mixed uniformly to a certain depth. For this reason, the concentration of radionuclides in the soil depends on the depth to which mixing is assumed to occur and the bulk density of the soil. For this study, the mixing depth was set to 15 cm and the bulk soil density set to 1.6 g/cm^3; these values are frequently used as nominal values in studies of this type.

8.2.3 Radionuclide Concentration in Soil – Agricultural Exposure

To estimate the concentration of radionuclides in soil for determining dose resulting from agricultural pathways, such as uptake by plants, removal processes in addition to radioactive decay must be considered. Two additional removal processes are (1) loss of activity by harvest and (2) leaching of radionuclides from the soil. Loss of activity by harvest models the amount of radionuclides taken up by vegetation while growing and assumes it is removed at harvest. For this study it was conservatively assumed that no activity was removed by harvesting. Fresh water from precipitation and irrigation can dissolve radionuclides in the root zone of the soil and transport them to a lower depth, where the activity will be unavailable for uptake by roots or resuspension into the air. The model used to estimate removal of radionuclides from the upper layer of soil assumes equilibrium between the pore water and soil. The partitioning coefficient, K_D, (i.e., distribution coefficient) describes the ratio of the concentration in soil to the concentration in water. This coefficient depends on a number of factors including the chemical natures of the soils and the radionuclide ions. Appropriate values for the radionuclides modeled were carefully studied and selected, as shown in Table 8-1 and described in Appendix C. Additional important variables in the model include the annual precipitation rate, the surface soil moisture content fraction, and the bulk soil density. The surface soil moisture content fraction was estimated to be 0.22 using characteristics for sandy loam (porosity of 0.4), a saturated hydraulic conductivity of 540 m/y, and an infiltration rate of 0.373 m/y. As with the soil concentration used for direct exposure, the soil depth was set to 15 cm and the bulk soil density set to 1.6 g/cm^3. Since the K_D changes for each chemical species, these data yield a removal rate constant for the activity of each radionuclide in the surface soil layer. This removal rate constant is used in addition to and in a manner similar to the radioactive decay constant to estimate the loss of radioactivity in the soil layer by leaching; this provides an estimate of the annual average radionuclide concentration in the surface soil layer.

Table 8-1 Soil Distribution Coefficients for Surface Soil Leaching Calculations

Nuclide	Kd (mL/g)	Nuclide	Kd (mL/g)
^{3}H	0	^{99}Tc	2.49*
^{32}P	173*	^{103,106}Ru	55
^{35}S	7.5	$^{129, 131}$I	1.55*
^{60}Co	60	$^{134, 137}$Cs	59
^{65}Zn	200	^{141,144}Ce	490
^{89,90}Sr	3041*	^{231,234}Th†	3000
^{90}Y†	510	U (all isotopes)	1000
^{95}Zr	600	Pu (all isotopes)	4100
^{95}Nb	160	^{241}Am	2000

*This table lists the number of significant digits that were presented in the primary sources.
†These isotopes are daughters of the primary isotopes considered in the report

8.2.4 Radionuclide Concentration in Shoreline Sediments – Direct Exposure

The concentration of radionuclides in shoreline sediments depends on the deposition of radionuclides from the adjacent contaminated body of water. The removal of radionuclides is considered to be limited to radioactive decay. As with other soil concentrations, the average concentration over a year is used to estimate doses. The mathematical model describing the concentration in sediments is very similar to the

model for soil concentrations used for direct exposure. The key variable for this model, in addition to the decay constant for each radionuclide, is the deposition rate for sediments. The deposition rate is stated in terms of the transfer rate constant; for this study the transfer rate constant was set equal to the default value of 25,400 $L/m^2/y$ used in the GENII computer code (The original estimate had one significant figure, but three significant figures were retained by the GENII code to reflect the conversion from English to metric units and to allow trace back to the historical value). This value of the transfer rate constant was derived for several radionuclides by using measured values of concentrations in shoreline sediments and in the water column of the Columbia River. Two additional important variables determining the sediment concentration are the sediment density and the sediment depth; for this study the shoreline sediment density was set equal to the GENII code default of 240 kg/m^2 and the depth, as with other soil layers, was set equal to 15 cm.

8.3 Radionuclide Concentration in Terrestrial Vegetation

In general, contaminants may enter terrestrial vegetation by deposition on plant surfaces and by uptake through plant roots. Because the rate of contaminant entry into the plant is generally not affected by the concentration in the plant, concentration induced by direct deposition and by root uptake may be calculated separately. The total concentration of a radionuclide in a particular plant may then be calculated by summing the concentrations induced by direct deposition and by root uptake; since the mass of the plant is the same for both types of uptake, adding concentrations is equivalent to summing the radionuclide mass from each entry mechanism.

8.3.1 Plant Concentration from Direct Deposition

Deposition of radionuclides on the surfaces of plants (usually the leaves) can generally result from:

(1) dry deposition from contaminated air,

(2) wet deposition from contaminated air,

(3) deposition of radionuclides resuspended from contaminated soil, and

(4) deposition from irrigation with contaminated water.

As explained elsewhere in this Section, irrigation with contaminated water was not considered a viable pathway. Dry and wet deposition from contaminated air is discussed in Section 8.2.1. Deposition of radionuclides resuspended from contaminated soil is discussed in Section 8.3.1.1. Once these three deposition rates ((1), (2), (3)) have been determined, the radionuclide concentration in the vegetation is computed using a mass balance relationship; processes removing radionuclides from the plant surfaces include radioactive decay and weathering. The calculation of concentration in vegetation from direct deposition is discussed in Section 8.3.1.2.

8.3.1.1 Deposition of Resuspended Activity

Resuspension of radionuclides deposited on soil and plant surfaces causes an incremental addition to the concentration in the air above the affected surfaces. Radionuclides are resuspended by turbulence in the air and by mechanical agitation of the surface, e.g., by automobile traffic, pedestrian traffic, and agricultural operations such as plowing, cultivating, and harvesting. For most studies of this type, the concentration of radionuclides in the air is considered to be in equilibrium with the surface concentration of radionuclides; i.e., the forces tending to resuspend activity are balanced by forces tending to cause the activity to settle on surfaces. For equilibrium conditions the relationship between air and soil concentration is given by:

$$C_{ar} = RF \cdot ?_{s} \qquad (8\text{-}2)$$

Where C_{ar} is the concentration induced in the air by resuspension (Bq/m^3)
RF is the resuspension factor, a constant, (m^{-1})
$?_{s}$ is the areal concentration of radionuclides in the soil (Bq/m^2)

The areal concentration may be obtained from the mass-based concentration, C_s, by multiplying by the bulk soil density, $?_s$, and soil depth, d_s:

$$?_{s} = C_s \cdot ?_s \cdot d_s \qquad (8\text{-}3)$$

The mass-based soil concentration, C_s (Bq/kg), is the average annual concentration obtained as described in Section 8.2.2. As with other cases involving the soil concentration, the soil depth was set to 15 cm and the bulk soil density set to 1.6 g/cm^3, so $?_s \cdot d_s$ has a value of 24 g/cm^2 or 240 kg/m^2.

Two separate values of resuspension factor were used in this study, one for farms and one for other environments. These values, representative of different land uses, were chosen from a compilation of measured resuspension factors (Kennedy and Strenge, 1992). Because agricultural operations with heavy equipment, such as tractors, greatly disturbs the soil surface a resuspension factor value of 10^{-5} m^{-1} was chosen for agricultural exposure locations; this value is 100 times larger than the value of 10^{-7} m^{-1} chosen for urban, suburban, and non-agricultural rural exposure locations. Farming locations using the higher value of resuspension factor were taken to be: Girard (Rural Family #1), New Ellenton (Migrant Family), and Williston (Rural Family #2). All other exposure locations used the smaller value of resuspension factor.

Once the incremental addition to the concentration in the air above the affected surfaces is computed by equation (8-2), the deposition rate of this activity on plant surfaces is obtained from the product of the air concentration and a deposition velocity, similar to equation (8-1). The deposition velocity used for all radionuclides and all plants was chosen to be 0.001 m/s, which is a representative value.

8.3.1.2 Radionuclide Concentration in Plants from Direct Deposition

Radionuclide concentration in plants from direct deposition is calculated from a mass balance that considers radionuclide deposition from the air and removal by radioactive decay and weathering of the radionuclides from the plant surfaces. The net uptake of radionuclides is computed by integrating the uptake rate over the growing period for the particular crop. Radionuclide concentration is given by:

$$C_{dci} = [R_{aid} \cdot r_{dc} + R_{aiw} \cdot r_{dw} + C_{ci} \cdot RF_c \cdot V_{di} \cdot r_{ac}] \cdot [Tvc/Bc] \cdot [(1\text{-}\exp\{-?_{ei} T_{gc}/365d/y\})/?_{ei}] \qquad (8\text{-}4)$$

Where,

C_{dci} = concentration from deposition, d, of radionuclide i in crop type c
R_{aid} = the rate of dry (d) deposition of radionuclide i from air (a)
R_{aiw} = the rate of wet (w) deposition of radionuclide i from air (a)
r_{dc} = the dry (d) deposition fraction for crop type c
r_{dw} = the wet (w) deposition fraction for crop type c
C_{ci} = the concentration of radionuclide i in the soil for crop type c
RF_c = resuspension factor for the soil for crop type c
V_{di} = deposition velocity for radionuclide i
r_{ac} = the deposition fraction for resuspension for crop type c
Tvc = the translocation factor for crop type c
Bc = the standing biomass for crop type c
$?_{ei}$ = $?_{wi} + ?_i$ = effective loss rate contant (y-1), which is the sum of the weathering rate constant, $?_{wi}$, and the radioactive decay constant, $?_i$
T_{gc} = the growing period for crop type c

Growing periods for different types of crops are shown in Table 8-2. The dry and wet deposition rates are discussed in Section 8.2.1; deposition rates from resuspended activity are discussed in Section 8.3.1.1. Since plant surfaces do not generally cover the entire area subject to radionuclide deposition, a deposition fraction is applied to account for the fraction of the surface covered by vegetation; a standard value of 0.25 is used in this study for both dry and wet deposition calculations. Variables related to radionuclide removal from plants include the radioactive decay constant and the weathering constant. Radioactive decay constants are included in a data library in the GENII code. The weathering constant, which describes removal of radionuclides by precipitation, wind, and similar processes, is expressed as a weathering rate half-life; for this study a standard value of 14 days was selected for the weathering rate half-life.

Table 8-2 Values used for the point-estimate case for the variables: growing period (days), translocation factor, and standing biomass (kg/m2).

Crop Types	Growing Period (days)	Translocation Factor	Standing Biomass (kg/m^2)
Leafy vegetables	70	1	0.7
Root vegetables	70	0.1	0.7
Fruit and Grain	145	0.1	0.7
Poultry, Milk, and Egg Animal Feed	145	0.1	2.4
Beef and Milk Animal Forage	30	1	1.8

Although the radionuclides are absorbed through the plant surfaces, once inside the plant radionuclides migrate to different parts of the plant at different rates. Since the interest is in the edible portion of the crop, the fraction of absorbed radionuclides that migrate to that edible part, termed the “translocation factor”, is an important quantity; the translocation factor has been measured for a variety of crops. Since the absorbed radionuclides spread throughout the plant, the concentration in the plant depends on the total biomass present; this is accounted for by the “standing biomass”, which represents the total biomass per unit area of cultivated ground. Values of translocation factor and standing biomass used in this study for various crops are shown in Table 8-2.

8.3.2 Plant Concentration from Root Uptake

The plant concentration at harvest from root uptake is based on a radionuclide partitioning model that assumes equilibrium between the radionuclide concentration in the plant and the radionuclide concentration in the soil. The concentration of radionuclides in the plant is given by the following relation:

$$C_{rci} = [C_{ci} \cdot RP_{sc} \cdot Bv_{ci} \cdot fc]/P_3 \qquad (8\text{-}5)$$

Where C_{rci} = concentration of radionuclide i in crop type c from root uptake for a one-year period (Bq/kg wet weight)

C_{ci} = average concentration of radionuclide i in farmland soil for crop type c for the current one year period (Bq/m^2)

RP_{sc} = fraction of plant type c having roots in surface soil zone (dimensionless)

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)

The fraction of plant roots in the surface soil, RP_{sc}, was conservatively determined to be 1.0 for all plants, which indicates that the entire root system is in the soil zone where contamination is modeled to occur. Many crops have roots mainly in the surface soil zone. Assuming the entire root is in contaminated soil, when part may be in uncontaminated soil, will overestimate radionuclide uptake by the plant. Because this fraction was set to a value of 1.0, the fraction of the root below the surface soil (15 cm depth) was set to 0 in all cases. The areal density of farmland was set to 240 kg/m^2, consistent with values previously used for bulk soil density and soil depth. Values used for the concentration ratio for root uptake of radionuclide i in crop type c (Bq/kg dry plant per Bq/kg dry soil) are shown in Table 8-3. The source for these values is provided in Appendix E. The dry to wet ratio for various plant types is shown in Table 8-4.

A three-step process, shown in Figure 8.1, was used to select transfer factor values for this report (i.e., the concentration ratios shown in Table 8-3 and Table 8-5). The first step was to consider values based on local data. Where local data were not available, generic values were used. Among generic values, those that were applicable to conditions at the SRS were preferred; e.g., choosing an uptake factor of 1.7 for root vegetables, which was the average for sand and pH of 5, corresponding to conditions at the SRS. The first reference source for generic values was *Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Temperate Environments* [IAEA, 1994]. Where [IAEA, 1994] did not contain a generic value, the GENII default was used.

Table 8-3 Values of ratio of concentration in plants to concentration in soil (kg/kg) for various plant types and elements.

Element (i)	PLANT TYPE (c)			
	Cereal and Grain	Leafy Vegetables, Forage, and Hay	Other Vegetables and Root Vegetables	Fruit
P	3.5	3.5	3.5	3.5
S	1.5	1.5	1.5	1.5
Co	3.7E-03	0.20	0.11	7 E-03
Zn	1.6	3.3	12	0.9
Sr	0.15	1.7	1.7	0.2
Y	0.01	0.01	0.01	0.01
Nb	2.5 E-2	2.5 E-2	1.7E-02	2.5E-02
Zr	1E-03	1E-03	1E-03	1E-03
Tc	0.73	940	28	1.5
Ru	5E-03	0.2	0.04	0.04
I	2E-02	3.4E-03	0.02	0.02
Cs	0.02	5.31	0.9	0.22
Ce	3E-02	3E-02	3E-02	3E-02
Th	3.4E-05	1.1E-02	6.9E-03	2.5E-04
U	1.3E-03	2.3E-02	0.011	4 E-03
Pu	6E-05	2.2E-03	8.2E-04	4.5E-05
Am	2.2E-05	0.067	8.4E-04	2.5E-04

Table 8-4 Variable values for the dry-to-wet ratio for plant type c (kg dry plant/kg wet plant).

Crop Types (c)	Ratio of Dry to Wet Weight
Leafy vegetables	0.1
Root vegetables and Fruit	0.15
Grain	0.91
Poultry and Egg Animal Feed	0.91
Beef and Milk Animal Forage	0.22

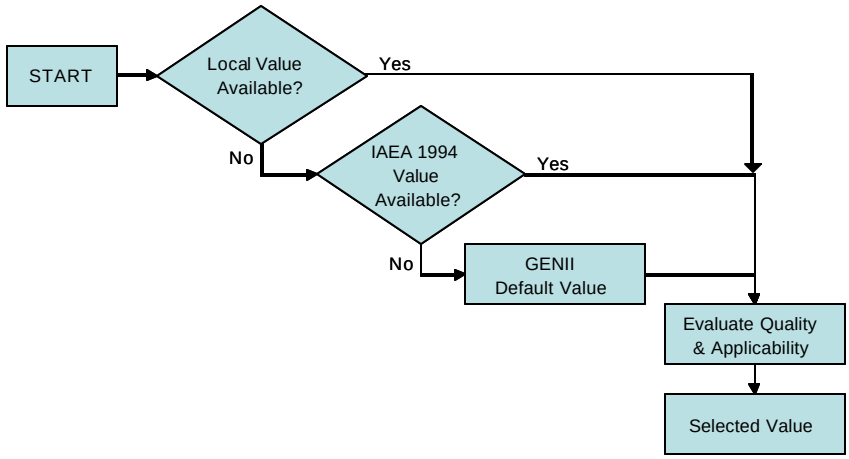

Figure 8-1 Process for Selecting Transfer Factor Values

8.4 Radionuclide Concentration in Terrestrial Animals

The concentration of radionuclides in food products from terrestrial animals (e.g., eggs, milk, and beef) depends on the amount of radionuclides ingested by those animals. In general, animals may ingest contaminated water, soil, and feed (food). For this study drinking water for either animals or humans was not considered to be contaminated in the vicinity of the SRS. This is because water contaminated with liquid releases from the SRS was not used for such purposes, while the water that was used was likely to be uncontaminated (well water) or only slightly contaminated (reservoirs and ponds). Consequently, uptake of radionuclides by terrestrial animals from drinking water was not modeled in this study. Because ingestion of soil was not considered to be a significant pathway for animal product contamination, it was not modeled in this study.

For ingestion of feed as the viable pathway for radionuclide ingestion, the concentration of radionuclides in animal products is given by equation (9.9) in the GENII SDD and which is adapted here:

$$C_{hai} = F_{ai} \cdot \sum_{f=1}^{N_{af}} C_{cfi} d_{af} U_{af} \qquad (8\text{-}5)$$

Where,

C_{hai} = concentration of radionuclide i in animal product a at harvest of the animal product for a one-year period (Bq/kg)

F_{ai} = transfer coefficient that relates daily intake rate by an animal to the concentration in an edible animal product a (e.g., Bq/(L milk) per Bq/d for milk, and Bq/(kg meat) per Bq/d for beef)

C_{cfi} = concentration of radionuclide i in animal feed type f at the time of consumption for a one-year period (Bq/kg wet weight)

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).

The calculation of the concentration in animal feed grown in the vicinity of the SRS has been discussed in Section 8.3. There were 5 types of animal feed considered for this study: poultry, milk, and egg animal feed and beef and milk animal forage. Although beef animal feed, in general, is a possibility, site specific information indicated that cattle farmers near the SRS used forage exclusively. Table 8-5 shows values for each feed type for d_{af} (the fraction of feed type f intake that is contaminated) and U_{af} (daily feed intake rate for feed type f (kg/d)). Table 8-6 shows the values of the transfer factors, F_{ai}, for the various radionuclides and the four animal types considered.

Table 8-5 Values used for the point-estimate case for the variables: fraction of feed that is contaminated and daily feed intake rate (kg/d

Feed Types	Fraction Contaminated	Feed Intake Rate (kg/d)
Poultry Animal Feed	0.5	0.12
Milk Animal Feed	1.0	13
Egg Animal Feed	0.5	0.12
Beef Animal Forage	1.0	36
Milk Animal Forage	1.0	29

Table 8-6 Values of transfer factors used for the point estimate case; i.e., the ratio of concentration in animal products to daily rate of intake of radionuclides

Element (i)	ANIMAL PRODUCT (a)			
	Animal Milk (kg/L)	Beef Animal Meat (kg/kg)	Poultry (kg/kg)	Egg (kg/kg)
P	1.6E-02	5E-02	0.19	1.0
S	1.6E-02	2E-01	2.3	7.0
Co	3E-04	1E-02	2	0.1
Zn	0.01	0.1	7	3
Sr	2.8E-03	8E-03	0.08	0.2
Y	2E-05	1E-03	.01	.002
Nb	4.1E-07	3E-07	.0004	.001
Zr	5.5E-07	1E-06	6E-05	.0002
Tc	2.3E-05	1E-04	0.03	3
Ru	3.3 E-06	0.05	8	.005
I	0.01	0.04	0.01	3
Cs	7.9E-03	0.05	10	0.4
Ce	3E-05	2E-05	.003	6.5E-05
Th	5E-06	4E-05	.006	.004
U	4E-04	3E-04	1	1
Pu	1.1E-06	1E-05	.003	.0005
Am	1.5E-06	4E -05	.006	.004

8.5 Radionuclide Concentration in Aquatic Animals

Uptake of radionuclides by aquatic animals can be complex because these animals eat other organisms that are contaminated and may take up radionuclides directly from the water they inhabit. For fish, which is an important human food, the uptake of radionuclides is generally simplified. The simplified model states that the radionuclide concentration in a given type of aquatic food is equal to the product of the radionuclide concentration in water and a bioaccumulation factor, which is specific for the organism and radionuclide. This simplified approach, which is implemented in the GENII computer code, is stated by the equation:

$$C_{hqi} = C_{wi} \cdot B_{qi} \qquad (8\text{-}6)$$

Where,

C_{hqi} = concentration of radionuclide i in aquatic food type q at the time of harvest (Bq/kg);

C_{wi} = average concentration of radionuclide i in water over the year;

B_{qi} = bioaccumulation[1] factor for radionuclide i in aquatic food type q (Bq/kg in wet fish per Bq/L of water).

The concentration in water at the two water exposure locations used in the study is obtained as described in Chapter 7. The bioaccumulation factors for freshwater fish that have been used in this study are presented in Table 8-7; Appendix F contains a description of how these were obtained. Some are generic values, but several (marked with "‡") are specific to the SRS site.

Table 8-7 Bioaccumulation Factors Selected for Freshwater Fish Consumption (L/kg)

Element*	Factor	Element*	Factor
P	50,000†	Ru	10†
S	800†	I	40†
Co	300†	Cs	4,700‡
Zn	1,000†	Ce	30†
Sr	450‡	Th	100†
Y	30†	U	10†
Nb	300†	Pu	4,700‡
Zr	300†	Am	2,400‡
Tc	20†		

*The same factor is used for each isotope of an element.
†International Atomic Energy Agency (IAEA) default value based on several references (IAEA, 1994).
‡Selected value calculated from data in (Friday, 1996), or from a combination of data from (Friday, 1996) and (IAEA, 1994).

[1] Some authors reserve the term "bioaccumulation" for processes in which uptake of contaminants is from both water and food, while the term "bioconcentration" is used to describe uptake that depends only on the water concentration, as stated in equation (8-6). See: Hemond and Fechner-Levy, 2000, p. 156 ff.

8.6 Effect of Delay and Storage Times on Concentrations

The expressions for radionuclide concentrations in plants, terrestrial animals, and aquatic animals presented respectively in Sections 8.2, 8.3, and 8.4 are correct for the time of harvest or collection. However, the consumption of these foods, by either humans or animals, may be delayed. Animal foods, such as forage or feed, may be stored after harvest and fed to the animals at a later time; during storage radionuclides will continue to undergo radioactive decay, which results in lower concentrations in the foods when they are consumed. Similarly human foods, such as vegetables, slaughtered meat, fish, and milk, may be delayed getting to market and table, because the food must be processed, or transported, or both. Again radioactive decay will reduce the radionuclide concentration in the foods consumed.

The concentration of the food consumed is given by the following expression:

$$C_{efi} = C_{hfi} \cdot \exp\{-?_i T_d\} \qquad (8\text{-}7)$$

Where,

C_{efi} = the concentration in animal or human food at the time it is consumed;

C_{hfi} = the concentration in animal or human food at the time it is harvested;

$?_i$ = radioactive decay constant for radionuclide i in units commensurable with T_d;

T_d = the storage time for animal feed or the delay time for human food.

Radionuclide concentrations in animal and human food are derived according to the methods described in the three sections preceding this one. Radioactive decay coefficients are contained in a library file in the GENII code. Storage times for animal foods are listed in Table 8-8. These times were based on site specific information. Both beef and milk animals were allowed to forage all year long, so there was never any storage time associated with this type of animal food.

Table 8-8 Values used for the point-estimate case for the storage time for animal foods
A value for each animal feed type (f) used is shown.

Feed Types	Index (f)	Storage Time (d)
Poultry Animal Feed	2	180
Milk Animal Feed	3	90
Egg Animal Feed	4	180
Beef Animal Forage	5	0
Milk Animal Forage	6	0

Delay times between food product harvest and consumption are listed in Table 8-9 (plant products) and Table 8-10 (animal products). These delay times were based on a combination of generic and site specific data, as explained in Appendix F. In addition, the characteristics stated for the scenarios were used to interpret this source data and obtain values appropriate for this study. For example, longer delay times were assumed for persons living in cities or towns than for farmers or persons eating food grown in their own gardens or raised in their backyards. Three families consumed fish obtained from waters contaminated by liquid releases from the SRS: the Outdoors Person Family, Family Living Near the River, and Delivery Person Family; the delay time for fish consumed by these receptors was taken to be

one day. Fish consumed by other families was considered to be uncontaminated, because the waters they fished were not contaminated by liquid releases from the SRS.

Table 8-9 Delay Times for Consumption of Plant Products (days)

Location	Leafy Vegetables	Root Vegetables	Fruit	Grain
Girard	1	14	1	1
Waynesboro	NA*	14	NA	NA
Augusta	7	14	7	7
Jackson	1	14	1	1
New Ellenton	1	14	1	1
Barnwell	7	14	7	7
Martin	1	14	1	1
Allendale	NA	14	NA	NA
Williston	1	14	1	1
Onsite	NA	14	NA	NA

*NA – not applicable.

Table 8-10 Delay Times for Consumption of Terrestrial Animal Products (days)

Location	Beef	Poultry	Milk	Eggs
Girard	6	6	3	1
Waynesboro	NA*	NA*	NA*	NA*
Augusta	6	6	3	7
Jackson	6	6	3	1
New Ellenton	6	6	3	1
Barnwell	6	6	3	7
Martin	6	6	3	1
Allendale	NA‡	NA‡	NA‡	NA‡
Williston	6	6	3	1
Onsite	NA‡	6	NA‡	NA‡

*NA – not applicable; location for school only.
‡NA – not applicable; location for work only.

8.7 Special Models for Tritium and Carbon-14

The models describing uptake of radionuclides by vegetation and animals presented in Section 8.3 and 8.4 are largely based on an assumption that the radionuclides are trace elements in the plant and animal tissues; i.e., the concentrations of radionuclides and non-radioactive isotopes of the same element in the organism are small. Generally this is the case and the models are appropriate. However, for two important radionuclides, tritium and carbon-14, this assumption is not true. In the environment, carbon-14 behaves

much like its non-radioactive, more common isotope carbon-12. Similarly tritiated water, with each water molecule containing either one tritium atom and one normal hydrogen atom or two tritium atoms, behaves like normal water in the environment. A principal component of plant and animal tissue is carbon and both plants and animals contain significant percentages of water (plant tissue is usually 75% or higher water by weight).

The GENII code has incorporated special models for plant uptake of tritium and carbon-14, as described in Section 9.6 of the GENII SDD (Napier et al., 2002):

The concentrations of tritium or carbon-14 in environmental media (soil, plants, and animal products) are assumed to be related to the specific activity (Becquerels of radionuclide per kilogram of soluble element) in the contaminating medium (air or water). The fractional content of hydrogen or carbon in a plant or animal product is then used to compute the concentration of tritium or carbon-14 in the food product under consideration. The hydrogen contents in both the water and the non-water (dry) portion of the food product are used when calculating the tritium concentration. The creation of organically-bound tritium [OBT] in plant and animal products from intake of HTO [tritiated water] is also addressed.

The model for tritium also considers tritium released in elemental form. Further details of these special models may be found in the cited reference.

Because of the specialized nature of these models, the default values for various coefficients built into the GENII code were used. Until the results of this study were evaluated to estimate the significance of doses from tritium, it was not considered appropriate to evaluate whether site-specific characteristics warranted changes in these values or if any site-specific data to support such changes were available. Nevertheless, a few variables used in these models were specifically selected for this study.

The tritium model for uptake by plants has as a key parameter the absolute humidity of the air; this is because the relative fraction of tritiated water to normal water in the air is given by the ratio of the tritium concentration to the absolute humidity. The value selected for the point estimate case is a site-specific average over 42 years and has a value of 0.01125 kg/m3, with a standard deviation of 0.00053 kg/m3 (Hamby, 1993, p.34). Tritium concentrations in animals are based on their uptake of tritium from contaminated water and food. Since the water consumed by livestock was considered to be uncontaminated (as explained elsewhere), the fraction of contaminated water was set to zero, which meant the uptake from water was zero. However, as explained in Section 8.4, livestock did consume contaminated crops; the quantities of crops consumed and fractions contaminated specified in Section 8.4 were also employed in the tritium model.

A key variable in determining the uptake of carbon-14 by plants from the atmosphere is the ratio of carbon-14 to normal carbon. The concentration of carbon-14 in the vicinity of the SRS is calculated according to the approach described in Chapter 5; the concentration of normal carbon in the atmosphere is based on a nominal value, which is built-into the code.

8.8 References

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9 EXPOSURE ROUTES AND PATHWAYS

This chapter discusses how the hypothetical receptors receive a radiation dose from SRS releases by coming into contact with contaminated media (air, water, soil, and food). The models used to derive doses from exposure to contaminated media are discussed in a semi-quantitative fashion, because the details of these models are fully explained in the Software Design Document (Chapter 10) for the GENII[1] code. These models do not calculate dose directly, but instead calculate "intake of radionuclides by each ingestion and inhalation exposure pathway, and exposure to radionuclides from external exposure pathways." Chapter 10 explains how these radionuclide intakes and exposures produce receptor doses.

This chapter also summarizes the values for the variables chosen to obtain the point-estimates of radiation dose and risk. Variable values related to receptor activities, in accordance with the scenarios discussed in Chapter 3, are summarized here; the complete rationale for their selection is given in Appendix E. Other variable values not related to receptor activities are detailed in Appendix F.

9.1 Introduction

Radionuclide releases from SRS facilities into the air (Chapter 5) and water (Chapter 7) are transported, by advection and dispersion in air (Chapter 6) and water (Chapter 7), to various exposure locations. These transported radionuclide releases produce contaminated media at the exposure locations (Chapter 3). Air, water, soil, and food are the contaminated media investigated in this study. Contamination of soil and foodstuffs by contaminated air and water is discussed in Chapter 8. At the various exposure locations the hypothetical receptors engage in activities specified in accordance with the scenarios described in Chapter 3, such as swimming, breathing, boating, and eating; these activities bring the receptors into contact with different kinds of contaminated media, which causes radiation exposure. The three radiation exposure routes considered in this study are:

1. INHALATION of contaminated air and contamination resuspended from soil
2. INGESTION of contaminated food, water, and soil
3. DIRECT EXPOSURE to contaminated air, water, and soil (including river sediment)

Although additional exposure routes may be important under some circumstances, they were not considered important for this dose reconstruction. For example, absorption of radionuclides through skin exposed to contaminated air or water is a possible exposure route, but is typically less than other exposure routes for the same contaminated media. Thus direct exposure from air immersion and water immersion is generally more significant than dermal absorption respectively in air and water for most beta-gamma emitters, such as Ar-41. Direct exposures by air and water immersion were included in this study, but dermal exposures were not included. Ingestion of contaminated drinking water was not included in this study; only inadvertent ingestion of water while swimming was modeled. The main rationale for this is that the main body of water directly contaminated by liquid releases from the SRS, the Savannah River, was not used for drinking water in any of the exposure scenarios. The Savannah River is used for municipal water supplies far downstream (e.g., Port Jefferson), but this was not part of any scenario. Some contamination of local reservoirs near the SRS probably arose from deposition of airborne radionuclides into the surface-water basins feeding the reservoirs. However, a model for this type of contaminant transport was not readily available and the contamination level measured was found to be small and may not all have originated from the SRS (e.g., in 1981 the measured concentrations at the North Augusta Water Plant for undifferentiated alpha activity was 0.4 pCi/L and for undifferentiated beta activity was 3 pCi/L) (Ashley et al. 1984, p. 195).

[1] All references to GENII in this chapter refer to version 2 of GENII.

A total of eighteen potential exposure pathways were modeled in this study, as shown in Table 9-1. The Table is organized according to the exposure route (direct exposure, ingestion, and inhalation) and exposure pathway; it indicates for each exposure pathway whether the release was to water or air and the contaminated medium (air, water, soil, or foodstuffs) causing the exposure. The total dose is obtained by summing the incremental dose from each exposure pathway.

Table 9-1 Exposure Routes and Pathways for Air and Water Pathways

Exposure Route & Pathway	Air Release	Water Release	Contaminated Medium
Direct Exposure (External radiation):			
• Immersion in a plume of air	X		Air
• Exposure to contaminated soil	X		Soil
• Exposure to a contaminated shoreline		X	Soil (sediment)
• Exposure to contaminated water while swimming		X	Water
• Exposure to contaminated water while boating		X	Water
Ingestion:			
• Leafy vegetable consumption	X		Food
• Root vegetable consumption	X		Food
• Fruit consumption	X		Food
• Grain consumption	X		Food
• Beef consumption	X		Food
• Poultry consumption	X		Food
• Milk consumption	X		Food
• Egg consumption	X		Food
• Inadvertent soil consumption	X		Food
• Fish consumption		X	Food
• Inadvertent ingestion of water while swimming		X	Food
Inhalation:			
• Inhalation of contamination in the air	X		Air
• Inhalation of contamination resuspended from soil	X		Air

9.2 General Exposure Formula

Given the concentration of a radionuclide in a contaminated medium, the exposure models represent how the receptor comes into contact with radiation in a way that ultimately produces a radiation dose in the receptor. In particular the end point of these exposure models is to calculate “intake” of either (1) radioactive material through ingestion or inhalation routes or (2) radiation exposure from direct external radiation.

The exposure models determine different information depending upon the exposure route, as shown in Table 9-2.

Table 9-2 Intake for Direct Exposure, Ingestion, and Inhalation Exposure Routes

Exposure Route	Intake Calculated
Direct Exposure	Annual exposure [immersion in air (Bq/m^3) or water (Bq/L); proximity to soil or sediment (Bq/kg) or water (Bq/L); ground plane exposure (Bq/m^2)].
Ingestion	Annual radionuclide activity ingested (Bq in a year).
Inhalation	Annual radionuclide activity inhaled (Bq in a year).

As will be described in Chapter 10, these intake values will be multiplied by an appropriate dose conversion factor to obtain an incremental dose; i.e.,

$$\text{Dose} = \text{Intake} * \text{Dose Conversion Factor} \qquad (9\text{-}1)$$

However, the dose conversion factor depends upon the exposure route, the radionuclide, and sometimes other factors, such as solubility or lung clearance class. In addition, dose conversion factors are, in general, dependent on the age of the receptor. Because the scenario specifications clearly expressed a concern with the interaction of the age of the receptors and the time-history of releases from the site, doses were calculated using age-dependent dose conversion factors. This age dependency was represented by grouping the dose conversion factors into four age groups, as shown in Table 9-3:

Table 9-3 Age Groups Used for Dose Conversion Factors and Risks

Receptor Age Group	Age Group[1]
Infant/ Preschooler	0 – 5 year
School Age Child	5 – 15 year
Teenager/Young Adult	15 – 25 year
Adult	25 – 70 year

[1] Based on the Federal Guidance Report 13 (FRG-13) Cancer Risk Coefficients for Environmental Exposure to Radionuclides. (EPA 2002)

More details on dose conversion factors are presented in Chapter 10.

The exact nature of both the intake and the formula used to calculate the intake depend upon both the exposure route and the specific pathway described. The general formula for calculating the intake is:

$$I = C_m ? CR \cdot ED \cdot DAF \cdot AAF \qquad (9\text{-}2)$$

Where, I is the intake;

C_m is the concentration in the medium;
CR is the contact rate or uptake rate
ED is the exposure duration;
DAF is the daily activity factor;
AAF is the annual activity factor.

Table 9-4 describes each factor in the general intake equation and shows some examples of units for these various factors.

Table 9-4 Terms of the General Intake Equation (based on Table 10.1 of the GENII SDD)

General Term	Variable Abbreviation	Description	Example Units
Medium Concentration	C_m	Radionuclide concentration in the exposure medium.	Bq/L water Bq/m^3 air Bq/kg soil
Intake/Contact Rte	CR	Ingestion, inhalation, or exposure rate.	L water/d m^3 air/d
Exposure Duration	ED	Number of years over which the exposure is defined.	Y – (For this study, all exposures were calculated on an annual basis, so this was always 1Y.)
Daily Activity Factor	DAF	Daily activity pattern parameter (e.g. exposure events per day, hours of exposure per day).	hr/d events/d · h/event
Annual Activity Factor	AAF	Annual activity pattern parameter (e.g. days per year that exposure occurs).	days/year

As stated previously, the methods for calculating the concentrations in contaminated media are described in other Chapters: Chapter 5 describes the calculation for air; Chapter 7 describes the calculation for water; Chapter 8 describes the calculation for food chain media, i.e., soil, plants, and animals. These concentrations depend upon the time history of releases from the site and their migration in and uptake by the various media. The other four factors (variables) in Equation 9-2 depend upon the behavior of the receptors, as specified by the scenarios. The contact rate for the ingestion route is the ingestion rate, kg of a particular food ingested per year. The contact rate for inhalation is the inhalation rate, m^3 of air inhaled per day. The contact rate for direct exposure is unity. For this study the exposure duration was one year, since the release rate (Bq/y) was adjusted for each year and since dose and risk conversion factors were adjusted for the ages of the receptors. The daily activity factor and annual activity factor varied depending on the exposure pathway. For example, for school children, attendance at school was characterized by a daily activity factor of 7 hours/day spent at school on a school day and an annual activity factor of 180 days/year of school attendance. Those variables that depend on receptor behavior, (e.g., time spent in a particular exposure location), are sometimes called usage factors. Values for these variables, along with a rationale for the choice of each value for the point estimate calculation, are listed in Appendix E.

Dose to each receptor could have been calculated by specifying the appropriate variables in Equation 9-2 for every applicable exposure pathway. However, such a calculation would have been very laborious and could not be easily automated. As Equation 9-2 indicates, the increment of dose from any exposure pathway is calculated by multiplying a number of factors; this property was used to perform an efficient, file-driven calculation. For each pathway, doses were calculated for an adult on the basis of a unit contact rate (e.g., 1 kg ingested per year) and/or a unit exposure duration (e.g., one hour). Then each dose based on unit inputs was scaled up by a factor representing the actual contact rates and exposure durations for a particular receptor; in addition, doses were scaled by adjustment factors accounting for the age-dependent dose conversion factors. The derivation and computational use of these exposure factors and adjustment factors are described in Appendices E and G, respectively. This approach made the calculation of doses more efficient, but had no effect on the values of the computed doses or the precision of those estimates.

The following sections briefly discuss the intake models and variables for each of the three exposure routes modeled.

9.3 Direct Exposure Pathways

Direct exposure pathways modeled in this study include:

1. Immersion in a plume of air.
2. Exposure to contaminated soil.
3. Exposure to a contaminated shoreline.
4. Immersion in contaminated water while swimming.
5. Exposure to contaminated water while boating.

As shown in Table 9-1, the first two exposure pathways are associated only with radionuclide releases to air, while the last three exposure pathways are associated only with radionuclide releases to water. Soil was considered to be contaminated by deposition of airborne radionuclides. Soil was not considered to be contaminated by deposition of water-borne radionuclides, because farmers in vicinity of the SRS did not use the Savannah River and Lower Three Runs Creek for irrigation (as explained in Chapter 3). The Savannah River and Lower Three Runs Creek were the only two water bodies contaminated by liquid releases from the SRS and accessible to the public. For exposure to a contaminated shoreline, the contaminated medium is shoreline sediment, deposited by one of the two water bodies receiving liquid releases from the SRS.

9.3.1 Immersion in a Plume of Air

External exposures from immersion in a contaminated plume of air result from the receptor absorbing radiation emitted by radionuclides in the plume. Gamma rays produce most of the immersion dose, although beta and alpha radiation may also contribute. The receptor is assumed to be at the center of a cloud of radionuclides at a uniform concentration. Radiation emitted by atoms farther away from the receptor is more likely to be absorbed by the air and contaminants between the receptor and the emitting atoms. Therefore, nearby atoms contribute most to the dose and the dose calculated is not very sensitive to large-scale variations in concentration. Note that for this study, the use of a sector average model means the concentration is assumed to be constant in an entire 22.5º sector (360° divided by 16 sectors) at a given radius.

Key variables in determining the exposure from immersion in a contaminated plume of air are (1) the concentration of each radionuclide at a particular exposure location and (2) the time of exposure for a particular receptor at a particular location. In general shielding of a receptor may also be important, but it was conservatively assumed that indoor air concentrations equaled outdoor air concentrations. The approach used to calculate yearly air concentrations at various exposure locations is described in Chapter 5. The time spent by each receptor at various locations is provided in Table 9-5.

Table 9-5 Exposure Times (hours/year) for the Air Immersion Pathway

Individual	Adult Male	Adult Female	Child Born in 1955		Child Born in 1964	
			*Thru 1972**	*Starting 1973*	*Thru 1972**	*Starting 1973*
Rural Family One						
Girard	8,760	8,760	7,500	8,760	7,500	8,760
Waynesboro	0	0	1,260	0	1,260	0
Rural Family Two						
Williston	8,760	8,760	8,760	8,760	8,760	8,760
Urban/Suburban Family						
Augusta	6,760	8,760	8,760	6,760	8,760	6,760
Onsite SRS	2,000	0	0	2,000	0	2,000
Delivery Family						
Martin	306	306	306	306	306	306
Onsite SRS	400	0	0	400	0	400
Allendale	1,600	0	0	1,600	0	1,600
Barnwell	6,454	8,454	8,454	6,454	8,454	6,454
Outdoors Person Family						
Onsite SRS	2,000	0	0	2,000	0	2,000
Jackson	6,760	8,760	8,760	6,760	8,760	6,760
Family Near River						
Martin	8,760	8,760	8,760	8,760	8,760	8,760
Migrant Worker Family						
New Ellenton	4,380	4,380	4,380	4,380	4,360	4,380

*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.

9.3.2 Exposure to Contaminated Soil

External exposures from being on a contaminated surface result from the receptor absorbing radiation emitted by radionuclides in the contaminated surface. Gamma rays produce most of this dose from a contaminated surface, also called ground-plane dose. The receptor is assumed to be standing on a slab of material contaminated at a uniform concentration. Radiation emitted by atoms on the surface of the slab is partially absorbed by the air between the receptor and emitting atoms; radiation emitted by atoms within the slab is partially absorbed by the intervening air and slab material (usually considered to be soil). More distant decaying atoms generally contribute less to dose than those closer to the receptor. The model also considers excitation of intervening atoms and secondary emission of radiation. Therefore nearby atoms contribute most to the dose and the dose calculated is not very sensitive to large-scale variations in concentration. Note that for this study, the use of a sector average model means the concentration is assumed to be constant in an entire 22.5º sector at a given radius.

Key variables in determining the intake for exposure to contaminated soil are:

1. Concentration of each radionuclide in the soil at a particular exposure location.
2. Time of exposure for a particular receptor at a particular location.
3. Shielding of a receptor provided by buildings.
4. Fractions of time spent indoors and outdoors at each exposure location.

The approach used to calculate yearly soil concentrations at various exposure locations is described in Chapter 8. The time spent by each receptor at various locations is provided in Table 9-6. (Note that the exposure times in Table 9-6 are smaller than in Table 9-4 because receptors were assumed not to be exposed to radiation from ground contamination when they were swimming or boating.) The outdoor shielding factor was set equal to 1.0 for all scenarios, exposure locations, individuals, and years; the indoor shielding factor was set to 0.7 (Appendix E). The hours spent indoors and outdoors were determined based on data from The Exposure Factors Handbook (EPA, 1997) and the scenario specifications provided by CDC (Lockridge, 2002). From the times spent indoors and outdoors at each location for each receptor, the fraction of time spent indoors and outdoors was calculated (these fractions must sum to unity); indoor and outdoor fractions are summarized in Table 9-7. In addition, Appendix E lists the hours spent indoors and outdoors for each receptor and exposure location, and the indoor and outdoor fractions calculated from these hours.

Table 9-6 Exposure Times (hours/year) for Ground Contamination External Exposure Pathway

Individual	Adult Male	Adult Female	Child Born in 1955		Child Born in 1964	
			*Thru 1972**	*Starting 1973*	*Thru 1972**	*Starting 1973*
Rural Family One						
Girard	8,739	8,739	7,479	8,739	7,479	8,739
Waynesboro	0	0	1,260	0	1,260	0
Rural Family Two						
Williston	8,739	8,739	8,739	8,739	8,739	8,739
Urban/Suburban Family						
Augusta	6,643	8,643	8,643	6,643	8,643	6,643
Onsite SRS	2,000	0	0	2,000	0	2,000
Delivery Family						
Martin	189	189	189	189	189	189
Onsite SRS	400	0	0	400	0	400
Allendale	1,600	0	0	1,600	0	1,600
Barnwell	6,454	8,454	8,454	6,454	8,454	6,454
Outdoors Person Family						
Onsite SRS	1,740	0	0	1,740	0	1,740
Jackson	6,643	8,643	8,643	6,643	8,643	6,643
Family Near River						
Martin	8,447	8,447	8,447	8,447	8,447	8,447
Migrant Worker Family						
New Ellenton	4,370	4,370	4,370	4,370	4,370	4,370

*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 9-7 Indoor and Outdoor Fractions for Ground Contamination Pathway

Member	Location	Outdoor Fraction	Indoor Fraction	Member	Location	Outdoor Fraction	Indoor Fraction
Rural Family One				***Urban/Suburban Family***			
Infant	Girard	0.15	0.85	Infant	Augusta	0.14	0.86
Preschooler	Girard	0.15	0.85	Preschooler	Augusta	0.14	0.86
School Child	Girard	0.18	0.82	School Child	Augusta	0.17	0.83
Teen	Girard	0.13	0.87	Teen	Augusta	0.14	0.86
Teen	Waynesboro	0.29	0.71	Adult Male	Augusta	0.13	0.87
Adult Male	Girard	0.31	0.69	Adult Male	SRS	0.13	0.87
Adult Female	Girard	0.14	0.86	Adult Female	Augusta	0.13	0.87
Rural Family Two				***Family Near River***			
Infant	Williston	0.15	0.85	Infant	Martin	0.14	0.86
Preschooler	Williston	0.15	0.85	Preschooler	Martin	0.14	0.86
School Child	Williston	0.18	0.82	School Child	Martin	0.18	0.82
Teen	Williston	0.15	0.85	Teen	Martin	0.15	0.85
Adult Male	Williston	0.31	0.69	Adult Male	Martin	0.13	0.87
Adult Female	Williston	0.14	0.86	Adult Female	Martin	0.13	0.87
Delivery Person Family				***Outdoor Person***			
Infant	Martin	0.45	0.55	Infant	Jackson	0.15	0.85
Infant	Barnwell	0.14	0.86	Preschooler	Jackson	0.15	0.85
Preschooler	Martin	0.45	0.55	School Child	Jackson	0.18	0.82
Preschooler	Barnwell	0.14	0.86	Teen	Jackson	0.15	0.85
School Child	Martin	0.45	0.55	Adult Male	Jackson	0.14	0.86
School Child	Barnwell	0.18	0.82	Adult Male	SRS	1.0	0
Teen	Martin	0.45	0.55	Adult Female	Jackson	0.14	0.86
Teen	Barnwell	0.15	0.85	***Migrant Worker Family***			
Adult Male	Martin	0.45	0.55	Infant	New Ellenton	0.15	0.85
Adult Male	Barnwell	0.13	0.87	Preschooler	New Ellenton	0.15	0.85
Adult Male	SRS	0.50	0.50	School Child	New Ellenton	0.18	0.82
Adult Male	Allendale	0.16	0.84	Teen	New Ellenton	0.15	0.85
Adult Female	Martin	0.45	0.55	Adult Male	New Ellenton	0.31	0.69
Adult Female	Barnwell	0.13	0.87	Adult Female	New Ellenton	0.14	0.86

9.3.3 Exposure to a Contaminated Shoreline

External exposure from being on the shore of a river or stream is similar to external exposure from contaminated soil. The principal differences for this study are: (1) the contamination on the shoreline results from contaminated sediment deposited there by contaminated water, rather than from contaminated air; (2) the deposited sediment geometry is comprised of two relatively narrow strips on either side of the river or stream; and (3) the time spent at the shoreline is much less than the time spent on contaminated ground. As with external exposure from contaminated soil, the concentration of radionuclides in the narrow strips is assumed to be constant for a given year.

Key variables for determining the intake for exposure to contaminated sediments on the shoreline are:

- Concentration of each radionuclide in the sediment at a particular shoreline location.
- Shoreline width factor.
- Shoreline use daily event frequency (frequency of shoreline use per day) at the shoreline location.
- Duration of each shoreline use (hours per event).
- Shoreline use annual event frequency (number of days per year the shoreline is used).

The approach used to calculate yearly average radionuclide concentrations in sediment at various shoreline exposure locations is described in Chapter 8. The shoreline width factor is taken to be 0.2 for all locations. Because the source of radiation is comprised of two strips rather than an infinite plane, the radiation level is only a fraction of the infinite plane value, which is accounted for by this factor. This is the default value used in the GENII code, the value recommended by the NRC for river shorelines (NRC, 1977), and the value used in past environmental analyses for SRS (WSRC, 1991; WSRC, 1992; WSRC, 1993). Variables (3), (4), and (5) multiplied together equal the total time per year spent on the shoreline; values for these total times are provided in Table 9-7. Note that only the Delivery Family, Outdoors Family, and Near-River Family have any shoreline exposure. Although other scenarios may participate in shoreline activities, the shorelines are on bodies of water that receive no waterborne releases from the SRS; in these cases it was assumed that the water and shorelines were uncontaminated by SRS activities. Thus the shoreline exposure times for Rural Family One, Rural Family Two, the Urban/Suburban Family, and the Migrant Worker Family were all assumed to be zero.

For the remaining receptors, exposure times were determined as follows:

- All members of the Delivery Person Family split their shoreline use equally between Lower Three Runs Creek near Martin and the Savannah River at Smith Lake. Shoreline exposure rates are estimated using the following factors based on South Carolina recreational patterns cited in Hamby 1991 (pp.6 and 24):

  - Average number of shoreline usage events/year – 19.15
  - Average hours/shoreline usage event – 4.44

  85 hr/yr is the product of these values.

- The Outdoors Person Adult Male (and children when they become working adults) used the shoreline on the Savannah River downstream of SRS; this location represented job-related exposures associated with employment onsite at the SRS. This time includes time spent fishing and hunting. The exposure level assumes the adult male was “on the river” 8 hours/day (40 hours/week) during the summer (13 weeks)(Lockridge 2002). It further assumes that half the time spent “on the river” was spent on the shoreline, and the other half was spent on a boat. This results in an exposure time of 260 hours/year on the shoreline for the adult male.

- The Family Living Near the River used the shoreline on the Savannah River downstream of the SRS; an exposure time of 365 hours a year assumed an average of one hour per day shoreline exposure for every day of the year

Locations and exposure times for shoreline external exposure are summarized in Table 9-8.

Table 9-8 Exposure Times (hours/year) for Shoreline External Exposure Pathway

Scenario	Shoreline Usage Location	Exposure Time (hours/year)
Rural Family One	Briar Creek near Girard	0 (all years and individuals)*
Rural Family Two	Savannah River upstream of SRS and farm ponds around Williston	0 (all years and individuals)*
Urban/Suburban Family	Savannah River at Augusta	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%).	For all years and individuals: 42.5 on LTRC shoreline at Martin 42.5 on Savannah
Outdoors Person	Savannah River: Upstream of SRS for the adult female and children. Downstream of SRS for the adult male.	260 for the adult male on the Savannah River downstream of the SRS; also used for children after they reach age 18.
Family Living Near the River	Savannah River Downstream of SRS for all individuals.	365 (all years and individuals)
Migrant Worker Family	Savannah River upstream of SRS and farm ponds around New Ellenton	0 (all years and individuals)*

*The dose from shoreline external exposure is assumed to be zero, because the exposure location received no waterborne releases from the SRS; in these cases it was assumed that the water was uncontaminated by SRS activities.

9.3.4 Immersion in Contaminated Water While Swimming

In this study doses from swimming were modeled through two separate but related exposure pathways: (1) external exposure by immersion in contaminated water, discussed here, and (2) inadvertent ingestion of contaminated water, discussed in Section 9.4.

External exposures from immersion in a contaminated body of water are similar in nature to exposures from immersion in a contaminated plume of air, as discussed in Section 9.3.1. A significant difference is that radiation is attenuated more rapidly in water because of its higher density.

Key variables in determining the exposure for immersion in a contaminated body of water are:

1. Concentration of each radionuclide in the water at a location used for swimming.
2. Swimming daily event frequency (frequency of swimming per day) at the particular swimming location.
3. Duration of each swimming event (hours per event).

4. Swimming event annual frequency (number of days per year swimming occurs).

The approach used to calculate annual radionuclide concentrations in water at two exposure locations is described in Chapter 8. Variables (2), (3), and (4) multiplied together equal the total time per year spent swimming and therefore immersed in contaminated water; values for these total times are provided in Table 9-8.

Note that only the Delivery Family and Near-River Family have any exposure due to swimming in contaminated water. Although other scenarios may participate in swimming activities, that swimming was specified to take place in bodies of water that receive no waterborne releases from the SRS; for these scenarios it was assumed that the water was uncontaminated by SRS activities. Thus the swimming exposure times for Rural Family One, Rural Family Two, the Urban/Suburban Family, the Outdoors Person Family, and the Migrant Worker Family were all assumed to be zero.

Consistent with the scenarios described in Chapter 3, swimming locations were: (1) Lower Three Runs Creek near Martin, SC, for the Delivery Person Family and (2) the Savannah River downstream of SRS for the Family Living Near the River. Time spent swimming were based on South Carolina recreational patterns cited in Hamby 1991 (p.6 and 24). The Hamby values are based on "Outdoor Recreation Assessment and Policy Plan 1989," in the Georgia Recreation Planning Process, GA Department of Natural Resources, Atlanta, GA, 1990. Swimming times, not differentiated by age, represent warm-water fishing activity:

- Average number of lake swimming events/year – 8.12
- Average hours/lake swimming event – 2.61

This results in an exposure rate of 21.2 hours/year, which is applied to all individuals in the Delivery Person Family. For the Family Living Near the River, it was assumed that all members of the family spent one hour per day during the summer swimming in the river; this is more consistent with the characterization of this family as “always outdoors and in contact with the river” (Lockeridge, 2002)

Locations and total time immersed in contaminated water while swimming summarized in Table 9-9.

Table 9-9 Exposure Locations and Times (hours/year) for Swimming External Exposure (Water Immersion) Pathway

Scenario	Swimming Location	Exposure Time (hours/year)
Rural Family One	Briar Creek near Girard	0 (all years and individuals)*
Rural Family Two	farm ponds around Williston	0 (all years and individuals)*
Urban/Suburban Family	Savannah River at Augusta	0 (all years and individuals)*
Delivery Person	Lower Three Runs Creek (LTRC) at Martin	21.2 (all years and individuals)
Outdoors Person	Savannah River upstream of SRS	0 (all years and individuals)*
Family Living Near the River	Savannah River Downstream of SRS	91 (all years and individuals)
Migrant Worker Family	Savannah River upstream of SRS and farm ponds around New Ellenton	0 (all years and individuals)*

* The dose from swimming external exposure (water immersion) is assumed to be zero, because the exposure location received no waterborne releases from the SRS; in these cases it was assumed that the water was uncontaminated by SRS activities.

9.3.5 Exposure to Contaminated Water While Boating

External exposure from being in a boat on a contaminated body of water is similar to external exposure from contaminated soil. The differences are that: (1) the contaminated water, not soil, is the source of radiation and (2) the boat, not buildings, partially shields the receptor from the radiation

Key variables for determining the intake for exposure to contaminated water while boating are:

1. Concentration of each radionuclide in the water at a location used for boating.
2. Shielding factor for boating exposures.
3. Boating daily event frequency (frequency of boating per day) at the particular boating location.
4. Duration of each boating event (hours per event).
5. Boating event annual frequency (number of days per year boating occurs).

The approach used to calculate annual radionuclide concentrations in water at two exposure locations is described in Chapter 8. The shielding factor accounts for the shielding from external radiation provided by the structure and composition of the boat; the shielding factor was assumed to have a value of 1.0 for all scenarios and receptors; this conservatively assumes the boat provides no shielding. Variables (3), (4), and (5) multiplied together equal the total time (in hours) per year spent boating and therefore exposed to direct radiation from contaminated water; values for these total times are provided in Table 9-10.

Table 9-10 Exposure Times (hours/year) and Locations for Boating External Exposure Pathway

Scenario	Boating Exposure Location	Exposure Time (hours/year)
Rural Family One	No boating activity	0 (all years and individuals)
Rural Family Two	No boating activity	0 (all years and individuals)
Urban/Suburban Family	Savannah River at Augusta	0 (all years and individuals)*
Delivery Person	Savannah River Downstream of SRS.	96 (all years and individuals)
Outdoors Person	Savannah River Downstream of SRS.	356 for adult male and children age 18 and over; 96 for adult female and children under age 18.
Family Living Near the River	Savannah River Downstream of SRS.	192 (all years and individuals)
Migrant Worker Family	No boating activity	0 (all years and individuals)

* The dose from boating external exposure is assumed to be zero, because the exposure location received no waterborne releases from the SRS; in this and similar cases it was assumed that the water was uncontaminated by SRS activities.

The scenarios specified no boating activity for Rural Family One, Rural Family Two, and the Migrant Worker Family. For the Delivery Person Family, the Family Living Near the River, and the Outdoors Person boating occurred on the Savannah River downstream of SRS. Boating times are estimated using the factors for boating based on South Carolina recreational patterns cited in Hamby 1991 and shown below in Table 9-11. These values are based on "Outdoor Recreation Assessment and Policy Plan 1989,"

in the Georgia Recreation Planning Process, GA Department of Natural Resources, Atlanta, GA, 1990. The numbers apply to all age groups and include two categories – canoeing and boating/sailing.

Table 9-11 South Carolina Boating Usage Rates (adapted from Hamby 1991)

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	

The total rate (96 hours/year) was applied to all individuals in the Delivery Person Family. Twice this exposure time was assumed for the Family Near the River, because their contact with the water was specified as higher than normal. For the Outdoors Person family, all family members, but the Adult Male, were assumed to have the regional average exposure time, the same as the Delivery Person Family. However the Adult Male had both occupational and recreational exposure; the average recreational exposure of 96 hours/year was added to an occupational exposure of 260 hours/year for a total of 356 hours/year. For the Adult Male's occupational exposure the amount of time spent boating was assumed to be half the time spent "on the river," and the time spent "on the river" was cited in Lockridge 2002 as 8 hours/day (i.e., 40 hours/week) during the summer (i.e., 13 weeks) (0.5 x 40 x 13 = 260 hours/year).

9.4 Ingestion Exposure Route

Ingestion exposure pathways modeled in this study include:

- Ingestion of plants by humans, including:
  Leafy vegetables
  Root vegetables
  Fruit
  Grain
- Ingestion of animal products by humans, including:
  Beef
  Poultry
  Milk
  Eggs
  Fish
- Inadvertent consumption of contaminated soil
- Inadvertent consumption of contaminated water while swimming.

As shown in Table 9-1, the all these exposure pathways are associated only with radionuclide releases to air, with the exception of ingestion of fish and inadvertent ingestion of water while swimming; these last two pathways are associated only with radionuclide releases to water. With the exception of fish, contamination of plants and animals resulted from the contamination of soil by deposition of airborne radionuclides. Soil was not considered to be contaminated by deposition of water-borne radionuclides, because farmers in vicinity of the SRS did not use the Savannah River and Lower Three Runs Creek for irrigation (as explained in Chapter 3). In this study, ingestion of beef was used to represent consumption of all types of meat and meat products, except poultry.

9.4.1 Food-Chain Ingestion Exposures

The general intake equation (9-2) can be simplified for ingestion of foodstuffs to be:

$$I = C_f \cdot U \cdot ED \cdot T \qquad (9\text{-}3)$$

Where, I is the intake;

C_f is the radionuclide concentration in the contaminated food;
U is the consumption rate of the food, i.e., the contact rate for ingestion
ED is the exposure duration, set to one year, since this study examines doses on an annual basis;
T is a special form of the annual activity factor representing the fraction of the food consumed that was produced in the vicinity of SRS and therefore was considered contaminated.

The general food intake equation (9-3) was adapted further for this study to reflect the receptor behaviors specified by the CDC scenarios. In particular, the scenarios specified the locations from which the receptors obtained their food. This was an important aspect of the scenario specifications, since different locations potentially experienced different contamination levels from SRS releases, because of differing distances from the sources and the inhomogeneous air dispersion patterns at the SRS. In general the radionuclide concentration in the food (C_f·), the ingestion rate (U), and the fraction contaminated (T) may all be a function of the location where the food was produced. A more precise rendering of equation (9-3) is:

$$I_{total} = ?\, I_L = C_{fL} \cdot U_L \cdot ED \cdot T_L \qquad (9\text{-}4)$$

Where all the variables are defined as before, but the index "L" refers to location and I_{total} represents the total intake of a particular radionuclide for a particular receptor for a particular food. For example, as shown in Table 9-176 and Table 9-187, the Outdoors Person Family consumed as much meat (modeled as beef) as most other scenarios. A large fraction (75%) of this meat came from the SRS, while the remainder (25%) came from Jackson. The fraction of contamination of the meat from Jackson was set to 0.5 to reflect production of meat products distant from the SRS (e.g., hot dogs, lunch meats, and other processed meats); the fraction of contamination of meat from the SRS was set to 1.0 to reflect consumption of game taken from the site.

The source location of various terrestrial foods for each scenario is shown in Table 9-12. In general, both the amount of food consumed from each source location and the fraction of the food contaminated varies with the location and type of food. Note that for four scenarios all foods originate at a single location unique to that scenario: Rural Family #1, Rural Family #2, Near River Family, and the Migrant Worker Family.

Chapter 8 describes how the concentrations in food were calculated. The following subsections briefly provide the values chosen for consumption rate, U, and fraction contaminated, T, for the nine types of food considered, as well as the rationale for these choices.

Table 9-12 Source Locations for Various Terrestrial Food Types (and Soil Ingestion) for Each Scenario

CDC SCENARIO	FOOD TYPE								
	Beef	Poultry	Milk	Eggs	Leafy Veg.	Root Veg.	Fruit	Grain	Soil
Rural Family #1	G	G	G	G	G	G	G	G	G
Rural Family #2	W	W	W	W	W	W	W	W	W
Urban/Suburban	A	A	A/NE	A	A	A	A	A	A
Delivery Person	B/M	B/M	B/M	B/M	B/M	B/M	B/M	B/M	B/M
Outdoors Person	J/SRS	J	J	J	J	J	J	J	J
Near River	M	M	M	M	M	M	M	M	M
Migrant Worker	NE	NE	NE	NE	NE	NE	NE	NE	NE

Key to locations: G – Girard; W – Williston; A – Augusta; NE – New Ellenton; B – Barnwell; M – Martin; J – Jackson; SRS – Onsite SRS.

9.4.1.1 Ingestion of Leafy and Root Vegetables and Fruit

The Exposure Factors Handbook (EPA 1997) was used to determine consumption rates of leafy vegetables, root and other vegetables, and fruit. This reference is based on data from U.S. Department of Agriculture studies, including the periodic National Food Consumption Surveys (NFCS) and the Continuing Surveys of Food Intakes by Individuals (CSFII).

Ingestion rates determined for leafy and root vegetables and fruit are listed in Table 9-13. 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.

The fractions of foodstuffs contaminated (adjustment factors) are listed in Table 9-14. Note that for Rural Families One and Two the values change after 1959, but that values for all other scenarios are constant for the entire 39-year study period. The time dependencies of these values for different scenarios were mandated by the scenario specifications (Lockeridge, 2002).

Table 9-13 Ingestion Rates (kg/yr) for Three Produce Categories

Individual	All Other Scenarios‡			Delivery Person Family (Barnwell/Martin)†			Migrant Worker Family		
	LV*	RV*	F*	LV	RV	F	LV	RV	F
Adult M	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 F	16.7	57.2	56.6	8.35/ 8.35	28.6/ 28.6	28.3/ 28.3	8.35	28.6	28.3
1955 Child:									
Infant 1955	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 1965-68	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 1960-66	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 1967-73	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 1974-92	16.7	79.2	55.2	8.35/ 8.35	39.6/ 39.6	27.6/ 27.6	8.35	39.6	27.6
1964 Child:									
Infant 1964	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 1965-68	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 1969-75	8.1	41.9	52.0	4.05/ 4.05	20.95/ 20.95	26.0/ 26.0	4.1	20.95	26.0
Teen 1976-82	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 1983-92	16.7	79.2	55.2	8.35/ 8.35	39.6/ 39.6	27.6/ 27.6	8.4	39.6	27.6

*LV: Leafy Vegetables; RV: Root Vegetables; F: Fruit.
†The Delivery Person Family obtains half its produce from Martin and half from Barnwell; table entries represent this partion.
‡ Rural Families One and Two, Urban/Suburban Family, Outdoors Person Family, Near Water Family

Table 9-14 Ingestion Rates (kg/y) and Fraction Contaminated (Adjustment Factor) for Leafy Vegetable, Root Vegetable, and Fruit Ingestion Exposure Pathways

Individual	Rural Families One And Two	All Other Scenarios†
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:		
Thru 1959	0.75	0.50
1960 & on	0.625	0.50
1964 Child:	0.625	0.50

† Urban/Suburban Family, Delivery Person Family, Outdoors Person Family, Near River Family, Migrant Worker Family

9.4.1.2 Ingestion of Grain

For the grain ingestion pathways, consumption rate data from the Exposure Factors Handbook (EPA, 1997) was used, as shown in Table 9-15. No data on local consumption was identified. This data was interpreted by assuming that most grain and grain products consumed by receptors in the vicinity of the SRS (i.e. breads, pastas, flours, etc.), would originate outside the local region. However, corn was expected to be consumed as a vegetable (e.g., corn on the cob). For purposes of modeling radionuclide uptake, corn is considered a grain rather than a vegetable. The Exposure Factors Handbook data is presented in terms of g/kg-day of consumption and was converted into kg/y by using Tables 7-2 and 7-3 from in the same source to determine mean body mass as a function of age and gender. The Exposure Factors Handbook also presents consumption rates based on geographic region; however, differentiation by age and gender was not given by geographic region and differences between regions were small, so regional data were not used.

The contaminated fraction for the Migrant Worker Family was set to 0.5 to account for the fact that the family was completely absent from the SRS vicinity for one-half the year. For all the remaining scenarios, the contaminated fraction was set equal to 1.0.

Table 9-15 Ingestion Rate of Corn (kg/y)

Individual	All Other Scenarios	Delivery Person Family	
		Martin	Barnwell
Adult Male	4.1	2.05	2.05
Adult Female	3.5	1.75	1.75
1955 Child:			
Infant 1955	1.2	0.6	0.6
Preschool 1956-59	2.9	1.45	1.45
School 1960-66	3.9	1.95	1.95
Teen 1967-73	3.6	1.8	1.8
Adult 1974-92	4.1	2.05	2.05
1964 Child:			
Infant 1964	1.2	0.6	0.6
Preschool 1965-68	2.9	1.45	1.45
School 1969-75	3.9	1.95	1.95
Teen 1976-82	3.6	1.8	1.8
Adult 1983-92	4.1	2.05	2.05

9.4.1.3 Ingestion of Beef

Beef was used to represent all non-poultry and non-fish meat that was eaten by the hypothetical receptors. As explained in the White Paper, "Treatment of Radionuclide Concentrations in Wild Game in Dose Reconstruction Modeling" (McDougall, 2003) beef was used as a surrogate for venison from locally-hunted deer. The principal source of information on meat consumption was the Exposure Factors Handbook (EPA 1997).

Values used to characterize the consumption of beef reflects the scenario specifications; in particular the scenarios specified that: (1) the Delivery Person Family ate beef obtained from both the 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 " eaten by the Outdoors Person Family was venison from deer taken on the SRS site and one-quarter came from Jackson as farm-raised beef or other meat. Beef consumption rates are listed for each receptor in Table 9-16.

The fraction of the beef consumed that was considered to be contaminated (adjustment factor) took into account a number of assumptions that are discussed in Appendix E. For several scenarios 50% of beef purchased at local groceries was considered locally grown and therefore contaminated. The fraction of beef that is contaminated is listed for each receptor in Table 9-17.

Table 9-16 Consumption Rate (kg/y) of Beef (Meat)

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	New Ellenton
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
1955 Child:						
Infant 1955	25.2	12.6	12.6	6.3	18.9	12.6
Preschool 1956-59	31.4	15.7	15.7	7.85	23.55	15.7
School 1960-66	50.6	25.3	25.3	12.65	37.95	25.3
Teen 1967-73	75.6	37.8	37.8	18.9	56.7	37.8
Adult 1974-92	78.1	39.05	39.05	19.52	58.58	39.05
1964 Child:						
Infant 1964	25.2	12.6	12.6	6.3	18.9	12.6
Preschool 1965-68	31.4	15.7	15.7	7.85	23.55	15.7
School 1969-75	50.6	25.3	25.3	12.65	37.95	25.3
Teen 1976-82	75.6	37.8	37.8	18.9	56.7	37.8
Adult 1983-92	78.1	39.05	39.05	19.52	58.58	39.05

Table 9-17 Fraction of Beef and Poultry that is Contaminated (Adjustment Factors)

	SCENARIO							
	Rural Family One/ Two	Urban-Suburban Family	Delivery Person Family		Outdoors Person Family		Near River Family	Migrant Worker Family
Production Location ?	Williston/Girard	Augusta	Martin	Barnwell	Jackson	SRS Onsite	Martin	New Ellenton
Adult Male:								
1955-1959	0.75	0.5	0.625	0.5	0.5	1.0	0.5	0.5
1960-1992	0.625	0.5	0.625	0.5	0.5	1.0	0.5	0.5
Adult Female :								
1955-1959	0.75	0.5	0.625	0.5	0.5	1.0	0.5	0.5
1960-1992	0.625	0.5	0.625	0.5	0.5	1.0	0.5	0.5
1955 Child:								
1955-1959	0.75	0.5	0.625	0.5	0.5	1.0	0.5	0.5
1960-1992	0.625	0.5	0.625	0.5	0.5	1.0	0.5	0.5
1964 Child:	0.625	0.5	0.625	0.5	0.5	1.0	0.5	0.5

9.4.1.4 Ingestion of Poultry

For the poultry ingestion pathway, consumption rates for specific age and gender categories from the Exposure Factors Handbook (EPA, 1997; Table 11-10) were adapted to the age and gender categories used in the modeling by using the same approach as was used for beef consumption. The rates that result from this adjustment are shown in Table 9-18 for each scenario. The fraction of poultry that is considered to be contaminated for each scenario is based on the descriptions provided by the SRSHES (Lockeridge, 2002) and are the same fractions contaminated as used for beef ingestion. These fractions contaminated are shown for each scenario in Table 9-17.

Table 9-18 Ingestion Rate of Poultry (kg/y)

	All Other Scenarios	Delivery Person Family		Outdoors Person Family	
		Martin	Barnwell	Onsite SRS	Jackson
Adult Male	11.9	11.9	11.9	11.9	11.9
Adult Female	9.1	9.1	9.1	9.1	9.1
1955 Child:					
Infant 1955	1.5	1.5	1.5	1.5	1.5
Preschool 1956-59	6.4	6.4	6.4	6.4	6.4
School 1960-66	8.0	8.0	8.0	8.0	8.0
Teen 1967-73	11.7	11.7	11.7	11.7	11.7
Adult 1974-92	11.9	11.9	11.9	11.9	11.9
1964 Child:					
Infant 1964	1.5	1.5	1.5	1.5	1.5
Preschool 1965-68	6.4	6.4	6.4	6.4	6.4
School 1969-75	8.0	8.0	8.0	8.0	8.0
Teen 1976-82	11.7	11.7	11.7	11.7	11.7
Adult 1983-92	11.9	11.9	11.9	11.9	11.9

9.4.1.5 Ingestion of Milk

For the milk ingestion pathway, consumption rates were adapted from The Exposure Factors Handbook [EPA 1997]; these milk consumption rates are listed in Table 9-19. Note that of the milk consumed by the Urban/Suburban Family, half came from cows in Augusta, GA, and half came from cows in New Ellenton, SC. Similarly, for the Delivery Person Family the milk supply was split evenly between Barnwell and Martin. Because the scenarios specified that all milk was obtained from sources local to SRS, the fraction contaminated was set to unity for all scenarios.

Table 9-19 Consumption Rates (kg/y) for Milk

Individual	Rural Families One and Two, Outdoors Person Family, Near River Family	Urban/ Suburban Family	Delivery Person Family	Migrant Worker Family
		Augusta/New Ellenton*	Barnwell/ Martin*	New Ellenton
Adult Male	73.7	36.85/36.85	36.85/36.85	36.9
Adult Female	55.5	27.75/27.75	27.75/27.75	27.8
1955 Child:				
Infant 1955	131.8	65.9/65.9	65.9/65.9	65.9
Preschool 1956-59	130.2	65.1/65.1	65.1/65.1	65.1
School 1960-66	146.5	73.25/73.25	73.25/73.25	73.3
Teen 1967-73	169.5	84.75/84/75	84.75/84/75	84.8
Adult 1974-92	73.7	36.85/36.85	36.85/36.85	36.9
1964 Child:				
Infant 1964	131.8	65.9/65.9	65.9/65.9	65.9
Preschool 1965-68	130.2	65.1/65.1	65.1/65.1	65.1
School 1969-75	146.5	73.25/73.25	73.25/73.25	73.3
Teen 1976-82	169.5	84.75/84/75	84.75/84/75	84.8
Adult 1983-92	73.7	36.85/36.85	36.85/36.85	36.9

9.4.1.6 Ingestion of Eggs

For the egg ingestion pathway, consumption rates were adapted from The Exposure Factors Handbook [EPA 1997]; these egg consumption rates are listed in Table 9-20. Note that of the eggs consumed by the Urban/Suburban Family all came from hens in Augusta, GA, even though some foodstuffs came from New Ellenton, SC. For the Delivery Person Family the egg supply was split evenly between Barnwell and Martin. The quantity of eggs consumed by the Migrant Worker Family was set to one-half the quantity consumed by other scenarios, since they were absent from the SRS vicinity for one-half of each year modeled. Because the scenarios specified that all eggs were obtained from sources local to SRS, the fraction contaminated was set to unity for all scenarios.

Table 9-20 Consumption Rates (kg/y) for Eggs

Individual	Rural Families One and Two, Outdoors Person Family, Near River Family	Urban/ Suburban Family Augusta/New Ellenton	Delivery Person Family Barnwell/ Martin*	Migrant Worker Family New Ellenton
Adult Male	13.9	13.9/0	6.95/6.95	6.95
Adult Female	8.4	8.4/0	4.2/4.2	4.2
1955 Child:				
Infant 1955	1.8	1.8/0	0.90/0.90	0.90
Preschool 1956-59	7.7	7.7/0	3.85/3.85	3.85
School 1960-66	8.0	8.0/0	4.0/4.0	4.0
Teen 1967-73	10.8	10.8/0	5.4/5.4	5.4
Adult 1974-92	13.9	13.9/0	6.95/6.95	6.95
1964 Child:				
Infant 1964	1.8	1.8/0	0.90/0.90	0.90
Preschool 1965-68	7.7	7.7/0	3.85/3.85	3.85
School 1969-75	8.0	8.0/0	4.0/4.0	4.0
Teen 1976-82	10.8	10.8/0	5.4/5.4	5.4
Adult 1983-92	13.9	13.9/0	6.95/6.95	6.95

9.4.1.7 Ingestion of Fish

Radiation exposure through the aquatic food consumption pathway was modeled as occurring entirely from consumption of fish. Freshwater crustaceans (e.g., crayfish) and mollusks (e.g., fresh water mussel) that grew in waters contaminated by liquid releases from the SRS were not considered to be consumed in sufficient quantities to warrant modeling. Crabs, shrimp, oysters, and clams from estuarine waters were certainly consumed in significant quantities; however, because the habitat for these crustaceans and mollusks is located a significant distance downriver in brackish or salt water, far away from the SRS, the levels of radiation in those waters and animals, traceable to the SRS releases, would be quite small. Modeling these small doses was therefore not included in the study. Several references were consulted to determine fish consumption rates, including (EPA, 1997; Hamby, 1991; EPA, 2002; EPA, 1994; and EPA, 1991). None of these studies of fish consumption, however, were local to South Carolina and Georgia; therefore consumption rates were based on the Exposure Factors Handbook (EPA, 1997). For the Delivery Person Family, the source of the catch was assumed to be split evenly between Lower Three Runs Creek and the Savannah River. The consumption rate for the Migrant Worker Family reflected their presence in the SRS vicinity for only one-half of each year. The consumption rates for fish are summarized in Table 9-21.

Table 9-21 Ingestion Rate (kg/yr) for Fish

Scenario:	Rural Family One	Rural Family Two	Urban/ Suburban Family	Delivery Person Family		Outdoors Person Family	Family Near the River	Migrant Worker Family
Location:	Briar Creek	Creeks, ponds local to Williston	Savannah River near Augusta	Lower Three Runs Creek	Savannah River (Smith Lake)	Savannah River (various locations)	Savannah River (various locations)	Creeks, ponds of New Ellenton
Individual								
Adult M	9.9	9.9	9.9	4.95	4.95	9.9	9.9	4.95
Adult F	9.9	9.9	9.9	4.95	4.95	9.9	9.9	4.95
Children:								
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 consumed by the two Rural Families, the Urban/Suburban Family, and the Migrant Worker Family were assumed to come from bodies of water uncontaminated by SRS releases to surface water. However, all fish consumed by the Delivery Person Family, the Outdoors Person Family, and the Family Near the River were assumed to come from bodies of water contaminated by SRS releases to surface water. Therefore the contaminated fraction (adjustment factor) was set to unity for the Delivery Person Family, the Outdoors Person Family, and the Near River Family; all others were set to zero.

9.4.2 Inadvertent Soil Ingestion

The total mass of contaminated soil consumed over each year (kg/y) was based on the Exposure Factors Handbook (EPA, 1997). Daily rates of 100 milligrams per day for children, and 50 milligrams per day for adults, were apportioned among the exposure locations according to the amount of time that each receptor spent at each location. Note that unlike most foodstuffs, the consumption rate of soil is higher for children than for adults. These soil ingestion rates are summarized in Table 9-22.

9.4.3 Inadvertent water consumption while swimming

The hourly ingestion rate of water, while swimming, was set equal to 0.05 L/hr, which is the EPA default value (see Appendix E). Based on the scenario specifications, swimming exposures were set to zero for all receptors except the Delivery Family and the Near River Family, because only these families swam in water contaminated by liquid releases from the SRS. The Delivery Person family swam on Lower Three Runs Creek near Martin, and the Family Near the River swam on the Savannah River downstream of the site. Swimming times were 21.2 hours/year for the Delivery Person Family, and 91 hours per year for the Family Near the River. Hence, the total amount of contaminated water ingested while swimming was 1.06 L/year for all members of the Delivery Person Family and 4.6 L/year for all members of the Family Near the River.

Table 9-22 Soil Ingestion Rates (kg/year) for Each Scenario by Location of Soil Ingestion; Children's Ingestion Rates are Shown by Age

Scenario?		Rural Family One		Rural Family Two	Urban/ Suburban		Delivery Person				Outdoors Person		Near River	Migrant Worker
Location?		Girard	Wayne -sboro	Willi-ston	Augusta	Onsite SRS	Martin	Onsite SRS	Allen-dale	Barn-well	Onsite SRS	Jackson	Martin	New Ellenton
Person	Age													
Adult M	All	0.0183	0	0.0183	0.0141	0.00418	0.000693	0.000836	0.00334	0.0135	0.00418	0.0141	0.0183	0.009125
Adult F	All	0.0183	0	0.0183	0.0183	0	0.000393	0	0	0.0177	0	0.0183	0.0183	0.009125
Children Born in 1955 and 1964	Infant <1	0.0365	0	0.0365	0.0365	0	0.00128		0	0.0352	0	0.0365	0.0365	0.01825
	Pre-school 1-4	0.0365	0	0.0365	0.0365	0	0.00128	0	0	0.0352	0	0.0365	0.0365	0.01825
	School-child 5-11	0.0365	0	0.0365	0.0365	0	0.00128	0	0	0.0352	0	0.0365	0.0365	0.01825
	Teen 12-17	0.0313	0.00525	0.0365	0.0365	0	0.00128	0	0	0.0352	0	0.0365	0.0365	0.01825
	Adult M =18	0.0183	0	0.0183	0.0141	0.00418	0.00693	0.000836	0.0034	0.0135	0.00418	0.0141	0.0183	0.009125

9.5 Inhalation Exposure Route

The inhalation exposure route consists of (1) inhalation of air contaminated directly by releases to the atmosphere from the SRS and (2) inhalation of radionuclides that have been resuspended from soil after initial deposition from contaminated air. The general intake equation (9-2) can be simplified for inhalation to be:

$$I = C_a \cdot U \cdot ED \cdot T \qquad (9\text{-}5)$$

Where, I is the intake;

C_a is the radionuclide concentration in air resulting either directly from releases or from resuspension;

U is the breathing rate (m^3/h), i.e., the contact rate for inhalation;

ED is the exposure duration, set to one year, since this study examines doses on an annual basis;

T is the fraction of time spent at a particular location giving rise to the specified air concentration of radionuclides.

Chapter 5 describes how the concentrations in air resulting directly from atmospheric releases from the SRS were calculated. Chapter 8 describes how concentrations in soil were calculated and how concentrations of radionuclides in air from resuspended soil were calculated. The following subsections briefly provide the values for chosen for breathing rate, U, and fraction of time spent at different locations with contaminated air or soil, T.

9.5.1 Air Inhalation

Inhalation rates by age were based on data from the Exposure Factors Handbook (EPA, 1997). Breathing rates in the Exposure Factors Handbook were averaged over several age intervals to obtain age-interval-weighted breathing rates for the age groupings used in this dose calculation. Inhalation rates (units of m^3 per year) were created for each receptor at each exposure location by multiplying a constant daily inhalation rate, appropriate for the age and gender of the receptor, by the number of days in a year that the receptor was at a particular exposure location.

For this phase of the dose reconstruction it was not considered appropriate to refine the calculation by modeling the potential differences between indoor and outdoor radionuclide concentrations. Instead indoor concentrations were considered to be equal to outdoor concentrations, which is likely to be a pessimistic assumption. Furthermore this may better reflect conditions early in the site history, when air conditioning and tightly sealed buildings were not as common as today. Table 9-23 lists the volume of air breathed per year at various exposure locations for each scenario; these inhalation volumes are also related to the age and gender of the various receptors.

Table 9-23 Breathing Rates (m3/y) for the Family Members of Each Scenario by Location of Exposure; Children's Breathing Rates are Shown by Age

Scenario?		Rural One		Rural Two	Urban/Suburban		Delivery Person				Outdoors Person		Near River	Migrant Worker
Location ?		Girard	Waynes-boro	Williston	Augusta	Onsite SRS	Martin	Onsite SRS	Allen-dale	Barnwell	Onsite SRS	Jackson	Martin	New Ellenton
Person	Age*													
Adult M	All	5,548	0	5,548	4,281	1,267	194	253	1,013	4,088	1,267	4,281	5,548	2,774
Adult F	All	4,125	0	4,125	4,125	0	144	0	0	3,980	0	4,125	4,125	2,062
Child Born in 1955 or 1964	Infant <1	1,643	0	1,643	1,643	0	57	0	0	1,585	0	1,643	1,643	821
	Pre-school 1-4	2,811	0	2,811	2,811	0	98	0	0	2,712	0	2,811	2,811	1,405
	School-child 5-11	4,380	0	4,380	4,380	0	153	0	0	4,227	0	4,380	4,380	2,190
	Teen 12-17	5,045	848	5,892	5,892	0	206	0	0	5,686	0	5,892	5,892	2,946
	Adult M =18	5,548	0	5,548	4,281	1,267	194	253	1,013	4088	1,267	4,281	5,548	2,774

*Note that the year the breathing rate is to be applied may be calculated by summing the age and the birth year of the child.

9.5.2 Resuspended Soil

The same exposure variables that were used to calculate intake of radionuclides by breathing air contaminated directly by SRS releases to the atmosphere were used to calculate intake of radionuclides by breathing air contaminated by resuspension of contaminated soil. The only difference is that the air concentration used in equation (9-5) is the concentration based on resuspended radioactivity. As explained in Chapter 8, air concentration from resuspension is related to the soil concentration by a simple linear factor, the resuspension factor. For this study, higher values of the resuspension factor (producing higher air concentrations) were used for rural locations (Girard, New Ellenton, and Williston), while lower values were used for all other locations, which were assumed to have urban or suburban characteristics.

9.6 References

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10 DOSE AND RISK CALCULATIONS

10.1 Introduction

This chapter discusses the final step in obtaining estimates of doses and risks to the hypothetical receptors described in the scenarios. As indicated in Chapter 9, doses and risks are proportional to "intake of radionuclides by each ingestion and inhalation exposure pathway, and exposure to radionuclides from external exposure pathways."(GENII SDD). The intakes, estimated according to the approaches outlined in Chapter 9, depend on the estimated concentrations of radionuclides in various environmental media: air, water, soil, plants, and animal products. Methods for estimating concentrations are presented in Chapter 5 for air, Chapter 7 for water, and Chapter 8 for the remaining media. Intakes also depend on the behaviors described in the scenario specifications (Chapter 3) that bring the receptors into contact with these contaminated environmental media. Because the doses and risks are proportional to intake, linear coefficients are used to relate intake to dose and risk. These coefficients have been developed over many decades by the health physics community through national and international radiation protection organizations.

10.2 Basic Radiation Concepts

Additional information about radiation assessment and protection principles, and terminology, can be obtained from Internet sites on radiation such as those established by EPA (http://www.epa.gov/radiation) and the University of Michigan (http://www.umich.edu/~nradinfo)

10.2.1 Types of Radiation

Radionuclides released by the SRS into the environment emit two basic kinds of radiation:

- Particle radiation - tiny fast-moving particles that have both energy and mass (weight)
- Electromagnetic radiation - pure energy with no weight.

Particle radiation includes alpha and beta particles. An alpha particle is the positively charged nucleus of a helium atom. Alpha particles lose energy quickly when they collide with matter; therefore, their ability to penetrate is slight. A sheet of paper or layer of skin may completely absorb such particles. However, if radionuclides emitting alpha particles are inside the body, the alpha particles may cause harm to body cells. Beta particles are free, mobile electrons. Beta particles have a greater ability to penetrate matter than alpha particles. Electromagnetic radiation emitted by radionuclides includes gamma rays and x-rays. This radiation has more ability to penetrate matter than most particle radiation. All the types of radiation emitted by radionuclides may damage living cells by ionizing atoms or molecules within the cells.

10.2.2 Radiation Dose

The term "dose" has several meanings, depending on how it is used. For this study, several different terms for "dose" are needed to describe the effects of radiation[1]. The most fundamental definition of dose is the *absorbed dose*, which a measure of the amount of energy imparted to matter (e.g. tissue) by the radiation. Units of the *absorbed dose* are the rad or gray; the gray, the SI unit of absorbed dose, is equivalent to one joule of energy absorbed by a kilogram of tissue (J/kg). One gray equals 100 rad.

Although the amount of energy absorbed per unit mass, as measured by the absorbed dose, is fundamental to determining the adverse impact of radiation on the absorbing tissue and ultimately on the health of the

[1] The terms discussed here are appropriate for the low doses and stochastic health effects usually associated with exposures to environmental radioactivity.

exposed person, the adverse impact also depends upon the type of radiation absorbed. This is because different types of radiation are more or less efficient in producing damage in tissue, given the same amount of energy absorbed per unit mass. These differences are included in the concept of an *equivalent dose*,[2] which may be defined as:

$$H = D \cdot W_R \qquad (10\text{-}1)$$

Where, H is the equivalent dose (Sievert)
D is the absorbed dose (Gray)
W_R is the weighting factor (dimensionless)

The SI unit of equivalent dose is called the *Sievert* (Sv); another unit commonly used in the United States is the "*rem*," or "Roentgen equivalent man," which is one one-hundredth of a Sievert. A *millirem* (mrem) is one one-thousandth of a rem. The weighting factor[3] 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 sexes of reference radii and masses. Risk assessments are commonly performed using these standard physiological assumptions.

As discussed in previous chapters, especially Chapters 9, exposure to radiation may result from radionuclides inside or outside the body. Radionuclides were modeled as entering the body by inhalation and ingestion. Exposures to external radiation from radionuclides outside the body were modeled for:

- Immersion in a plume of air
- Exposure to contaminated soil
- Exposure to a contaminated shoreline
- Exposure to contaminated water while swimming
- Exposure to contaminated water while boating

The radiation exposure from these external sources tends to be uniform throughout the body of the exposed person, because the sources are large compared to the human body. This is generally different from therapeutic and diagnostic medical exposures, where the radiation is focused on a particular body organ or region. Once the human is removed from proximity to the medium (air, water, and soil) contaminated by radionuclides, the external radiation exposure ceases.

Exposure resulting from radionuclides within the body is substantially different. First, a radionuclide may lodge in or migrate to a particular organ of the body, where it may produce most of its damage. Second, although some types of radiation (alpha and beta) travel short distances, gamma rays may irradiate body organs some distance from the location of the radionuclides. Third, although some radionuclides may lodge in a particular organ (e.g., the lung for inhaled particles), in time they may migrate to organs that have a biochemical affinity for them (e.g., Sr tends to migrate to bones). Fourth, even though the uptake of a radionuclide by inhalation or ingestion may be a short-term or even one-time event, the radionuclides inside the body may continue to irradiate body organs. Finally, radionuclides inside the body may decay or be excreted over time, so their effect on the body lessens over time. To

[2] Except where noted, ICRP-60 terminology is used in this chapter.
[3] In ICRP-60 and other ICRP recommendations preceding ICRP-60, a weighting factor was called a quality factor.

address this complex biological and physical situation, mathematical models are used to describe movement and retention of radioactive material in the body and the doses that are imparted to various organs. A radionuclide taken into the body will impart a dose to a person not only for the first year of intake, but in all the following years until the radionuclide decays or is eliminated. To account for this long-lasting effect, the time-varying equivalent dose rate from radioactive material uptake at a given time is integrated (added) over an appropriate time period. For this study, the time period used is 70 years, representing a typical lifetime.[4] This integral of equivalent dose rate for internal radionuclides produces a *committed equivalent dose*, which is measured in Sieverts.

The models (sometimes called *biokinetic* models) used to describe the movement of radionuclides in the body and the resulting doses to various organs are quite complex, as indicated in the following summary (FGR-13):

> "The dosimetric methodology used in FGR-13 is that of the ICRP... The methodology considers two sets of anatomical regions within the body. A set of source regions is used to specify the location of radionuclide within the body. The set of target regions consists of those organs and tissues for which the radiation dose is of interest. For a specific radionuclide, the set of source regions consists of anatomical regions along the route of intake (respiratory and gastrointestinal tract), regions associated with the systemic behavior of the radionuclide, and regions along the routes of elimination of the radionuclide from the body. A region may consist of multiple compartments as necessary to represent the kinetics. Within each region the radionuclide is assumed to be uniformly distributed either by volume or, in some instances, by surface area. The mean absorbed dose to the target region is the fundamental dosimetric quantity.
>
> The energy deposition in the target regions is based on calculations of the radiation transport in an anthropomorphic phantom representing the newborn, 1 y, 5 y, 10 y, 15-y-old male, and adult male (with breasts, ovaries, and uterus added)."

Somewhat simpler models are used to estimate the doses to various organs in the body from external radiation.

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*. The effective dose may be defined as:

$$H_E = \sum_T W_T \cdot H_T \qquad (10\text{-}2)$$

Where, H_E is effective dose (Sv);

W_T is a weighting factor representing the ratio of the stochastic risk (cancers and hereditary effects) from irradiation of tissue T to that for the whole body when irradiated uniformly;

H_T is the equivalent dose in tissue T.

[4] 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.

Values for tissue weighting factors recommended by ICRP in 1977 [ICRP-26] and 1991 [ICRP-60] are listed in Table 10-1. As shown, the weighting factors recommended in ICRP-60 are different from those recommended in ICRP-26.[5] Additional information on these weighting factors may be found in original ICRP documents cited above and in the documentation for FGR-13 (FGR-13, FGR-13U), FGR-12, and FGR-11; information on how these are employed in the GENII-2 code may be found in Chapter 11 of the GENII SDD.

Table 10-1 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.

The concept of effective dose is used for doses resulting from both external and internal exposures. Furthermore, for internal doses, the concept of effective dose is combined with the concept of committed dose, yielding the *committed effective dose*, which is sometimes shortened to *effective dose* and is the time integral of the effective dose rate. For both internal and external exposures, the effective dose depends on the age of the exposed individual. This is because the risk of cancer depends on the latency period over which cancer may develop. Persons exposed early in life have a higher risk of radiation-induced disease than persons exposed later in life, because these diseases have a greater time to develop and because other

[5] 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.

causes of mortality are less likely to arise. In addition, for internal exposures, the committed dose is higher for persons exposed earlier in life than those exposed later in life, because the residual radionuclides have a longer time to irradiate body organs. In addition, the models used to derive the organ doses from internal incorporate age-dependent factors into the models, e.g., the size of various organs, metabolic rates. For all these reasons, the coefficients used to relate effective doses to internal or external exposures are age-dependent. In this study these age-dependent dose coefficients were used to estimate doses, so the changing ages of children in the various scenarios would be accounted for.

10.2.3 Risk from Radiation Exposure

As discussed in the preceding section, the concept of effective dose incorporates the risk of cancer incidence for various organs in the body. "The effective dose equivalent is intended to replace the complex dose distribution pattern from internal and external irradiation by an equivalent, uniform, whole-body dose." (Shapiro, 1990). 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 *incidence (morbidity)* occurring over a lifetime from exposure to radioactive material. Incidence (morbidity) is the risk of getting radiation-related cancer whether or not the cancer is fatal. For the point estimate calculations described in Chapter 11, the effective dose equivalent, the individual organ doses, the cancer incidence risk, and the cancer fatality risk were all calculated and recorded on an annual basis for each receptor in each scenario. For the uncertainty analysis described in Chapter 12, only the effective dose equivalent over the 39-years studied, not the risk, was recorded for each receptor in each scenario, because of the large amount of data involved.

10.3 Calculation of Dose or Risk

Doses and risks are proportional to the intakes calculated according to the methods outlined in Chapter 9. The constant of proportionality (dose coefficient, dose conversion factor, or risk coefficient) depends on the type of exposure; i.e., whether the exposure is external, inhalation, or ingestion. For external exposure the dose coefficient depends on the geometry of the contaminated medium relative to the receptor; for example, the dose coefficient depends on whether the receptor is immersed in a plume of radioactive contaminants, is standing on the surface of contaminated ground, or is on a contaminated body of water. For internal exposure the dose coefficient depends upon whether the radioactive material was inhaled or ingested. In addition, for inhaled radionuclides, the dose coefficient depends upon the inhalation solubility class. The solubility class is important because in the metabolic models used to determine dose, the solubility of the nuclide determines how long it stays in the lungs and its ability to migrate to other organs in the body. The dose coefficient also depends on the age of the receptor for the reasons described at the end of Section 10.2.2. Finally, the dose coefficient depends on the identity of the particular radionuclide causing the exposure. Because different radionuclides emit different types of radiation (particles and electromagnetic waves) of different energies as they decay, the doses produced from internal or external exposure are unique for each radionuclide.

The constants of proportionality, the dose coefficients or dose conversion factors, have been compiled for a large number of radionuclides by assuming a unit concentration in the appropriate contaminated medium (Bq/m^3 for immersion or Bq/m^2 for ground plane) or a unit uptake (Bq for inhalation and ingestion). These dosimetric models and the resulting dose coefficients have been developed over many years and are promulgated by international standards organizations (e.g., ICRP), national standards organizations (e.g., NCRP), and federal agencies (e.g., EPA). For this report, the dose and risk

coefficients are almost all based on EPA's April 2002[6] Update [FGR-13U] to Federal Guidance Report No.13 [FGR-13]. These coefficients are almost, but not quite, identical to those used by the ICRP:

> "The age-specific dose coefficients [in FGR13]…were calculated using the biokinetic and dosimetric models used in the calculations of the risk coefficients. These models are consistent with those used by the ICRP in its recent series of publications tabulating dose coefficients for the general public, which is similar ICRP-60, but may be slightly different." (FGR-13)

However, for most radionuclides and organs, these differences are negligible, especially considering other uncertainties. These minor differences may be revealed by comparing the documentation for FGR-13 and ICRP-60.

Dose conversion factors are derived using models that represent the physics and biology of the interaction of the human body with radiation or radioactive material. For external exposure the models consider the geometry and physics of the exposure (immersion in air or water, exposure to a contaminated ground plane, exposure to shoreline strips of contamination) coupled with a representation of a standard human body absorbing the radiation. For internal exposure from inhaled or ingested radionuclides, the dose conversion factors are based on models representing the complex interactions of the radionuclide's physical and chemical attributes with human physiology. Once the dose conversion factors are developed, they may be applied to any dose assessment, thereby avoiding the need to repeat the complex modeling for every dose assessment. Conversion of doses to risks of cancer incidence and fatality are based on epidemiological data that relate radiation exposures to the incidence of cancer at various organ sites in exposed individuals and the subsequent mortality among those individuals.

Given the preceding discussion, the simple formula that relates dose to intake, stated in Chapter 9,

$$\text{Dose} = \text{Intake} * \text{Dose Conversion Factor} \qquad (9\text{-}1)$$

may be stated in a more general form:

$$ED_{iae} = I_{ie} \cdot DC_{iaec} \qquad (10\text{-}3)$$

Where,

ED_{iae} = Incremental equivalent dose from radionuclide i for age group a and exposure route e
I_{ie} = Intake of radionuclide i through exposure route e
DC_{iaec} = Dose conversion factor for radionuclide i for age group a exposure route e and inhalation class c inhalation class.

Equation (10-3) recognizes the explicit dependence of the dose conversion factor, DC_{iaec}, on the radionuclide, age of the receptor, exposure route, and inhalation class; however, equation (10-1) still retains the linear relationship between dose and intake. Similar equations can be used to generate risks of cancer incidence and fatality, by replacing the term ED_{iae}, by a cancer incidence term, RI_{iae}, or a cancer fatality term, RF_{iae}; in both cases the conversion factor, DC_{iaec}, must be appropriately adjusted. Doses and risks can be further disaggregated into contributions from specific organs. Intakes, as discussed in Chapter 9, are based on radioactive material inhaled or ingested or direct exposure to external penetrating radiation.

[6] A supplement was first issued in 2000, but this supplement contained errors in the viewer and was replaced by the April 2002 version.

For exposures of persons from inhaling or ingesting radionuclides, the study used the following coefficients from FGR-13U:

- Age-dependent dose coefficients for 23 organs and bodily tissues, plus effective dose based on ICRP-60 weighting factors (see Table 10.2).
- Age-dependent cancer risk coefficients (fatality and incidence) for 15 cancer sites, plus the sum of cancers across all cancer sites.

Table 10-2 lists the organs and bodily tissues considered in the dose coefficients, and the cancer sites considered in the risk coefficients. Table 10-3 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 10-2 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	Extra-thoracic Region	Testes	Colon	Bladder
Breast	Lung	Thymus	Liver	Kidneys
Stomach Wall	Muscle	Thyroid	Lung	Thyroid
Small Intestine Wall	Ovaries	Uterus	Bone	Leukemia
Upper Lower Intestine Wall	Pancreas	Urinary Bladder Wall	Skin	Residual†
Lower Lower Intestine Wall	Red Bone Marrow	Effective Dose		Total

†Residual cancer sites.

Table 10-3 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, the physical and chemical form of some radionuclides is specified; this is denoted by the subscript "c" in equation (10-1). The radionuclide "class" is important for some radionuclides, because the radionuclide's chemical and physical form affects the rate at which the radionuclide is removed from the lungs and subsequently migrates elsewhere in the body or is excreted. The study assumed that 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.

It was assumed that some radionuclides existed as a gas or vapor, based on the Phase II information regarding releases. The assumptions for the lung absorption types used in this report are listed in Table 10-4.

Table 10-4 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 - tritium)	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

*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.

For external exposures resulting from (1) immersion in a "cloud" of radionuclides in air, and (2) proximity to a contaminated ground surface, the study used the following coefficients from FGR-13U:

- Adult dose coefficients for 23 organs and bodily tissues, plus effective dose based on ICRP-60 weighting factors (see Table 10-1).

- Age-specific cancer risk coefficients (fatality and incidence) for 15 cancer sites, plus the sum of cancers across all cancer sites.

As noted, FGR-13U provides 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]. The risk coefficients for these types of external exposures use the same age ranges as those listed in Table 10-3.

For external exposures while swimming in water or while boating, dose and risk coefficients from FGR-12 were used because coefficients for immersion in contaminated water are not included in FGR-13U. 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 (because they are based on FGR-12) rather than ICRP-60 (see Table 10-1). Risk was estimated 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, the dose and risk coefficients were grouped 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 10-5. Also listed is the exposure duration used for each age group.

Table 10-5 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.

10.4 References

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11 POINT ESTIMATE RESULTS

This chapter summarizes the doses and risks calculated for each of the four hypothetical individuals (family members) comprising each of the seven exposure scenarios as described in Chapter 3. Each family consists of:

- An adult female.
- An adult male.
- A male child born in 1955.
- A male child born in 1964.

The chapter is organized into two main sections:

Section 11.1 is an introduction and overview of results. The introduction (Section 11.1.1) summarizes the exposure routes and pathways considered for each exposure scenario. The overview of results (Section 11.1.2) summarizes the range of radiation doses and cancer risks calculated for all hypothetical members of all scenarios, and identifies those exposure pathways and radionuclides that consistently caused the largest doses and cancer risks among the hypothetical family members.

Section 11.2 present radiation doses and cancer risks for each member of each family exposure scenario. It is divided into seven subsections – one for each exposure scenario. Each subsection addresses:

1. Effective dose and cancer risks for each family member, summed over the 39 years covered by this study.
2. Annual effective dose for each family member.
3. Radionuclides that dominated the radiation dose.
4. Effective dose for each family member from external exposure to radiation, and from ingesting and inhaling radionuclides.
5. The principal exposure pathways (e.g., eating contaminated foods) that led to the radiation dose.

Effective doses and cancer risks are presented in two significant figures. This format was chosen because it facilitates comparison of doses and risks that are far apart as well as those that are similar but not identical. Effective doses presented as the percent of the entire effective dose received over 39 years are shown to the nearest 0.1%.

11.1 Introduction and Overview of Results

11.1.1 Introduction

Radiation dose in this chapter is presented as effective dose. Effective dose represents the sum of equivalent doses calculated for up to 23 bodily tissues and organs (e.g., lungs, bone, thyroid) as weighted by a set of factors (Chapter 10) that have been recommended by the International Commission on Radiation Protection (ICRP) [ICRP-60]. These weighting factors account for the different sensitivity of different bodily tissues to radiation-induced cancers. Results arer generally presented in units of milliSieverts (mSv). A milliSievert is one-one thousandth of a Sievert (Sv), the recommended

international unit for radiation dose. We also often present equivalent results in units of millirem (mrem), the radiation dose unit most commonly used in the United States. A millirem is 0.01 milliSieverts[1]

The cancer incidence and cancer fatality risks presented in this chapter represent the sum of risks calculated for 14 organs (or cancer sites) of the body (see Chapter 10). Both cancer incidence and fatality risks, as presented here, result solely from exposure to radionuclides released from SRS activities. These risks are in addition to those risks of cancer that the person would have without this radiation exposure. We present cancer incidence and fatality risks in units of percent: For example, a person with a 1% cancer incidence risk would face a one-in-one hundred lifetime risk of developing cancer due to the radiation exposures discussed here.

Radiation doses and cancer risks are calculated for 18 exposure pathways as addressed in detail in Chapter 10 and summarized in Table 11-1.[2] Table 11-1 summarizes each pathway, provides a shorthand description of each pathway, distinguishes whether the pathway resulted from radionuclides released by SRS into either the air or into surface water, and identifies the exposure route resulting from each exposure pathway.

Table 11-1 Exposure Routes and Pathways for Air and Water Pathways

Exposure Route & Pathway	Shorthand Description	Air Pathways	Water Pathways
External radiation:			
Immersion in a plume of contaminated air	Air Immersion	X	
Exposure to soil contaminated with radionuclides deposited from the air	Ground Contamination	X	
Exposure to a shoreline contaminated with radionuclides deposited from water	Shoreline		X
Exposure to contaminated water while swimming	Swimming		X
Exposure to contaminated water while boating	Boating		X
Ingestion:			
Leafy vegetable consumption	Leafy Vegetables	X	
Root vegetable consumption	Root Vegetables	X	
Fruit consumption	Fruit	X	
Grain consumption	Grain	X	
Beef consumption*	Beef	X	
Poultry consumption*	Poultry	X	
Milk consumption	Milk	X	

[1] One Sievert is equal to 100 rems. One milliSievert (1 mSv) = 1/1,000 Sv = 100 millirems (100 mrem). See Appendix D for additional information.
[2] We present radiation doses and risks for individual receptors as summed over all applicable pathways, as well as radiation doses received by each receptor from each pathway.

Exposure Route & Pathway	Shorthand Description	Air Pathways	Water Pathways
Egg consumption	Eggs	X	
Inadvertent soil consumption	Soil	X	
Fish consumption	Fish		X
Inadvertent ingestion of water while swimming	Inadvertent Swimming Ingestion		X
Inhalation:			
Inhalation of contamination in a plume of air	Air Inhalation	X	
Inhalation of contamination resuspended from soil after deposition from the air	Resuspended Soil	X	

*Beef consumption is a surrogate for consumption of all types of beef, including venison acquired through deer hunting on or near SRS. See Chapter 8 for an explanation of the reasons for this. Poultry consumption is a surrogate for consumptions of chicken and other fowl, including that acquired through bird hunting on or near SRS.

As shown, thirteen of these eighteen exposure pathways are associated with release of radionuclides by SRS into the air (*air pathways*), while five are associated with release into surface water (*water pathways*). Each hypothetical member of each exposure scenario may have received radiation exposures from some or all of these exposure pathways. Members of Rural Family One, Rural Family Two, the Urban/Suburban Family, and the Migrant Worker Family all received radiation exposures only from the air pathways. Members of the Delivery Person Family, the Outdoors Person Family, and the Family Living Near the River all received radiation exposures from the water as well as the air pathways.

11.1.2 Overview of Dose Results

Table 11-2 presents the effective dose received by each member of each hypothetical exposure scenario, as summed over the 39 years covered by this study. Doses for each scenario are presented for all air pathways; for all water pathways, and for air and water pathways combined.

The smallest radiation dose from all air pathways was received by the Child Born in 1964 of Rural Family One, while the largest radiation doses from all air pathways was received by the Child Born in 1955 of the Outdoors Person Family. The smallest radiation dose from all water pathways was received by the Child Born in 1955 of the Outdoors Person Family, while the largest radiation dose from all water pathways was received by the two adults of the Delivery Person Family. Considering combined air and water pathways, the smallest dose by any member of any exposure scenario was received by the Child Born in 1964 of the Rural Family Scenario, while the largest dose was received by the Child Born in 1955 of the Outdoors Person Family.

For any exposure scenario, most of the dose (i.e. from about 50 percent to more than 90 percent) received through all air pathways by the two adults and the Child Born in 1955 came from drinking milk and eating beef containing ^{131}I. Doses from tritium and Ar-41 were also important for these three family members. Most doses from tritium came from eating milk and beef containing this radionuclide, while most doses from Ar-41 came from the air immersion pathway. I-131, tritium, and Ar-41 were mostly released into the air during the very early days of SRS operation. In fact, about 99% of all I-131 released over 39 years had been released by the end of 1961.

Table 11-2 39-Year Effective Dose (mSv) for Each Member of Each Scenario

Scenario	Pathways	Adult Female	Adult Male	Child Born in 1955	Child Born in 1964
Rural Family One	Air	0.30	0.42	1.6	0.072
	Water	—	—	—	—
	All	0.30	0.42	1.6	*0.072*
Rural Family Two	Air	0.70	0.97	3.8	0.14
	Water	—	—	—	—
	All	0.70	0.97	3.8	0.14
Urban/Suburban Family	Air	0.33	0.73	2.7	0.11
	Water	—	—	—	—
	All	0.33	0.73	2.7	0.11
Migrant Worker Family	Air	0.45	0.62	2.2	0.083
	Water	—	—	—	—
	All	0.45	0.62	2.2	0.083
Delivery Person Family	Air	0.40	0.57	2.1	0.12
	Water	5.7	5.7	3.1	2.0
	All	6.1	6.3	5.2	2.1
Outdoors Person Family	Air	1.6	2.5	8.3	0.36
	Water	1.5	1.7	1.2	1.5
	All	3.0	4.2	*9.4*	1.8
Near Water Family	Air	0.31	0.42	1.7	0.088
	Water	1.8	1.8	1.4	1.7
	All	2.1	2.2	3.1	1.8

The Child Born in 1964 was born after the largest releases into the air from SRS. For this reason, his doses received through the air pathways were consistently smaller than those received by any other member of any family exposure scenario. The Child Born in 1964 received most of his dose from the air pathways from ingestion or inhalation of tritium, followed by external exposure to Ar-41. The two ingestion pathways of most importance for this family member were the milk and beef ingestion pathways. I-131 was consistently the third most important radionuclide for this family member, mainly from eating milk and beef.

The dose received by any family member from all air pathways was highly dependent on that family member's assumed exposure locations, particularly the locations where the family member obtained food, lived, or worked. For example, the dose received by the Adult Female from all air pathways ranged across all seven scenarios from 0.30 to 1.6 mSv, or a factor of about five. This range in dose was notably larger than the range in dose that could be accounted for considering the differences in activities performed by the Adult Female in each scenario (e.g., a larger fraction of her foods was contaminated in some scenarios than in others). Radionuclide concentrations in the exposure locations depended on the meteorological parameters that influenced calculations of radionuclide dispersion in air. Among these parameters were

the distances from the release points and the distributions of average wind speeds and atmospheric stability conditions.

Almost the entire dose received by any family member from all water pathways came from eating fish containing radionuclides. The three radionuclides that contributed the most to these doses were Cs-137, P-32, and Sr-90. The relative importance of any radionuclide depended on whether the fish came from the Savannah River or from Lower Three Runs Creek.

11.2 Detailed Results for Each Scenario

11.2.1 Rural Family One

This hypothetical family lived in Girard, GA, and spent much of their work, home activities, and recreation time outdoors (see Figure 11-1). The Adult Male was a farmer, and the Adult Female worked at home. The family hunted, fished, and swam around the Girard area and in the nearby area of Briar Creek. The family did no boating. The children attended grade school in Girard and high school in Waynesboro, GA. Otherwise, the children stayed in Girard and became farmers when they grew up.

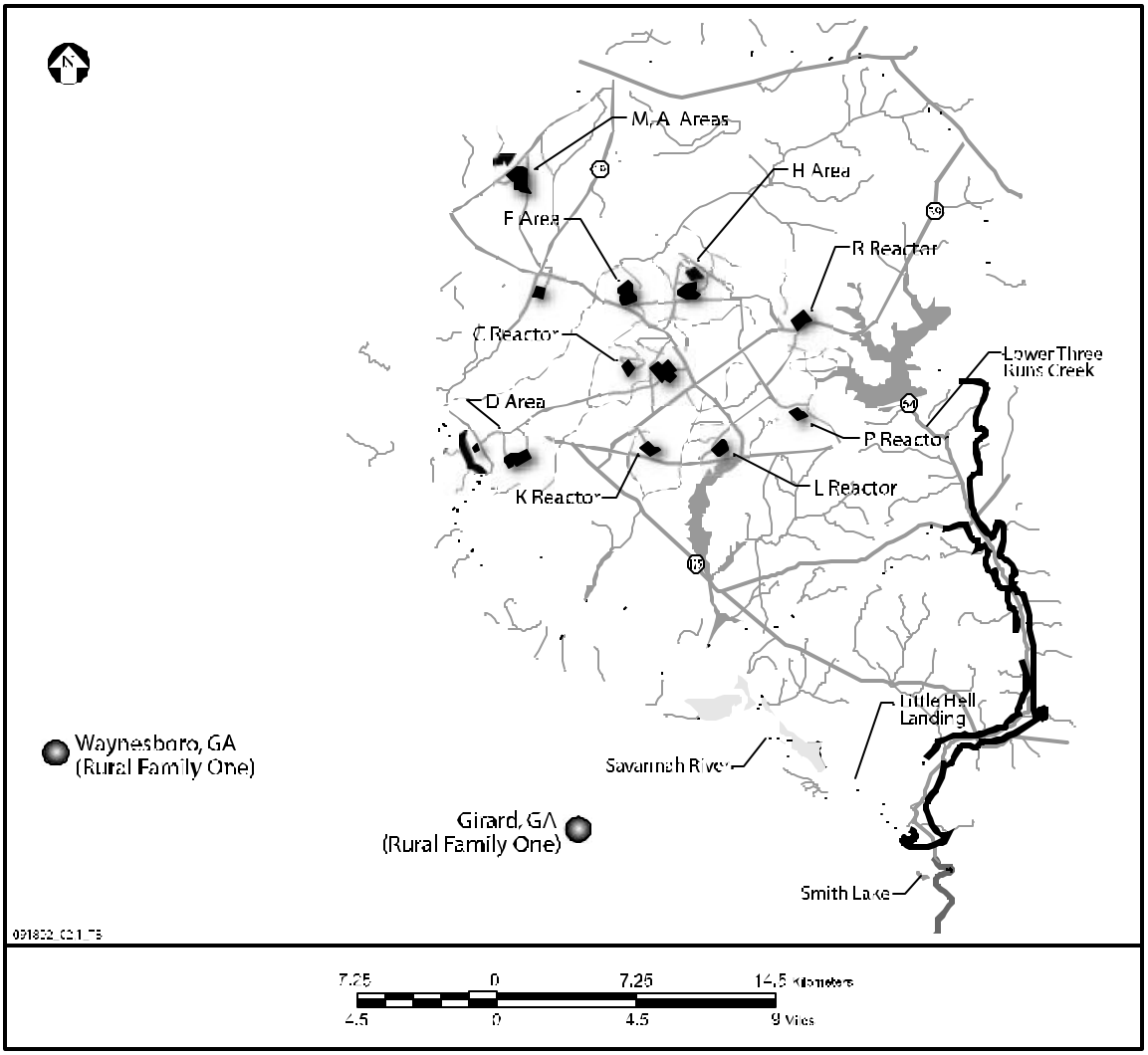


Figure 11-1 Exposure Locations for Rural Family One

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 SRS, none of the fish eaten by the family were affected by SRS release of radionuclides to surface water.

During the 1950s, 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 Girard. Half of this food was locally grown or produced, and the remaining half came from sources away from the SRS area. Beginning in 1960, only 25% of their beef, poultry, vegetables, and fruit was grown or produced on the family farm. The remaining 75% came from other sources such as stores. Half of this remaining food was grown or produced in Girard, and half came from sources outside the SRS area.[3] All of the locally-produced grain eaten by the family was corn.[4]

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.

11.2.1.1 Effective Dose and Total Risks

Table 11-3 lists the effective dose and cancer risks for each member of Rural Family One, as summed over the 39 years covered in this study. All of these doses and risks came from exposure to radionuclides that had been released by SRS into the air.

Table 11-3 39-Year Effective Dose and Cancer Risks for Rural Family One

Dose or Risk	Adult Female	Adult Male	Child Born in 1955	Child Born in 1964
Effective Dose (mSv)	0.30	0.42	1.6	0.072
Cancer Incidence Risk (%)	0.00083	0.0011	0.016	0.0011
Cancer Fatality Risk (%)	0.00030	0.00038	0.0025	0.00069

The Child Born in 1955 received the largest dose and risks. He received an effective dose of 1.6 mSv (160 mrem), a cancer incidence risk of 0.016%, and a cancer fatality risk of 0.0025%. The Child Born in 1964 received the smallest dose and risks. The effective dose for the Child Born in 1964 was 4% of that for the Child Born in 1955.

11.2.1.2 Effective Dose by Year

Figure 11-2 shows the percent of the entire 39-year effective dose received each year by each family member.[5] Figure 11-3 shows the annual dose received by each family member from 1954 through 1992. Note that the vertical axis (y-axis) of this figure is in units of Sieverts (rather than milliSieverts) and that

[3] It was assumed that locally-grown food was produced at the same location in Girard as the family residence. It was also assumed that all locally-grown vegetables and fruit, whether grown on the family farm or obtained by Girard stores from local farms, contained radionuclides from SRS operations. Similarly, it was assumed that all locally-produced beef and poultry was raised in Girard, and therefore contained radionuclides from SRS operations.

[4] This assumption was made for all receptors and scenarios. As discussed in Appendix F, although individuals in the SRS vicinity would have eaten grain products such as breads, pasta, or flours, almost all such grain products was likely grown or produced out of the SRS vicinity and was therefore unaffected by SRS operations. But individuals in the SRS vicinity could plausibly have eaten locally-grown corn. This could have occurred for persons living in a suburban as well as a rural environment. Therefore, corn was treated as a grain surrogate for purposes of the dose reconstruction assessment.

its scale is logarithmic. A logarithmic scale is used because the annual doses range by a factor of more than 1000.[6]

Table **11-4** combines the information in these two figures. It lists the percent of the entire 39-year effective dose received each year by each family member, as well as their annual dose.

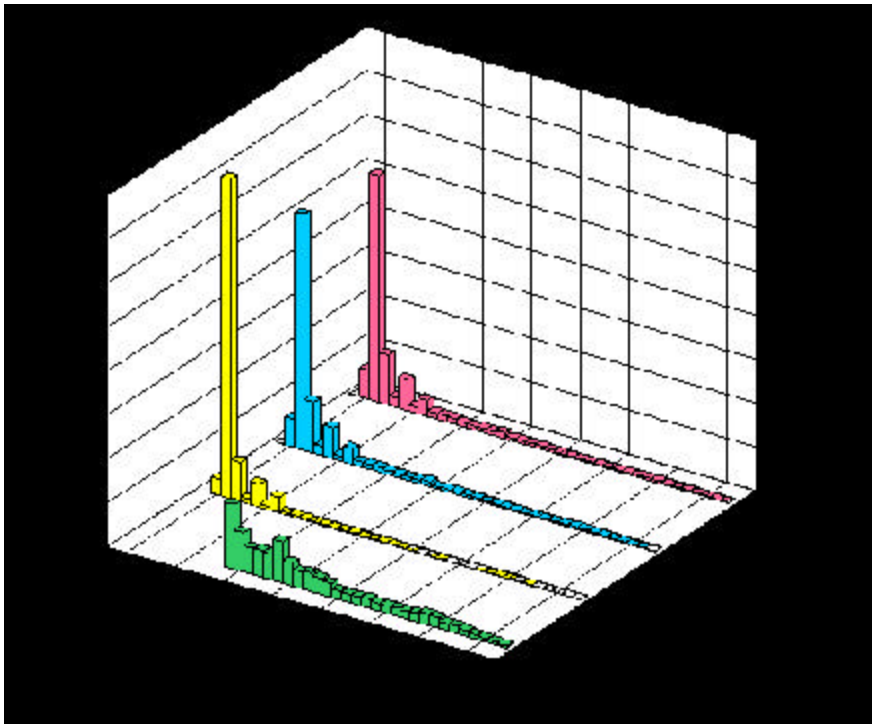


Figure 11-2 Percent of 39-Year Effective Dose by Year for Rural Family One

[5] Graphs and tables showing cancer incidence and fatality risks by year are available at {Reference or Link to Excel files}.
[6] Each of the units on the scale of the vertical axis is ten times as large or as small as the next unit. As shown in Figure 11.2.1.3, for example, the Child Born in 1955 received an effective dose of 0.000058 Sv (0.058 mSv) in 1955 and an effective dose of 0.0012 Sv (1.2 mSv) in 1956. The dose received in 1956 was 21 times larger than the dose received in 1955.

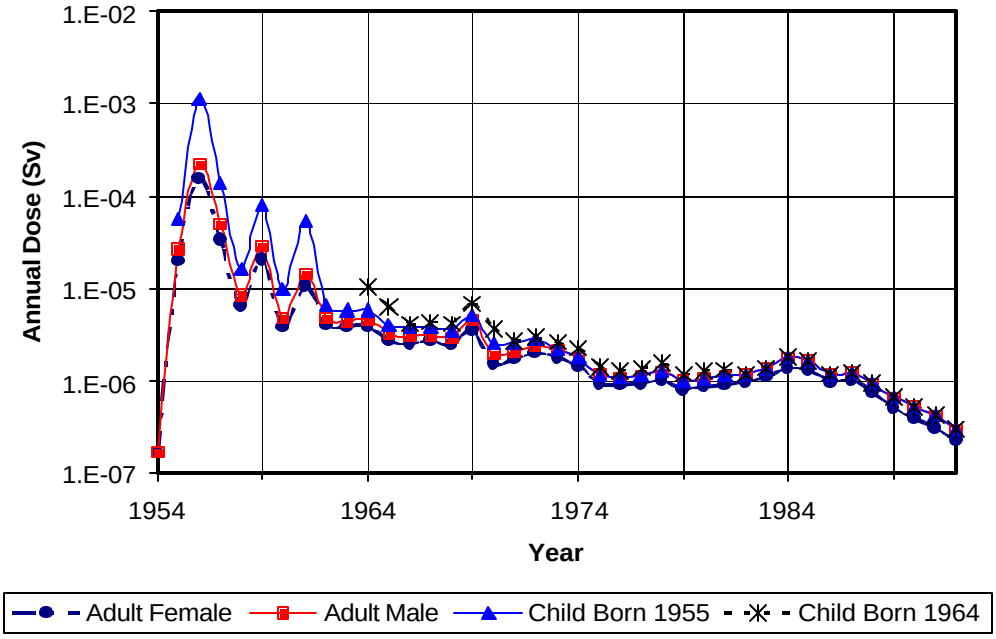


Figure 11-3 Annual Effective Dose (Sv) for Rural Family One

Table 11-4 Annual Effective Dose (mSv) for Rural Family One

	Adult Female		Adult Male		Child Born in 1955		Child Born in 1964	
Year	Dose	%	Dose	%	Dose	%	Dose	%
1954	$1.7x10^{-04}$	0.1	$1.7x10^{-04}$	<0.1				
1955	0.020	6.6	0.027	6.5	0.058	3.6		
1956	0.16	51.6	0.23	53.6	1.2	72.8		
1957	0.034	11.3	0.049	11.6	0.14	8.9		
1958	0.0066	2.2	0.0086	2.0	0.017	1.1		
1959	0.021	7.0	0.030	7.0	0.082	5.2		
1960	0.0039	1.3	0.0048	1.1	0.010	0.6		
1961	0.011	3.6	0.015	3.5	0.055	3.4		
1962	0.0040	1.3	0.0048	1.1	0.0066	0.4		
1963	0.0038	1.3	0.0046	1.1	0.0059	0.4		
1964	0.0039	1.3	0.0048	1.1	0.0059	0.4	0.011	14.7
1965	0.0027	0.9	0.0033	0.8	0.0040	0.3	0.0064	8.9
1966	0.0026	0.9	0.0031	0.7	0.0039	0.2	0.0043	5.9
1967	0.0027	0.9	0.0032	0.8	0.0038	0.2	0.0044	6.1
1968	0.0024	0.8	0.0030	0.7	0.0036	0.2	0.0042	5.9
1969	0.0036	1.2	0.0047	1.1	0.0053	0.3	0.0068	9.4
1970	0.0016	0.5	0.0020	0.5	0.0025	0.2	0.0038	5.2
1971	0.0017	0.6	0.0021	0.5	0.0026	0.2	0.0027	3.8

	Adult Female		Adult Male		Child Born in 1955		Child Born in 1964	
Year	**Dose**	**%**	**Dose**	**%**	**Dose**	**%**	**Dose**	**%**
1972	0.0020	0.7	0.0025	0.6	0.0029	0.2	0.0030	4.2
1973	0.0018	0.6	0.0022	0.5	0.0022	0.1	0.0026	3.6
1974	0.0015	0.5	0.0018	0.4	0.0018	0.1	0.0022	3.1
1975	$9.4x10^{-04}$	0.3	0.0012	0.3	0.0012	0.1	0.0015	2.0
1976	$9.1x10^{-04}$	0.3	0.0011	0.3	0.0011	0.1	0.0013	1.8
1977	$9.4x10^{-04}$	0.3	0.0012	0.3	0.0012	0.1	0.0014	1.9
1978	0.0010	0.3	0.0013	0.3	0.0013	0.1	0.0015	2.1
1979	$8.1x10^{-04}$	0.3	0.0010	0.2	0.0010	0.1	0.0012	1.7
1980	$8.7x10^{-04}$	0.3	0.0011	0.3	0.0011	0.1	0.0013	1.8
1981	$9.1x10^{-04}$	0.3	0.0011	0.3	0.0011	0.1	0.0014	1.9
1982	$9.7x10^{-04}$	0.3	0.0012	0.3	0.0012	0.1	0.0012	1.7
1983	0.0011	0.4	0.0014	0.3	0.0014	0.1	0.0014	2.0
1984	0.0014	0.5	0.0018	0.4	0.0018	0.1	0.0018	2.5
1985	0.0013	0.4	0.0017	0.4	0.0017	0.1	0.0017	2.4
1986	$9.9x10^{-04}$	0.3	0.0012	0.3	0.0012	0.1	0.0012	1.7
1987	0.0010	0.3	0.0013	0.3	0.0013	0.1	0.0013	1.7
1988	$7.4x10^{-04}$	0.2	$9.5x10^{-04}$	0.2	$9.5x10^{-04}$	0.1	$9.5x10^{-04}$	1.3
1989	$5.2x10^{-04}$	0.2	$6.8x10^{-04}$	0.2	$6.8x10^{-04}$	<0.1	$6.8x10^{-04}$	0.9
1990	$4.0x10^{-04}$	0.1	$5.3x10^{-04}$	0.1	$5.3x10^{-04}$	<0.1	$5.3x10^{-04}$	0.7
1991	$3.2x10^{-04}$	0.1	$4.2x10^{-04}$	0.1	$4.2x10^{-04}$	<0.1	$4.2x10^{-04}$	0.6
1992	$2.3x10^{-04}$	0.1	$3.1x10^{-04}$	0.1	$3.1x10^{-04}$	<0.1	$3.1x10^{-04}$	0.4
Total	0.30	100	0.42	100	1.6	100	0.072	100

Most of the dose was received during the first years of site operation. In 1956 the Child Born in 1955 received 1.2 mSv (120 mrem), or 73% of his entire dose, the Adult Female received 0.16 mSv (16 mrem), or 52% of her entire dose, and the Adult Male received 0.23 mSv (23 mrem), or 54% of his entire dose. Doses received during 1955, 1957, 1959, and 1961 were also relatively large. By the end of 1961, all of these three family members had received at least 84% of their entire radiation dose.

The Child Born in 1964 received his largest annual dose in 1964, when he received 0.011 mSv (1.1 mrem) or 15% of his entire dose. It represented about 1% of the largest annual dose received by the Child Born in 1955.

After 1961, the annual dose received by the family members gradually decreased from roughly 0.004 - 0.006 mSv per year to roughly 0.0003 mSv per year. This point is shown in Figure 11-3. When each of the children reached age 18 (in 1973 and 1982, respectively), their annual doses equaled the Adult Male's. This occurred because their radiation exposures were modeled to be the same as the Adult Male's. Annual doses for the Adult Female were always smaller than those for the Adult Male because she always ate less food and inhaled less air.

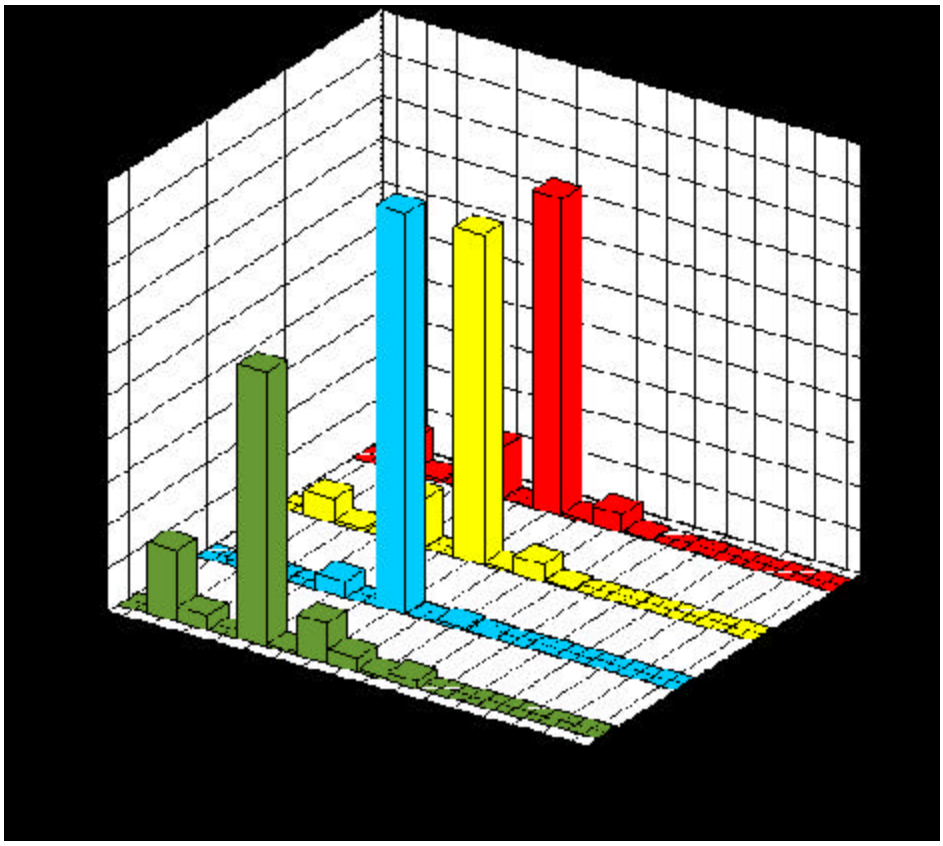


Figure 11-4 lists the radionuclides that caused the largest doses over 39 years for each family member.

The two adults and the Child Born in 1955 were exposed to largely the same quantities and distributions of radionuclides.[7] I-131 caused radiation doses mainly from eating beef and milk. It was also a major contributor to inhalation doses and a secondary contributor to doses from external radiation. Tritium caused radiation doses from ingestion and inhalation. Ar-41 was the largest contributor to doses from external radiation, while Pu-239 (along with I-131) was a major contributor to doses from inhalation. C-14 caused doses mainly through ingestion.

The Child Born in 1964 did not experience the very large releases of I-131 that occurred in the 1950s and early 1960s. Hence, I-131 dropped to third in order of importance for this child. Tritium accounted for most of his dose, primarily through ingestion and inhalation. I-131 was a secondary contributor to ingestion dose, followed by C-14. Ar-41 caused nearly his entire external radiation dose. Pu-238 was an important contributor to inhalation dose.

Most of the radiation dose received by this family came from eating food containing radionuclides (Figure 11-5). Ingestion contributed from 70 to 93 percent of the dose. External exposure to radiation contributed from 2 to17 percent of the dose. Inhalation contributed from 5 to 14 percent of the dose.

[7] Although the two adults received radiation doses during the year 1954, the Child Born in 1955 did not. But because the quantities of radionuclides discharged into the air were small compared to following years, the two adults and the Child Born in 1955 were each affected by nearly the same radionuclide source term.

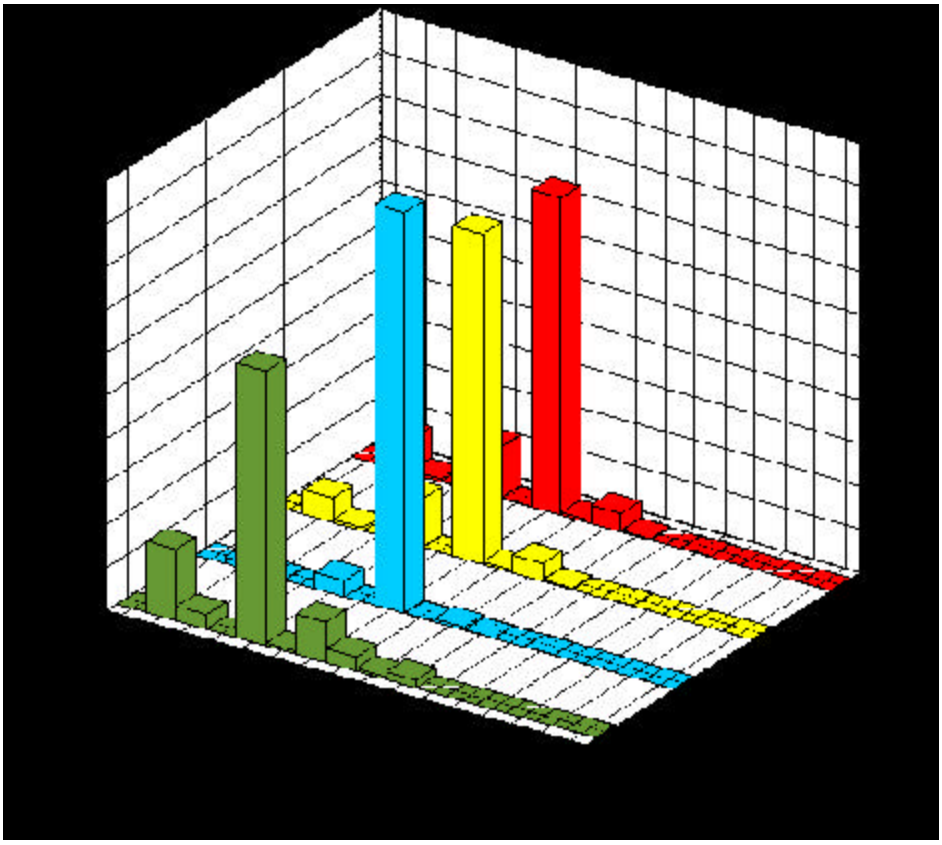


Figure 11-4 Percent of 39-Year Effective Dose by Dominant Isotopes for Rural Family One

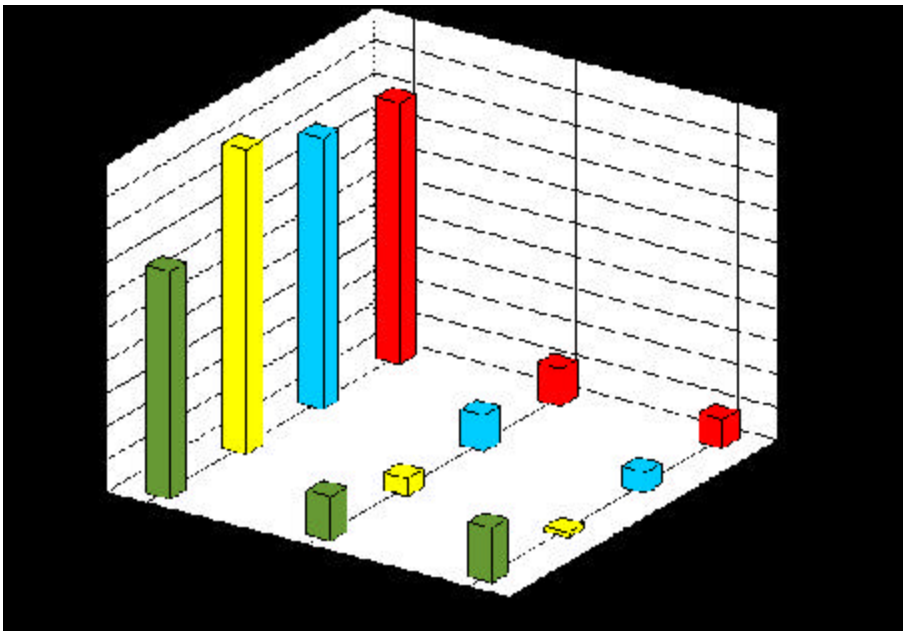


Figure 11-5 Percent of 39-Year Effective Dose by Exposure Route for Rural Family One

Compared to other family members, the Child Born in 1964 received a smaller dose from ingestion and a larger dose from external exposure to radiation and from inhalation. Again, this resulted from his missing the large releases of iodine and other radionuclides during the 1950s and early 1960s.

Table 11-5 lists the effective dose received over 39 years by each family member through each exposure pathway. Figure 11-6 illustrates the percent of effective dose. Tables of effective dose by radionuclide for each route and pathway are provided in Appendix K.

Family members received most of their dose from eating beef and milk. At least 50 percent of the dose received by the two adults came from eating beef, while 15 to 16 percent of their dose came from drinking milk. The Child Born in 1955 received most of his dose from drinking milk (44%) and from eating beef (43%). Beef and milk pathways contributed 51% of the dose received by the Child Born in 1964.

The next largest doses were generally from eating fruits and vegetables – i.e., from 6 to 15 percent of the entire dose over 39 years. Doses from eating grain, poultry, and eggs ranged from 0.4 to 4 percent of the entire dose. Except for the Child Born in 1964, eggs contributed less than 1% of the entire dose.

Table 11-5 Year Effective Dose (mSv) by Exposure Pathway for Rural Family One

		Adult Female		Adult Male		Child Born in 1955		Child Born in 1964	
Route	**Pathway**	**Dose**	**%**	**Dose**	**%**	**Dose**	**%**	**Dose**	**%**
External	Air Immersion	0.024	8.0	0.024	5.7	0.024	1.5	0.012	16.6
	Ground Contamination	0.0024	0.8	0.0025	0.6	0.0024	0.1	$9.3x10^{-5}$	0.1
Ingestion	Beef	0.15	50.7	0.24	57.1	0.69	43.2	0.011	15.3
	Eggs	0.0014	0.5	0.0023	0.6	0.0021	0.1	0.0014	2.0
	Fruit	0.011	3.6	0.0105	2.5	0.043	2.7	0.0054	7.5
	Grain	0.0011	0.4	0.0013	0.3	0.0036	0.2	$6.3x10^{-4}$	0.9
	Leafy Vegetables	0.018	5.9	0.018	4.2	0.030	1.9	$9.7x10^{-4}$	1.3
	Milk	0.049	16.1	0.065	15.3	0.70	43.9	0.026	35.4
	Poultry	0.0010	0.3	0.0012	0.3	0.0013	0.1	$8.1x10^{-4}$	1.1
	Root Vegetables	0.0073	2.4	0.010	2.4	0.014	0.9	0.0044	6.1
	Soil*	$4.9x10^{-7}$	<0.1	$4.9x10^{-7}$	<0.1	$7.4x10^{-6}$	<0.1	$8.1x10^{-8}$	<0.1
Inhalation	Air Inhalation	0.031	10.1	0.041	9.7	0.082	5.1	0.0091	12.6
	Resuspended Soil	0.0040	1.3	0.0054	1.3	0.0037	0.2	$7.9x10^{-4}$	1.1
Total		0.30	100	0.42	100	1.59	100	0.0721	100

*Doses from the soil ingestion pathway were no more than 0.0005% of any family member's entire 39-year dose.

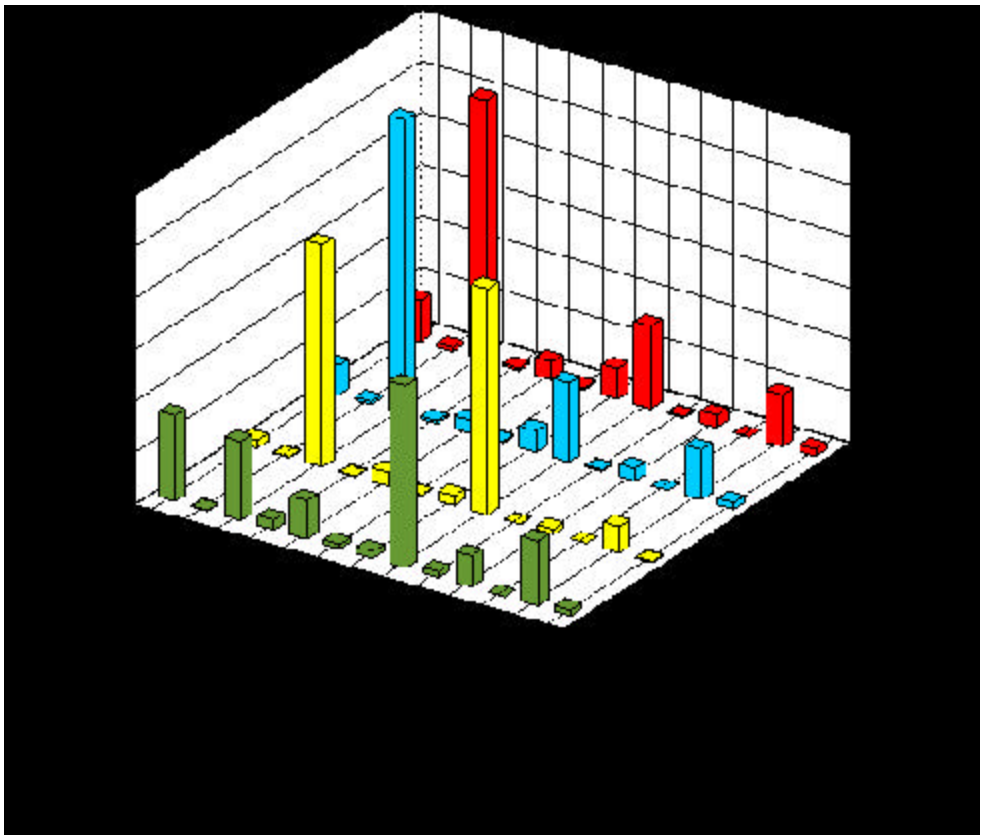


Figure 11-6 Percent of 39-Year Effective Dose by Exposure Pathway for Rural Family One

Differences in doses for the two adults arose because of differences in their eating patterns. For example, the Adult Male and Adult Female each ate the same quantities of leafy vegetables, and each received the same radiation dose from this pathway. But the Adult Male ate 1.6 times as much beef as the Adult Female (see Appendix F), and thus received 1.6 times the dose from this pathway.

The Child Born in 1955 received a larger ingestion dose than did the two adults, especially from drinking milk. His dose from drinking milk was ten times larger than the doses received by the two adults. His doses from most of the other pathways were also somewhat larger. Differences came primarily from changes, as the Child Born in 1955 aged, in his annual rates of eating foods, and, while growing from a child to an adult, his larger effective dose per quantity of radionuclide ingested (see Appendix D).

The Child Born in 1964 received a smaller ingestion dose than did any of the other family members. The distribution of dose among ingestion pathways was also different. The ingestion dose for the Child Born in 1964 was mostly caused by drinking milk and by eating beef containing tritium (see Appendix K).

Of the two external exposure pathways, at least ten times as much dose was received from exposure to radionuclides in the air than from radionuclides that had been deposited on soil or other surfaces.

External doses from air immersion were slightly larger for the two adults than for the Child Born in 1955. Because external radiation doses were determined as if all family members were always adults,[8] the small difference in dose between the two adults and this child resulted from: (1) differences in annual levels of exposure during the years the child attended high school in Waynesboro (the two adults always stayed in Girard); and (2) the additional year of radiation exposure (1954) experienced by the two adults.

For the two adults and the Child Born in 1955, the small differences in doses from external exposure to contaminated ground surfaces were largely caused by differences in the fractions of their time spent indoors and outdoors. Structures provided radiation shielding against exposures from contaminated ground surfaces. Because the Adult Male spent more time outdoors than the Adult Female, he received larger doses. But the Child Born in 1955 spent more time inside in his early years than he did after he grew (see Appendix D). The outcome of these competing influences was that his dose was slightly larger than that for the Adult Female and slightly smaller than that for the Adult Male

Doses from inhalation pathways resulted from: (1) breathing radionuclides that were in the air before being deposited on the ground, and (2) breathing radionuclides that had been resuspended from soil after being deposited on the ground. Clearly most inhalation doses resulted from the first pathway. Only 4 to 12 percent of all inhalation doses came from inhalation of radioactive particles after they had been resuspended from soil.

- For the air inhalation pathway, the Adult Male received a somewhat larger dose than did the Adult Female because he had a larger breathing capacity (see Appendix E). However, the Child Born in 1955 received about twice as much dose as the two adults. This resulted from two competing influences: The breathing rate of the Child Born in 1955 was small as an infant but increased as he grew to manhood; conversely, the dose received per unit quantity of radionuclide inhaled was generally larger during his earlier years than during his later years.[9]

- For the soil resuspension pathway, the inhalation doses for the Adult Male were again larger than those for the Adult Female. However, inhalation doses for the Child Born in 1955 were smaller than those for the two adults. This pattern is different than that seen for the air inhalation pathway. This occurred because the quantities and distributions of radionuclides affecting these individuals were different for this pathway than for the air inhalation pathway, in addition to competing influences such as those described above.[10]

11.2.2 Rural Family Two

This hypothetical family was similar to Rural Family One, except that this family lived in Williston, SC, instead of Girard, GA (Figure 11-7). They spent much of their work, home activities, and recreation time

[8] External radiation dose coefficients are given in [FGR-13U] only for adults, an approximation that the authors of [FGR-13U] concluded would result in relatively small errors. Consequently, doses from external radiation sources were calculated as if all family members were always adults (see Appendix D).

[9] From [FGR-13U], for example, the effective dose coefficients for I-131 inhaled as a vapor are as follows in units of Sv per Bq inhaled: Infant (1.30×10^{-7}), 1-Year-Old (1.27×10^{-7}), 5-Year-Old ($7\ 34 \times 10^{-8}$); 10-Year-Old (3.71×10^{-8}), 15-Year-Old (2.43×10^{-8}), and Adult (1.54×10^{-8}). Doses per unit quantity of I-131 inhaled decrease for each successive age group.

[10] The Child Born in 1955 received a larger dose than the two adults for the air inhalation pathway but a smaller dose than the two adults for the resuspension pathway. This probably occurred because the family members were exposed to different quantities and distributions of radionuclides for the air inhalation pathway than for the resuspension pathway. For the air inhalation pathway, radionuclides were inhaled from a plume of radionuclides in air surrounding each family member. But radionuclides inhaled due to the resuspension pathway had to be first deposited on the soil and then dispersed back into the air due to wind or activities such as farming that disturbed the soil. Different radionuclides were deposited onto soil at different rates depending on their physical form (e.g., whether they existed as gasses or particulates). In addition, the concentrations of radionuclides in air from resuspension of radioactive particles from soil were 100 times smaller in Waynesboro, where the children attended high school, than in Girard (see Chapter 9).

outdoors. The Adult Male was a farmer and the Adult Female worked at home. The family hunted, fished, and swam in the Williston area. This family did no boating. The children attended grade and high school in Williston. When they grew up, the children became farmers, adopting the same activities as did their adult male parent.

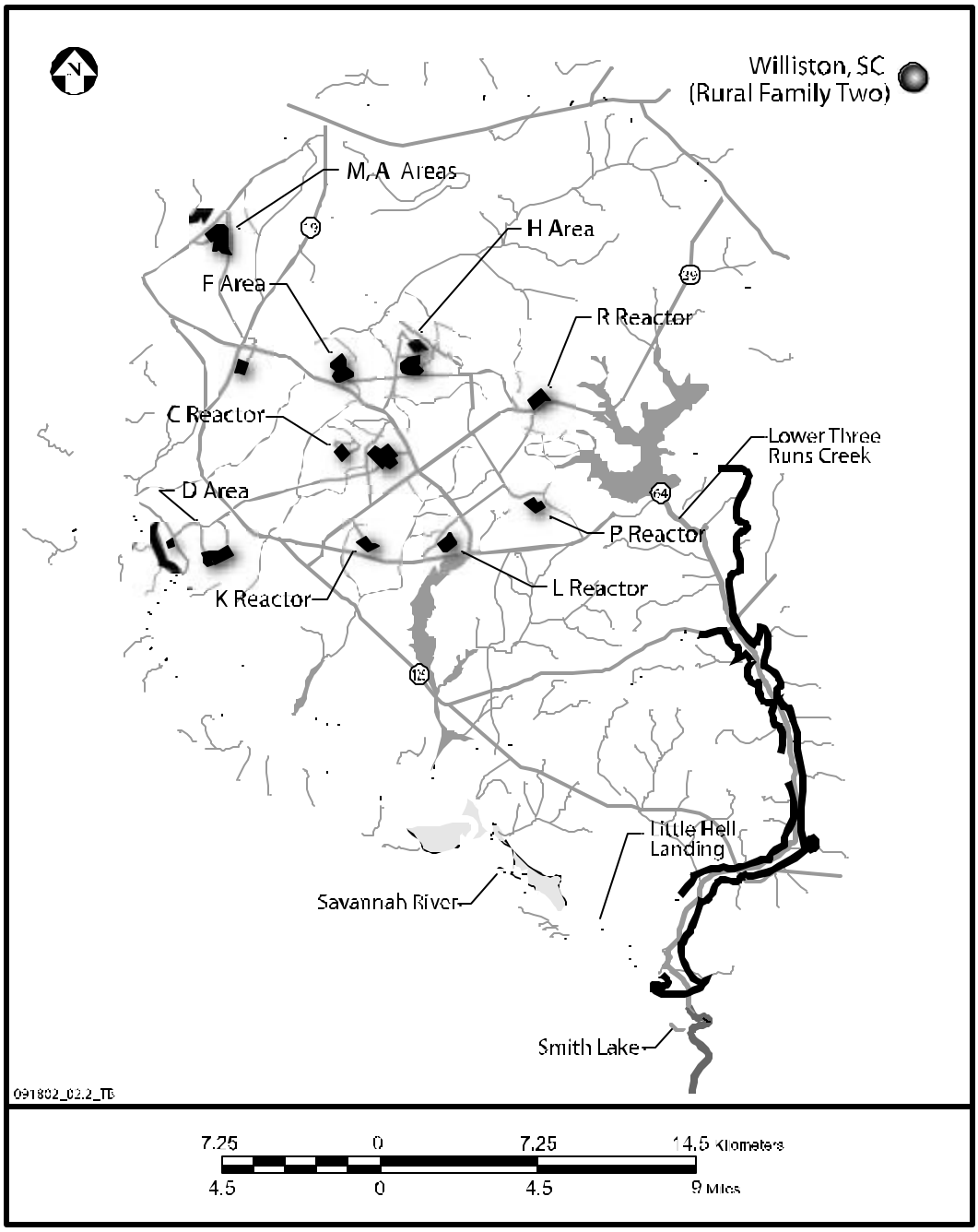


Figure 11-7 Exposure Location for Rural Family Two

All of the family's milk and eggs came from cows and hens located in Williston (on the family farm or nearby). All the fish eaten by the family was caught in streams and ponds in or near Williston. Because these streams and ponds are not located hydrologically downstream from SRS, none of the fish eaten by the family were affected by SRS release of radionuclides to surface water.

During the 1950s, 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% of their beef, poultry, vegetables, and fruit was grown or produced on the family farm. The remaining 75% 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.

11.2.2.1 Effective Dose and Total Risks

Table 11-6 lists the effective dose and cancer risks for each member of Rural Family Two over 39 years of SRS operation. All doses and risks resulted from exposure to radionuclides that had been released into the air.

Table 11-6 39-Year Effective Dose and Cancer Risks for Rural Family Two

Dose or Risk	Adult Female	Adult Male	Child Born in 1955	Child Born in 1964
Effective Dose (mSv)	0.70	0.97	3.8	0.14
Cancer Incidence Risk (%)	0.0019	0.0025	0.037	0.0021
Cancer Fatality Risk (%)	0.00064	0.00080	0.0056	0.0013

Doses and risks were about double those for Rural Family One (Table 11-3), which mainly resulted from the different exposure location (Williston vs. Girard and Waynesboro). The Child Born in 1955 received the largest dose and risks. He received an effective dose over 39 years of 3.8 mSv (380 millirems), a cancer incidence risk of 0.037%, and a cancer fatality risk of 0.0056%. The Child Born in 1964 again received the smallest dose and risks. The dose for the Child Born in 1964 was about 4% of that for the Child Born in 1955.

11.2.2.2 Effective Dose by Year

Figure 11-8 shows the percent of the entire 39-year effective dose received each year by each family member, while Figure 11-9 shows the annual effective dose (in units of Sieverts) received by each family member. Again, the vertical axis (y-axis) of Figure 11-9 is in logarithmic scale. The shapes of each figure are similar to corresponding figures for Rural Family One (Figure 11-2 and Figure 11-3). More detailed information is contained in Table 11-7 which lists the percent of the entire 39-year effective dose received each year by each family member, as well as their annual dose in milliSieverts.

Most of the dose was received during the early days of site operation. In 1956, the Child Born in 1955 received 2.8 mSv (280 mrem), or 74% of his entire dose over 39 years. During this year the Adult Female received 0.37 mSv (37 mrem), or 54% of her entire dose, and the Adult Male received 0.54 mSv (54 mrem), or 56% of his entire dose. The Child Born in 1964 received his largest dose in 1964 when he received 0.020 mSv (2 mrem), or 15% of his entire dose over 39 years.

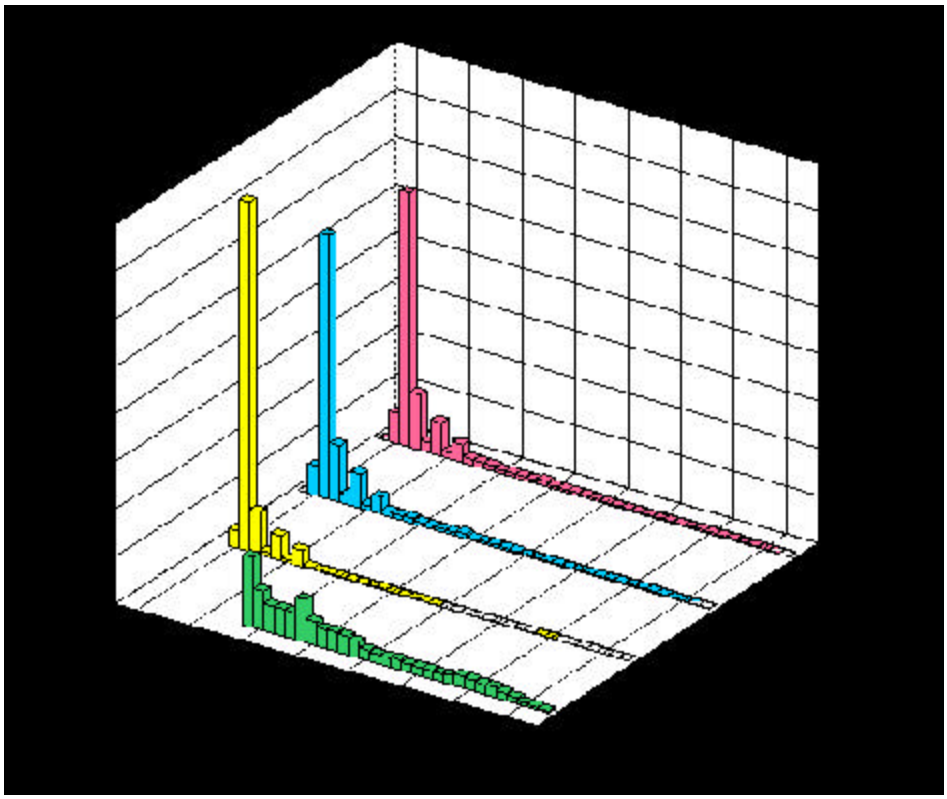


Figure 11-8 Percent of 39-Year Effective Dose by Year for Rural Family Two

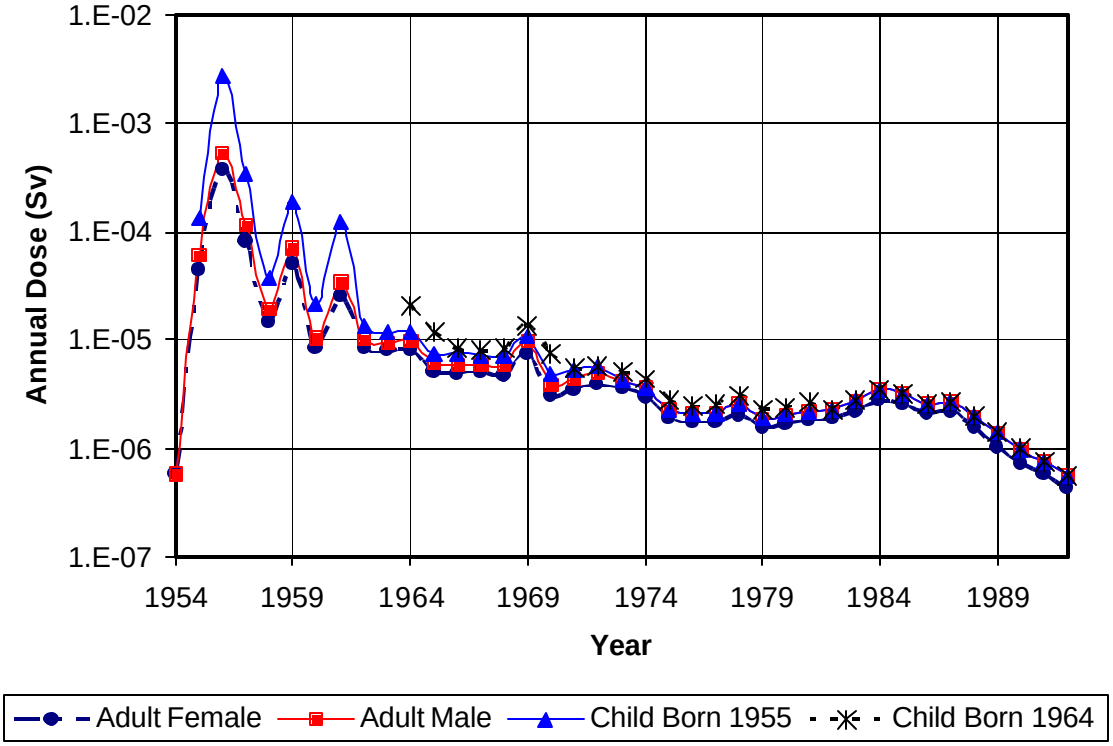


Figure 11-9 Annual Effective Dose (Sv) for Rural Family Two

Table 11-7 Annual Effective Dose (mSv) for Rural Family Two

	Adult Female		Adult Male		Child Born in 1955		Child Born in 1964	
Year	**Dose**	**%**	**Dose**	**%**	**Dose**	**%**	**Dose**	**%**
1954	$5.7x10^{-04}$	0.1	$5.8x10^{-04}$	0.1				
1955	0.045	6.5	0.061	6.3	0.14	3.6		
1956	0.37	53.6	0.54	55.5	2.8	73.7		
1957	0.081	11.6	0.12	11.9	0.33	8.9		
1958	0.015	2.1	0.019	2.0	0.037	1.0		
1959	0.049	7.1	0.070	7.1	0.19	5.1		
1960	0.0084	1.2	0.010	1.1	0.022	0.6		
1961	0.025	3.6	0.035	3.6	0.13	3.4		
1962	0.0084	1.2	0.010	1.0	0.014	0.4		
1963	0.0079	1.1	0.0094	1.0	0.012	0.3		
1964	0.0080	1.1	0.0096	1.0	0.012	0.3	0.025	14.9
1965	0.0051	0.7	0.0061	0.6	0.0074	0.2	0.014	8.2
1966	0.0049	0.7	0.0059	0.6	0.0073	0.2	0.0094	5.7
1967	0.0051	0.7	0.0060	0.6	0.0071	0.2	0.0095	5.8
1968	0.0048	0.7	0.0058	0.6	0.0071	0.2	0.0094	5.7
1969	0.0075	1.1	0.0097	1.0	0.011	0.3	0.015	9.0
1970	0.0031	0.4	0.0038	0.4	0.0049	0.1	0.0083	5.0
1971	0.0035	0.5	0.0043	0.4	0.0053	0.1	0.0065	4.0
1972	0.0039	0.6	0.0048	0.5	0.0057	0.2	0.0068	4.1
1973	0.0036	0.5	0.0043	0.4	0.0043	0.1	0.0064	3.9
1974	0.0029	0.4	0.0036	0.4	0.0036	0.1	0.0055	3.4
1975	0.0018	0.3	0.0023	0.2	0.0023	0.1	0.0036	2.2
1976	0.0018	0.3	0.0021	0.2	0.0021	0.1	0.0031	1.9
1977	0.0017	0.3	0.0022	0.2	0.0022	0.1	0.0031	1.9
1978	0.0020	0.3	0.0026	0.3	0.0026	0.1	0.0036	2.2
1979	0.0015	0.2	0.0019	0.2	0.0019	0.1	0.0028	1.7
1980	0.0017	0.2	0.0020	0.2	0.0020	0.1	0.0029	1.8
1981	0.0018	0.3	0.0022	0.2	0.0022	0.1	0.0031	1.9
1982	0.0019	0.3	0.0023	0.2	0.0023	0.1	0.0028	1.7
1983	0.0022	0.3	0.0027	0.3	0.0027	0.1	0.0032	2.0
1984	0.0027	0.4	0.0035	0.4	0.0035	0.1	0.0041	2.5
1985	0.0025	0.4	0.0032	0.3	0.0032	0.1	0.0038	2.3
1986	0.0021	0.3	0.0026	0.3	0.0026	0.1	0.0035	2.1
1987	0.0022	0.3	0.0027	0.3	0.0027	0.1	0.0034	2.1
1988	0.0016	0.2	0.0020	0.2	0.0020	0.1	0.0025	1.5
1989	0.0010	0.1	0.0014	0.1	0.0014	<0.1	0.0019	1.1
1990	$7.4x10^{-04}$	0.1	$9.8x10^{-04}$	0.1	$9.8x10^{-04}$	<0.1	0.0010	0.6
1991	$5.7x10^{-04}$	0.1	$7.6x10^{-04}$	0.1	$7.6x10^{-04}$	<0.1	$8.3x10^{-04}$	0.5
1992	$4.2x10^{-04}$	0.1	$5.6x10^{-04}$	0.1	$5.6x10^{-04}$	<0.1	$5.6x10^{-04}$	0.3
Total	0.70	100	0.97	100	3.8	100	0.16	100

11.2.2.3 Dominant Radionuclides, Exposure Routes, and Pathways

Figure 11-10 shows the radionuclides that caused the largest doses over 39 years for each family member.

Generally similar radionuclides dominated dose to each family member as those for Rural Family One (see Figure 11-4). Yet there were small differences: For example, the two adults received larger doses from Pu-238 than from C-14 (unlike Rural Family One), and the distribution of dose from the principal radionuclides was slightly different (e.g., I-131 caused 74% of the dose to the Adult Male in Rural Family One and 79% of the dose to the Adult Male in Rural Family Two).

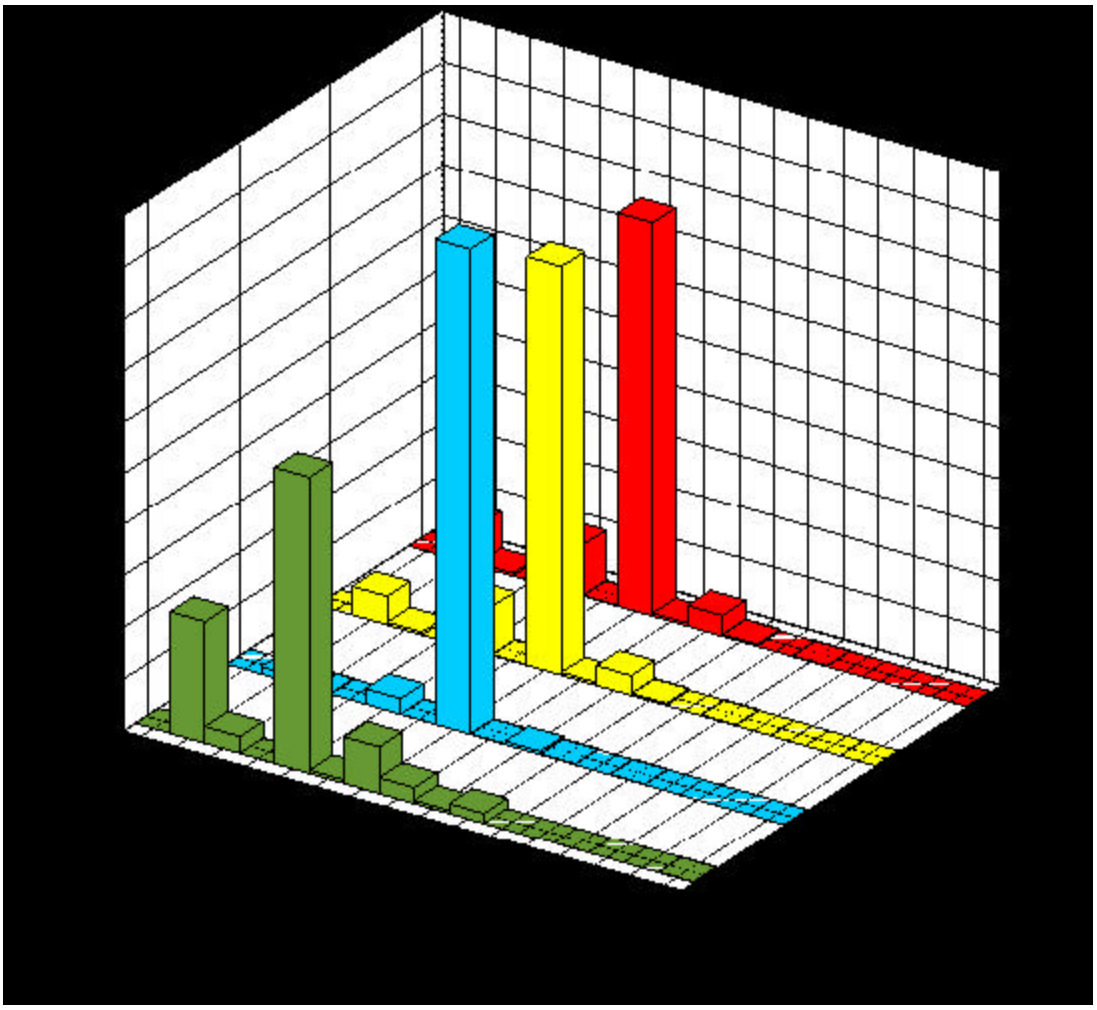


Figure 11-10 Percent of 39-Year Effective Dose by Dominant Isotopes for Rural Family Two

These differences occurred because Rural Families One and Two were located at different directions and distances from the points were radionuclides were released from SRS into the air. The distributions of average wind speeds and stability classes were different, resulting in different patterns of radionuclide dispersion in air. The average concentrations of radionuclides in air were different, over the 39 years considered in the study, at Waynesboro than they were at Girard.

Most of the radiation dose received by this family came from eating foods containing radionuclides (Figure 11-11). All family members received from 68 to 94 of their entire dose over 39 years from

ingestion. From 2 to 19 percent of their entire dose came from exposure to external radiation, and from 5 to 14 percent of their entire dose came from inhalation of radionuclides. This pattern of dose is similar to that seen for Rural Family One (Figure 11-5).

Table 11-8 lists the effective dose over 39 years, by pathway, for each family member. Figure 11-12 illustrates the percent of the effective dose received through each pathway over 39 years. Although the doses listed in Table 11-8 are larger for each pathway than those for Rural Family One (Table 11-5), the percent of dose caused by each pathway was similar.

For all family members, and especially the Child Born in 1955, most of their dose came from eating beef and milk (i.e., from 50 to 88 percent of their entire dose). For all family members, from 5 to 14 percent of their entire dose came from eating fruit and vegetables. A smaller dose was received from eating grain, poultry, and eggs. Eating these three foods contributed from 0.4 to 4 percent of each family member's entire dose. Relatively tiny doses came from inadvertently eating soil containing radionuclides – i.e., no more than 0.0005% of any family member's entire dose.

Most of the dose from external exposure to radiation came from immersion in a plume of air contaminated with radionuclides, rather than from radionuclides after they had been deposited on the ground. Similarly, most inhalation doses came from inhalation of radionuclides from this contaminated plume, as opposed to inhalation of radionuclides that had been resuspended from soil. This pattern is comparable to that seen for Rural Family One.

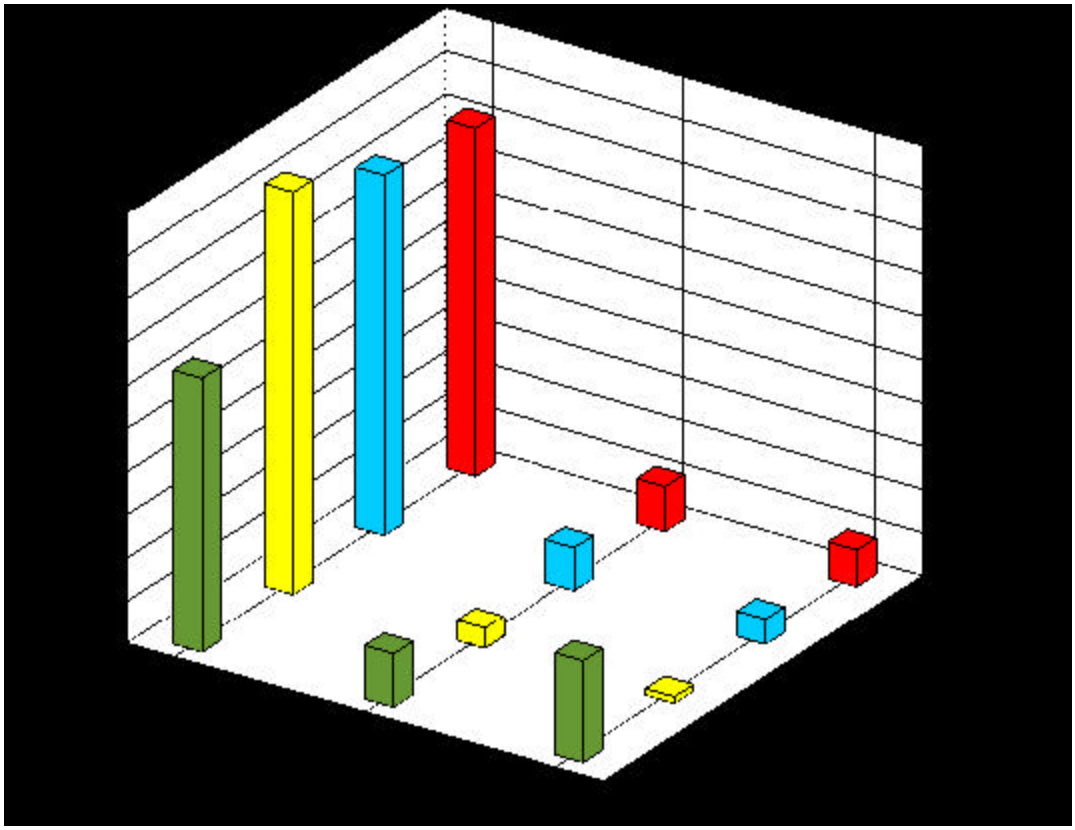


Figure 11-11 Percent of 39-Year Effective Dose by Exposure Route for Rural Family Two

Table 11-8 39-Year Effective Dose (mSv) by Exposure Pathway for Rural Family Two

		Adult Female		Adult Male		Child Born in 1955		Child Born in 1964	
Route	**Pathway**	**Dose**	**%**	**Dose**	**%**	**Dose**	**%**	**Dose**	**%**
External	Air								
	Immersion	0.054	7.8	0.054	5.6	0.054	1.4	0.039	23.5
	Ground Contamination	0.0056	0.8	0.0060	0.6	0.0057	0.2	$2.2x10^{-4}$	0.1
Ingestion	Beef	0.36	52.4	0.57	58.8	1.64	43.7	0.024	14.6
	Eggs	0.0027	0.4	0.0044	0.5	0.0040	0.1	0.0029	1.8
	Fruit	0.023	3.3	0.023	2.3	0.10	2.7	0.011	6.8
	Grain	0.0023	0.3	0.0028	0.3	0.0082	0.2	0.0013	0.8
	Leafy Vegetables	0.042	6.0	0.042	4.3	0.071	1.9	0.0021	1.3
	Milk	0.11	16.1	0.15	15.3	1.66	44.2	0.053	32.4
	Poultry	0.0019	0.3	0.0024	0.2	0.0024	0.1	0.0017	1.0
	Root Vegetables	0.015	2.1	0.021	2.1	0.029	0.8	0.0086	5.2
	Soil*	$1.2x10^{-6}$	<0.1	$1.2x10^{-6}$	<0.1	$1.8x10^{-5}$	<0.1	$1.9x10^{-7}$	<0.1
Inhalation	Air								
	Inhalation	0.063	9.0	0.084	8.7	0.17	4.6	0.019	11.4
	Resuspended Soil	0.0099	1.4	0.013	1.4	0.0093	0.2	0.0019	1.2
	Total:	0.70	100	0.97	100	3.8	100	0.16	100

*Doses from the soil ingestion pathway were no more than 0.0005% of any family member's entire 39-year dose.

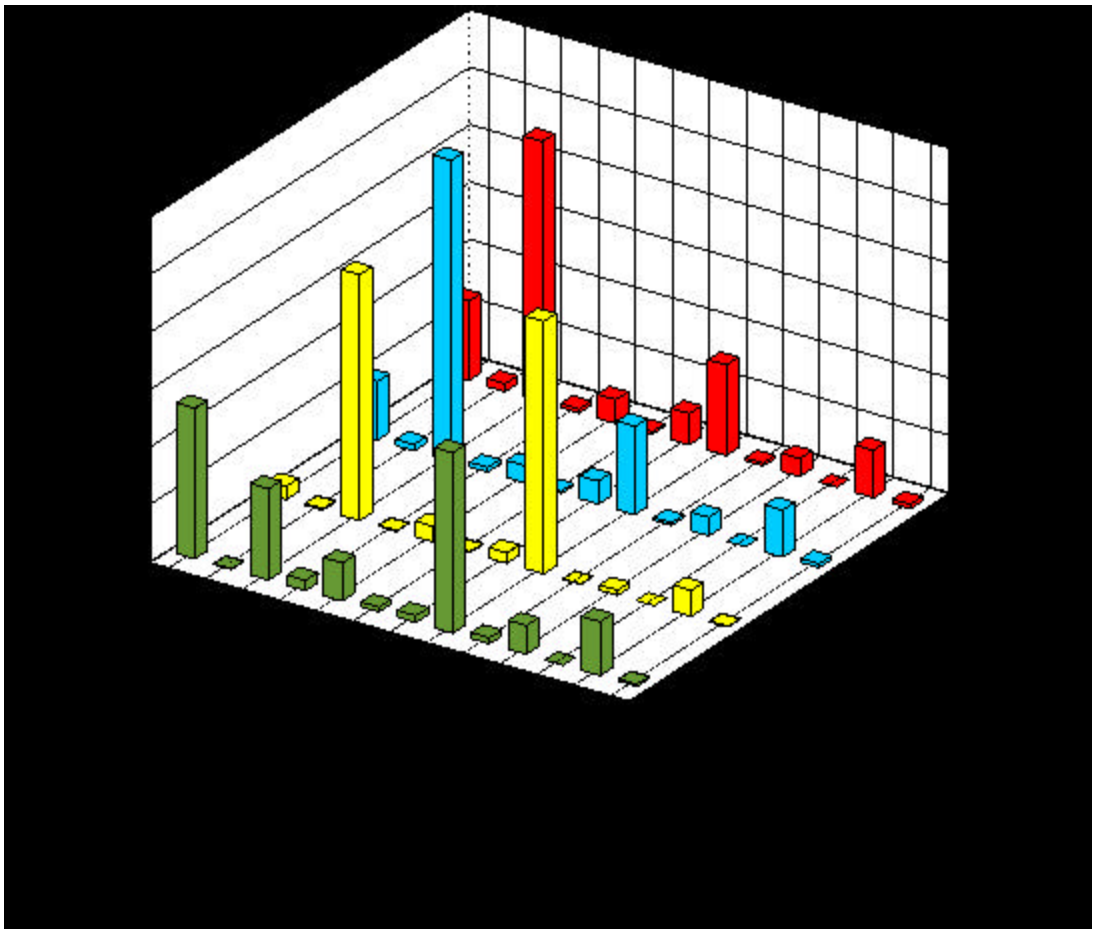


Figure 11-12 Percent of 39-Year Effective Dose (mSv) by Exposure Pathway for Rural Family Two

11.2.3 Urban/Suburban Family

This hypothetical family lived in Augusta, GA, and, except for employment for the Adult Male and for the children when they each reached age 18, all family members stayed in Augusta for all activities, including school and church (Figure 11-13). The Adult Male worked onsite at SRS for all 39 years. When the children grew up, they lived in Augusta and worked onsite at SRS (beginning in 1973 for the Child Born in 1955 and in 1982 for the Child Born in 1964). All family members swam, boated, and fished in the Savannah River flowing through Augusta upstream of SRS.

Half the family's milk came from cows located in the Augusta area, and half came from cows located in the New Ellenton area. All eggs came from hens located in the Augusta area. Half of the beef, poultry, leafy vegetables, root vegetables, and fruit was grown or produced in the Augusta area, and half came from unaffected non-local sources. All of the corn eaten by the family was grown locally. Fish came from surface water sources assumed by be unaffected by releases from SRS (e.g., from the Savannah River upstream of SRS).

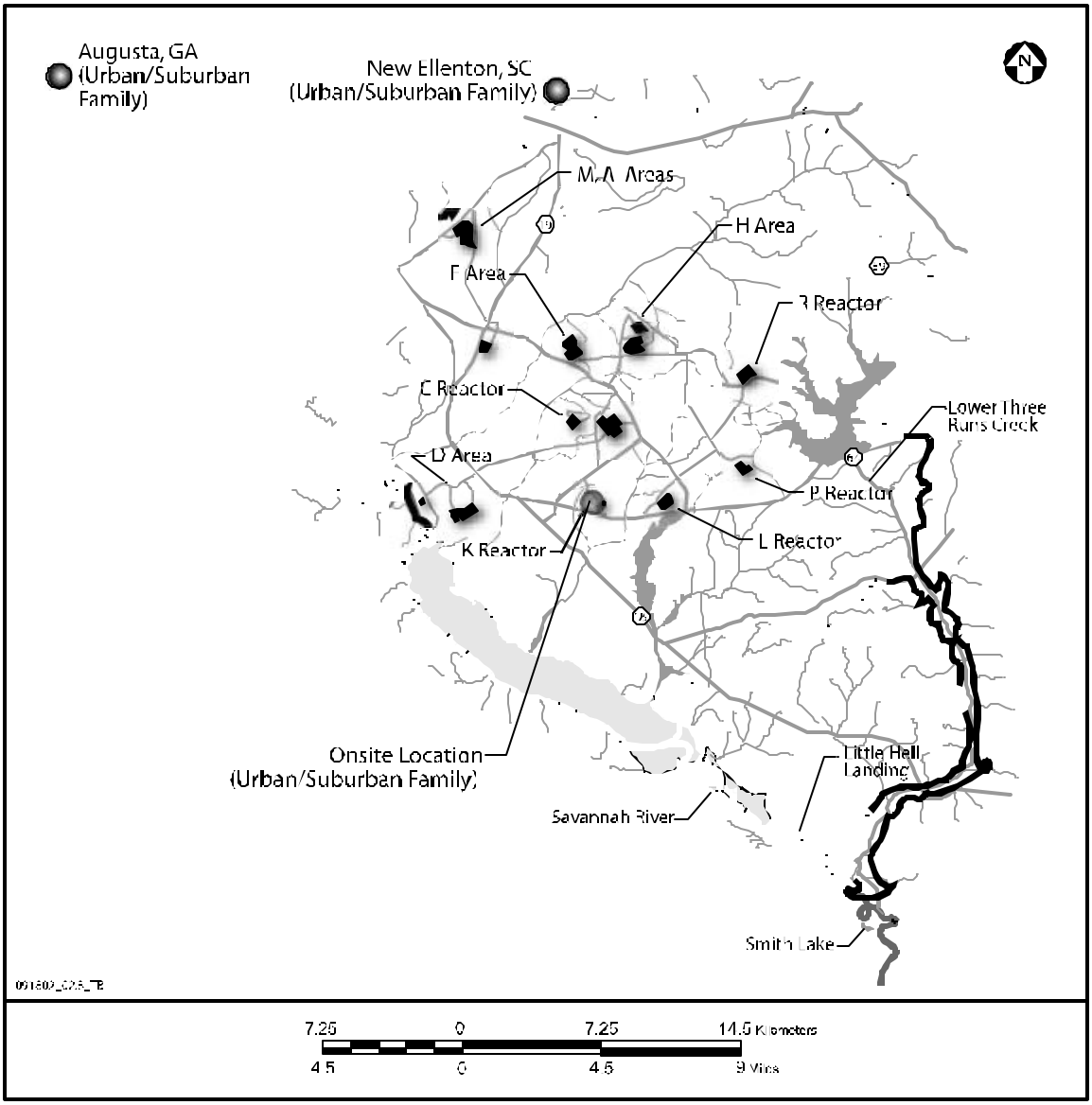


Figure 11-13 Exposure Locations for Urban/Suburban Family

11.2.3.1 Doses and Total Risks

Table 11-9 lists the effective dose and cancer risks determined for each member of the Urban/Suburban Family over 39 years of SRS operation. All doses and risks came from exposure to radionuclides that had been released into the air.

The Child Born in 1955 received the largest radiation dose and cancer risks in the scenario. He received an effective dose of 2.7 mSv (270 mrem), a cancer incidence risk of 0.027%, and a cancer fatality risk of 0.0041%. The Child Born in 1964 received the smallest dose and risks which is 4% of that for the Child Born in 1955.

Table 11-9 39-Year Effective Dose and Cancer Risks for Urban/Suburban Family

Dose or Risk	Adult Female	Adult Male	Child Born in 1955	Child Born in 1964
Effective Dose (mSv)	0.33	0.73	2.7	0.11
Cancer Incidence Risk (%)	0.00090	0.0025	0.027	0.0016
Cancer Fatality Risk (%)	0.00032	0.0013	0.0041	0.00098

The Adult Male received more than twice the dose than did the Adult Female. This difference in dose between the two adults is more significant than was the case for Rural Family One (Table 11-3) and Rural Family Two (Table 11-6). The reason is as follows: For the Urban/Suburban Scenario the Adult Female spent her entire time in the Augusta area, while the Adult Male spent 2000 hours each year on the SRS site. But for the two rural family scenarios, the Adult Male and Adult Female both spent their entire time "at home" in Girard and Williston.

11.2.3.2 Effective Dose by Year

Figure 11-14 shows the percent of the entire 39-year effective dose received each year by each family member, while Figure 11-15 shows the annual effective dose (in units of Sieverts) received by each family member. Table 11-10 lists the percent of the entire 39-year effective dose received each year by each family member, as well as their annual dose. Again, most of the dose was received during the early days of site operation.

In 1956, the Child Born in 1955 received 2.0 mSv (200 mrem), or 73% of his entire dose. During this year, the Adult Female received 0.17 Sv (17 mrem), or 53% of her entire dose, and the Adult Male received 0.26 mSv (26 mrem), or 36% of his entire dose.[11] In 1964, the Child Born in 1964 received 0.014 mSv (1.4 mrem), or 13% of his entire dose. This dose was 1% of the largest annual dose received by the Child Born in 1955.

[11] This information was obtained from the tables of effective dose by year presented in Appendix I for each scenario and receptor.

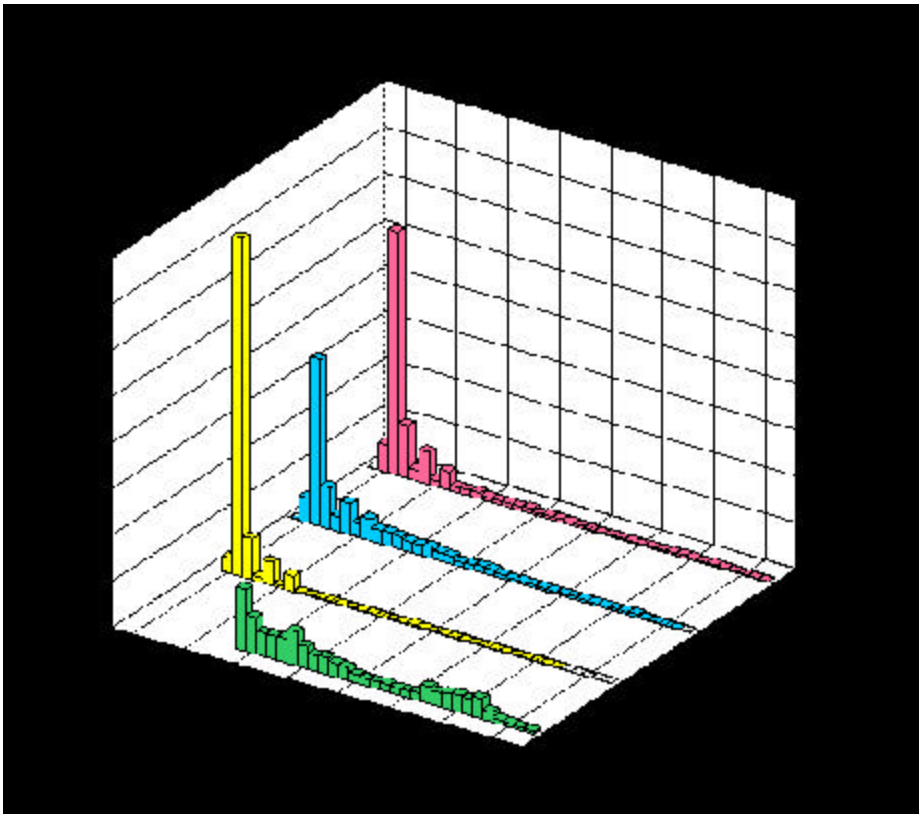


Figure 11-14 Percent of 39-Year Effective Dose by Year for Urban/Suburban Family

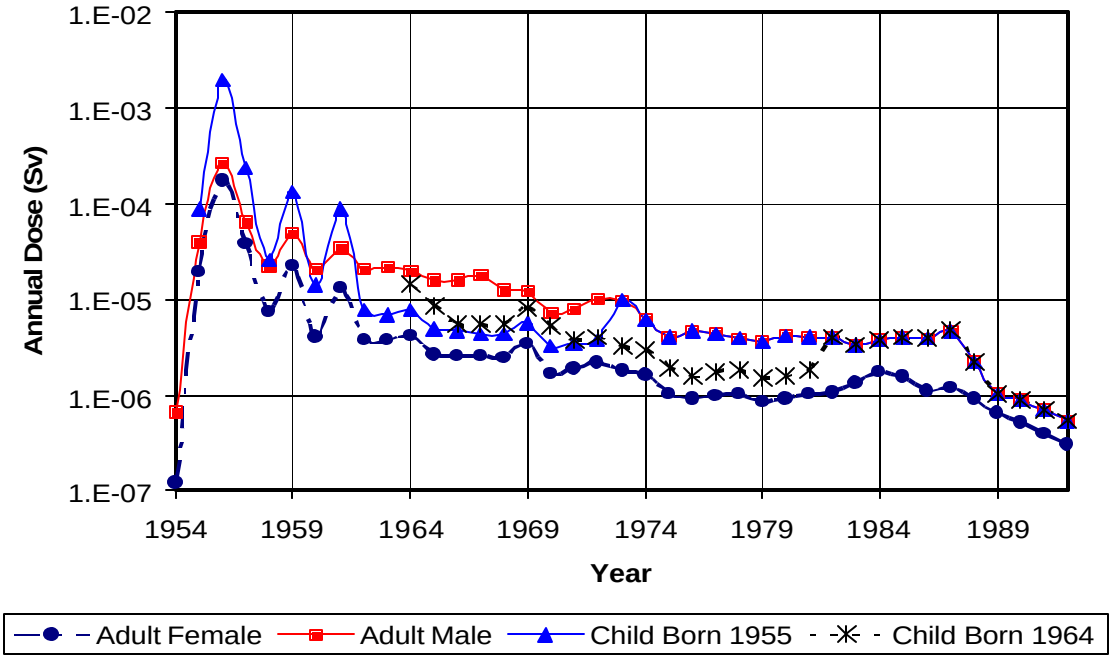


Figure 11-15 Annual Effective Dose (Sv) for Urban/Suburban Family

Table 11-10 Annual Effective Dose (mSv) for Urban/Suburban Family

	Adult Female		Adult Male		Child Born in 1955		Child Born in 1964	
Year	**Dose**	**%**	**Dose**	**%**	**Dose**	**%**	**Dose**	**%**
1954	$1.2x10^{-04}$	0.0	$6.7x10^{-04}$	0.1				
1955	0.021	7.9	0.046	7.0	0.046	2.7		
1956	0.13	49.7	0.21	32.1	1.2	71.5		
1957	0.030	10.9	0.055	8.3	0.15	8.7		
1958	0.0062	2.3	0.021	3.2	0.018	1.0		
1959	0.018	6.7	0.043	6.5	0.084	5.0		
1960	0.0036	1.3	0.020	3.0	0.010	0.6		
1961	0.010	3.9	0.030	4.6	0.059	3.5		
1962	0.0034	1.3	0.020	3.1	0.0059	0.4		
1963	0.0033	1.2	0.022	3.3	0.0054	0.3		
1964	0.0037	1.4	0.019	2.9	0.0060	0.4	0.0081	9.5
1965	0.0024	0.9	0.016	2.4	0.0039	0.2	0.0064	7.5
1966	0.0023	0.8	0.016	2.4	0.0037	0.2	0.0041	4.8
1967	0.0023	0.8	0.018	2.7	0.0035	0.2	0.0041	4.8
1968	0.0022	0.8	0.013	1.9	0.0035	0.2	0.0042	4.9
1969	0.0039	1.4	0.013	2.0	0.0057	0.3	0.0072	8.4
1970	0.0015	0.5	0.0068	1.0	0.0025	0.1	0.0038	4.5
1971	0.0016	0.6	0.0077	1.2	0.0027	0.2	0.0028	3.3
1972	0.0019	0.7	0.0096	1.5	0.0030	0.2	0.0031	3.6
1973	0.0016	0.6	0.0096	1.5	0.0096	0.6	0.0025	3.0
1974	0.0014	0.5	0.0059	0.9	0.0059	0.3	0.0023	2.7
1975	0.0010	0.3	0.0040	0.6	0.0040	0.2	0.0015	1.7
1976	$9.1x10^{-04}$	0.3	0.0047	0.7	0.0047	0.3	0.0012	1.4
1977	$9.9x10^{-04}$	0.3	0.0042	0.6	0.0042	0.3	0.0014	1.6
1978	0.0010	0.4	0.0037	0.6	0.0037	0.2	0.0015	1.8
1979	$8.6x10^{-04}$	0.3	0.0035	0.5	0.0035	0.2	0.0012	1.4
1980	$9.0x10^{-04}$	0.3	0.0042	0.6	0.0042	0.2	0.0012	1.4
1981	0.0009	0.3	0.0039	0.6	0.0039	0.2	0.0014	1.7
1982	0.0009	0.3	0.0038	0.6	0.0038	0.2	0.0038	4.5
1983	0.0011	0.4	0.0031	0.5	0.0031	0.2	0.0031	3.6
1984	0.0015	0.5	0.0034	0.5	0.0034	0.2	0.0034	4.0
1985	0.0013	0.5	0.0038	0.6	0.0038	0.2	0.0038	4.5
1986	0.0010	0.4	0.0037	0.6	0.0037	0.2	0.0037	4.3
1987	0.0010	0.4	0.0045	0.7	0.0045	0.3	0.0045	5.3
1988	$9.3x10^{-04}$	0.3	0.0021	0.3	0.0021	0.1	0.0021	2.4
1989	$6.4x10^{-04}$	0.2	0.0010	0.1	0.0010	0.1	0.0010	1.1
1990	$5.1x10^{-04}$	0.2	$8.7x10^{-04}$	0.1	$8.7x10^{-04}$	<0.1	$8.7x10^{-04}$	0.9
1991	$3.9x10^{-04}$	0.1	$7.0x10^{-04}$	0.1	$7.0x10^{-04}$	<0.1	$7.0x10^{-04}$	0.7
1992	$3.0x10^{-04}$	0.1	$5.4x10^{-04}$	0.1	$5.4x10^{-04}$	<0.1	$5.4x10^{-04}$	0.6

Total	0.2702	100	0.6588	100	1.6789	100	0.0856	100

The pattern shown in Figure 11-15 differs notably from that shown for Rural Family One (Figure 11-3) and Rural Family Two (Figure 11-9). For the two rural families, the annual doses for all family members were similar after the mid 1960s. But for the Urban/Suburban Family, annual doses for some members differed after the mid 1960s, for the following reasons: Although the Adult Male always worked on the SRS site, the children spent their early years entirely in Augusta. But when the children began work in 1973 and 1982, respectively, their annual doses equaled those for the Adult Male. The Adult Female always stayed in Augusta.

11.2.3.3 Exposure Routes and Pathways

Figure 11-16 shows the radionuclides that were the largest contributors of dose over 39 years for each family member.

The major contributors to dose were essentially the same as those identified for Rural Family One (Figure 11-4) and Rural Family Two (Figure 11-9Figure 11-10). Of interest is the larger importance of Ar-41, compared to tritium, for the Adult Male.

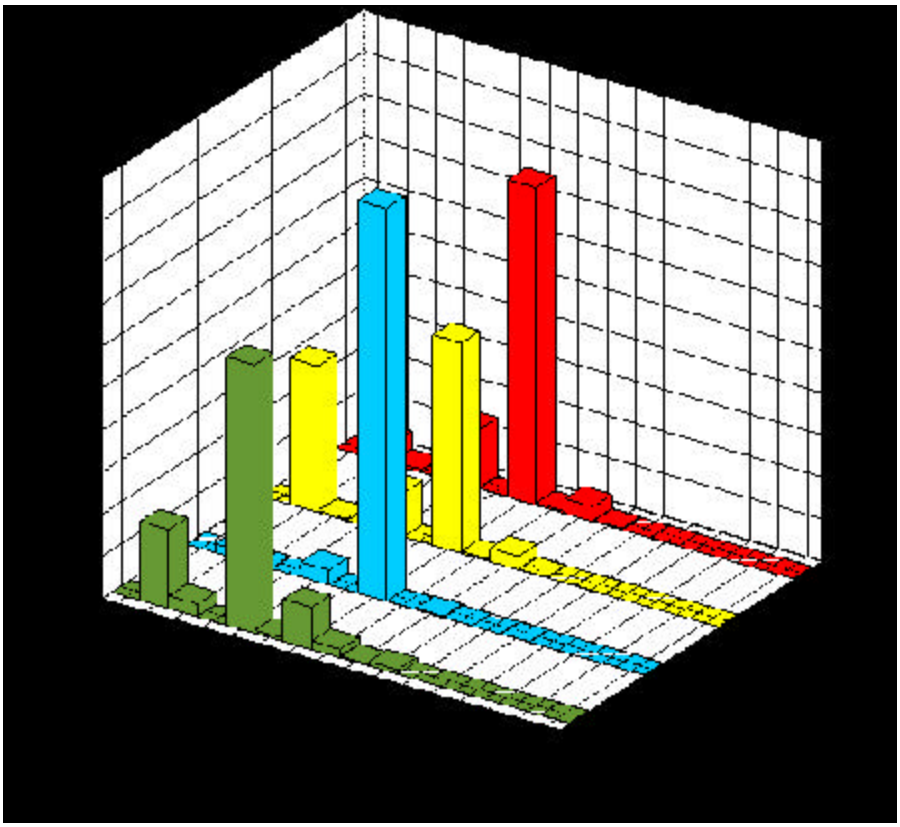


Figure 11-16 Percent of 39-Year Effective Dose by Dominant Isotopes for Urban/Suburban Family

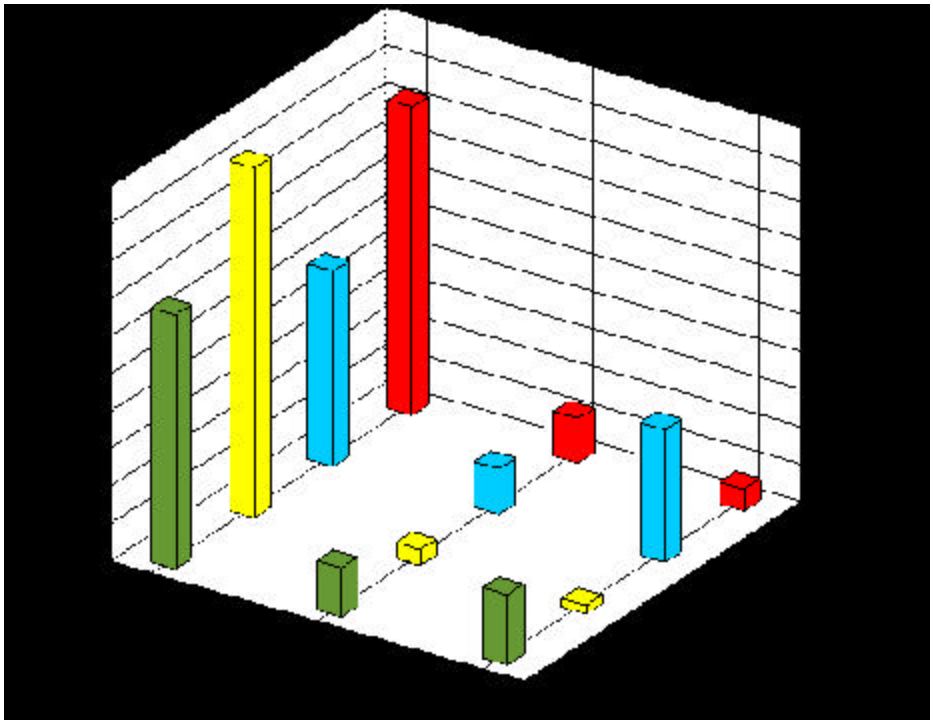


Figure 11-17 Percent of 39-Year Effective Dose by Exposure Route for Urban/Suburban Family

The larger dose from Ar-41 is partially illustrated by Figure 11-17. External exposure to radiation caused 36% of the entire dose for the Adult Male, a larger percent than that for any other member of the family.[12] Otherwise, doses from ingestion were again important. For all family members, from 52 to 93 percent of their entire 39-year dose came from eating foods containing radionuclides. Except for the Adult Male, the contribution to dose by ingestion was comparable to that seen for Rural Family One (Figure 11-5) and Rural Family Two (Figure 11-11).

Table 11-11 and Figure 11-18 show the dose, and percent of dose, over 39 years by pathway for each member of the family. The foods that contributed most to radiation dose were beef and milk. For all family members, from 48 to 91 percent of their entire dose came from eating beef and milk. The next largest doses generally came from eating fruit and vegetables (from 2 to 9 percent of their entire dose). Eating grain, poultry, and eggs contributed from 0.2 to 3 percent of their entire dose. Inadvertently eating soil containing radionuclides contributed no more than 0.0003% of any family member's entire dose.

Table 11-11 39-Year Effective Dose (mSv) by Exposure Pathway for Urban/Suburban Family

		Adult Female		Adult Male		Child Born in 1955		Child Born in 1964	
Route	**Pathway**	**Dose**	**%**	**Dose**	**%**	**Dose**	**%**	**Dose**	**%**
External	Air Immersion	0.017	6.2	0.257	38.6	0.0577	3.4	0.0207	23.6
	Ground Contamina-tion	0.0026	1.0	0.0052	0.8	0.0026	0.2	1.0×10^{-4}	0.1

[12] Ar-41 contributed 98% of the external exposure received by the Adult Male (see Appendix K).

Ingestion	Beef	0.12	42.6	0.18	27.4	0.51	30.4	0.0099	11.6
	Eggs	0.0017	0.6	0.0028	0.4	0.0026	0.2	0.0017	1.9
	Fruit	0.0075	2.8	0.0073	1.1	0.023	1.3	0.0050	5.9
	Grain	0.0011	0.4	0.0013	0.2	0.0029	0.2	$7.3x10^{-4}$	0.8
	Leafy Vegetables	0.0089	3.3	0.0089	1.3	0.014	0.8	$8.5x10^{-4}$	1.0
	Milk	0.065	24.1	0.087	13.1	0.93	55.7	0.027	31.7
	Poultry	0.0010	0.4	0.0012	0.2	0.0012	0.1	$7.6x10^{-4}$	0.9
	Root Vegetables	0.0065	2.4	0.0090	1.4	0.012	0.7	0.0041	4.8
	Soil*	$5.5x10^{-7}$	<0.1	$1.1x10^{-6}$	<0.1	$8.3x10^{-6}$	<0.1	$9.0x10^{-8}$	<0.1
Inhala-tion	Air Inhalation	0.039	14.5	0.090	13.6	0.12	6.9	0.014	16.6
	Resuspended Soil	0.0046	1.7	0.012	1.8	0.0044	0.3	$9.2x10^{-6}$	1.1
Total		0.27	100	0.66	100	1.7	100	0.086	100

* Doses from the soil ingestion pathway were no more than 0.0003% of any family member's entire 39-year dose.

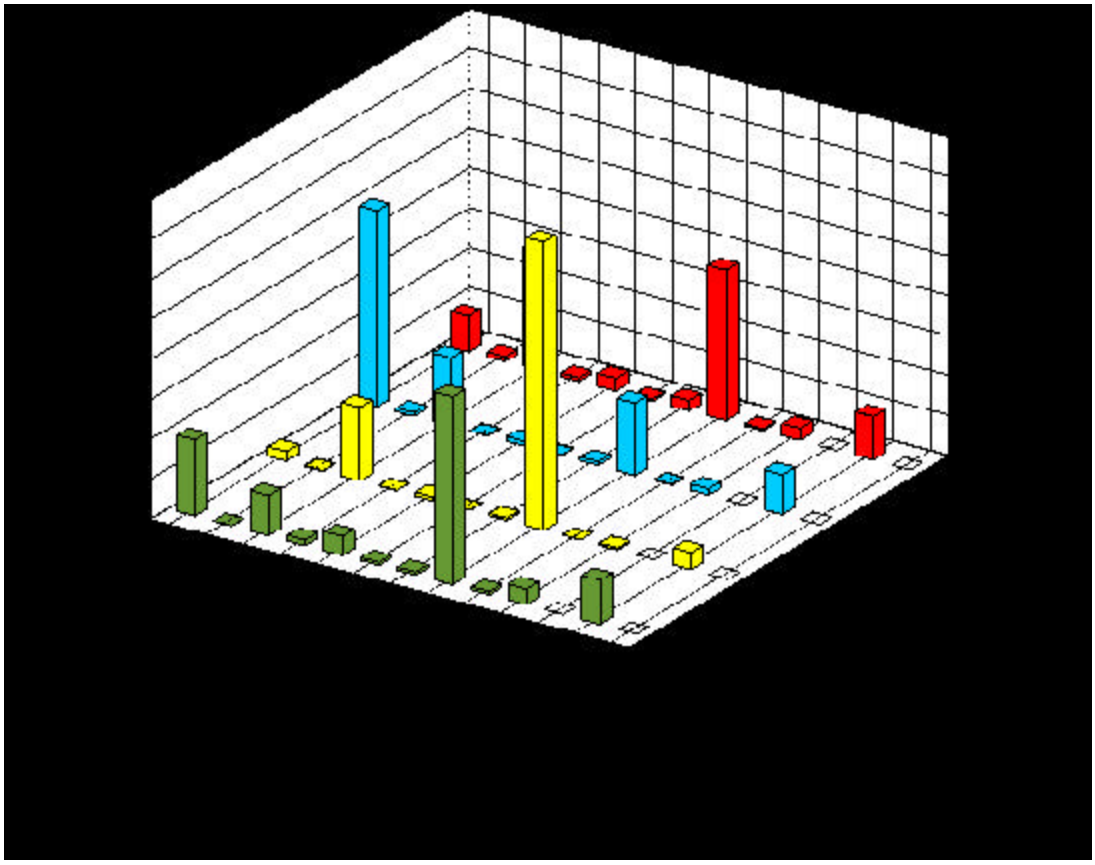


Figure 11-18 Percent of 39-Year Effective Dose for Exposure Pathway for Uraban/Suburban Family

The large external radiation dose received by the Adult Male came from the 2000 hours he spent each year at work. It was assumed that all hours were spent near K-Reactor. The great bulk of his external exposures resulted from immersion in a plume of radionuclides in air, rather than from exposure to radionuclides that had been deposited on the ground.

For all family members, doses from inhalation mainly came from breathing radionuclides from the contaminated air plume, rather than breathing radionuclides that had been resuspended from soil after being deposited on the ground.

11.2.4 Migrant Worker Family

As a hypothetical rural family, all family members spent much of their work, home activities, and recreation time outdoors. Because the Adult Male and Adult Female worked as migrant farm workers, the family lived in New Ellenton for half of each year (Figure 11-19). The family did no boating but did enjoy other water sports such as fishing and swimming in local pools, ponds and creeks. The children attended schools in New Ellenton. When grown, the children became migrant farmers spending half of each year in New Ellenton.

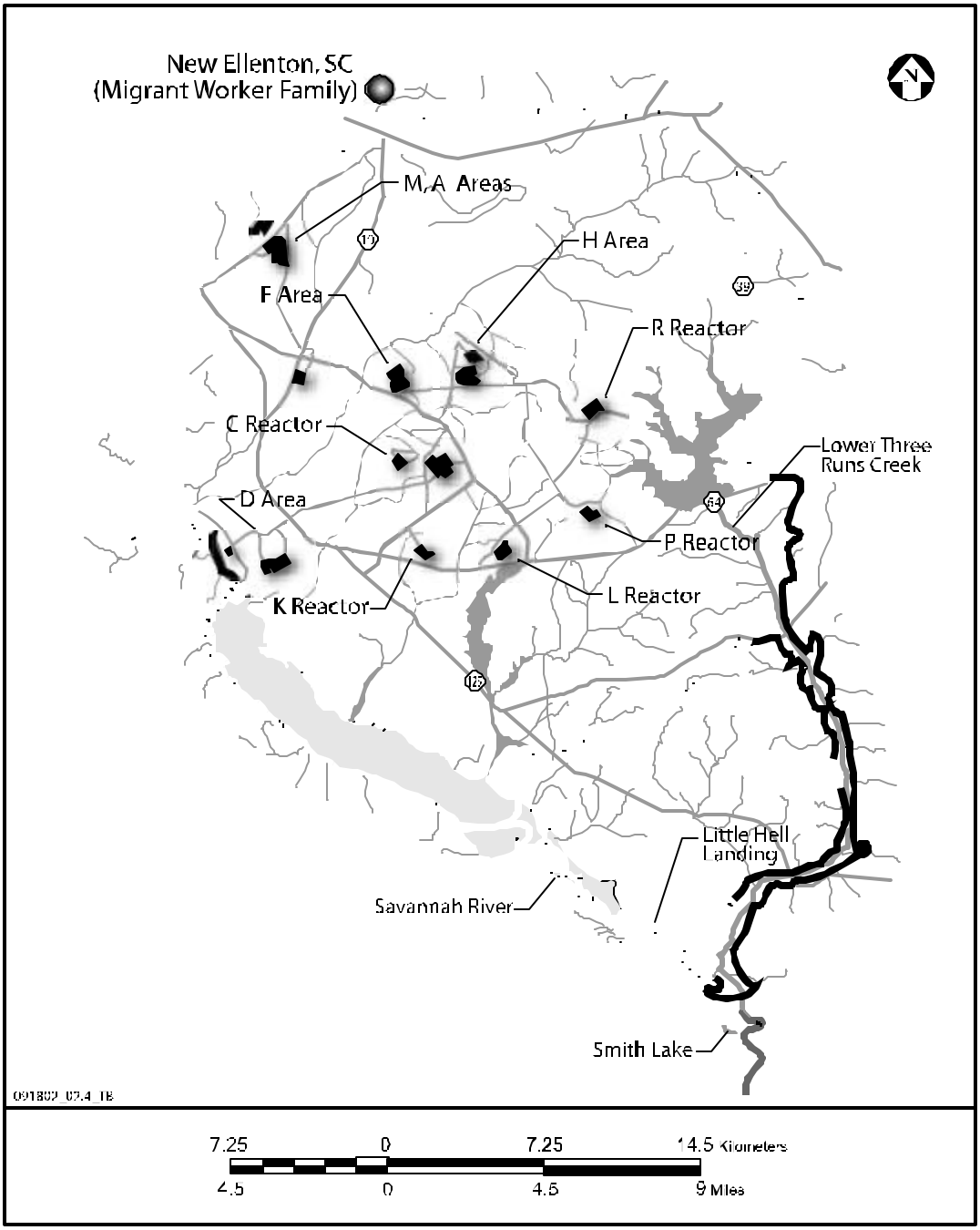


Figure 11-19 Exposure Location for Migrant Worker Family

During the six months of each year that the family lived in New Ellenton, all of their milk and eggs came from cows and hens located in New Ellenton. Half of the family's beef, poultry, leafy vegetables, root vegetables, and fruit was grown or produced in New Ellenton and half came from sources away from SRS. All of their corn was grown in New Ellenton. Because ponds and creeks in the vicinity of New Ellenton are not located hydrologically downstream from 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 sources unaffected by SRS releases.

11.2.4.1 Doses and Total Risks

Table 11-12 lists the effective dose and cancer risks assessed for each member of the Migrant Worker Family over 39 years of SRS operation. All doses and risks came from exposure to radionuclides that had been released into the air.

The Child Born in 1955 received the largest dose and risks – i.e., an effective dose of 2.2 mSv (220 mrem), a cancer incidence risk of 0.022%, and a cancer fatality risk of 0.0034%. The Child Born in 1964 received the smallest dose and risks. The dose for the Child Born in 1964 was 4% of that for the Child Born in 1955.

Table 11-12 39-Year Effective Dose and Cancer Risks for Migrant Worker Family

Dose or Risk	Adult Female	Adult Male	Child Born in 1955	Child Born in 1964
Effective Dose (mSv)	0.45	0.62	2.2	0.083
Cancer Incidence Risk (%)	0.0012	0.0016	0.022	0.0013
Cancer Fatality Risk (%)	0.00042	0.00052	0.0034	0.00078

Of interest is the relatively large doses received by these family members, compared to those received by members of the previous scenarios, even though the Migrant Worker Family was assumed to be in the vicinity of SRS only half of any year. The main reason is that the members of the Migrant Worker Family resided in New Ellenton, SC, which is immediately north of SRS, while members of other scenarios lived farther away from SRS, and in different directions. New Ellenton was the source of all of their milk and eggs, and half of their other foods.

11.2.4.2 Effective Dose by Year

Figure 11-20 shows the percent of the 39-year effective dose received each year by each family member, while Figure 11-21 shows the annual effective dose (in units of Sieverts) received by each family member. Table 11-13 lists the percent of the entire 39-year effective dose received each year by each family member, as well as their annual dose.

In 1956 the Child Born in 1955 received 1.6 mSv (160 mrem)), or 73% of his entire dose. During this year, the Adult Female received 0.23 mSv (23 mrem), or 52% of her entire dose, and the Adult Male received 0.34 mSv (34 mrem), or 54% of his entire dose.[13] In 1964, the Child Born in 1964 received 0.011 mSv (1.1 mrem), or 13% of his entire dose.

[13] This information was obtained from the tables of annual effective dose that are presented in Appendix I for each scenario.

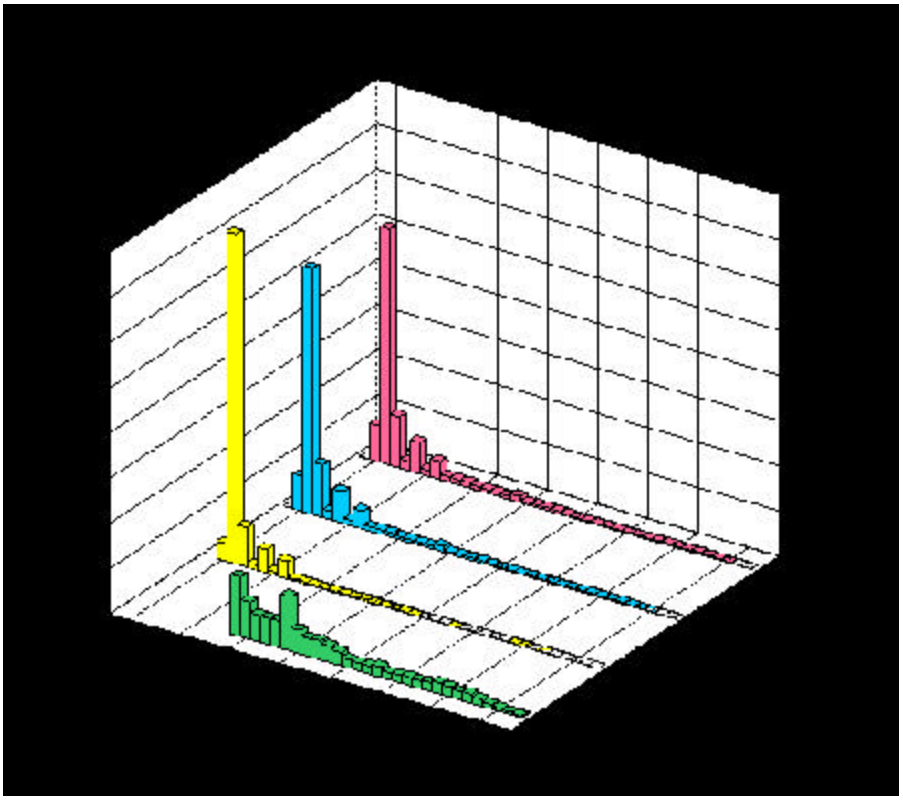


Figure 11-20 Percent of 39-Year Effective Dose by Year for Migrant Worker Family

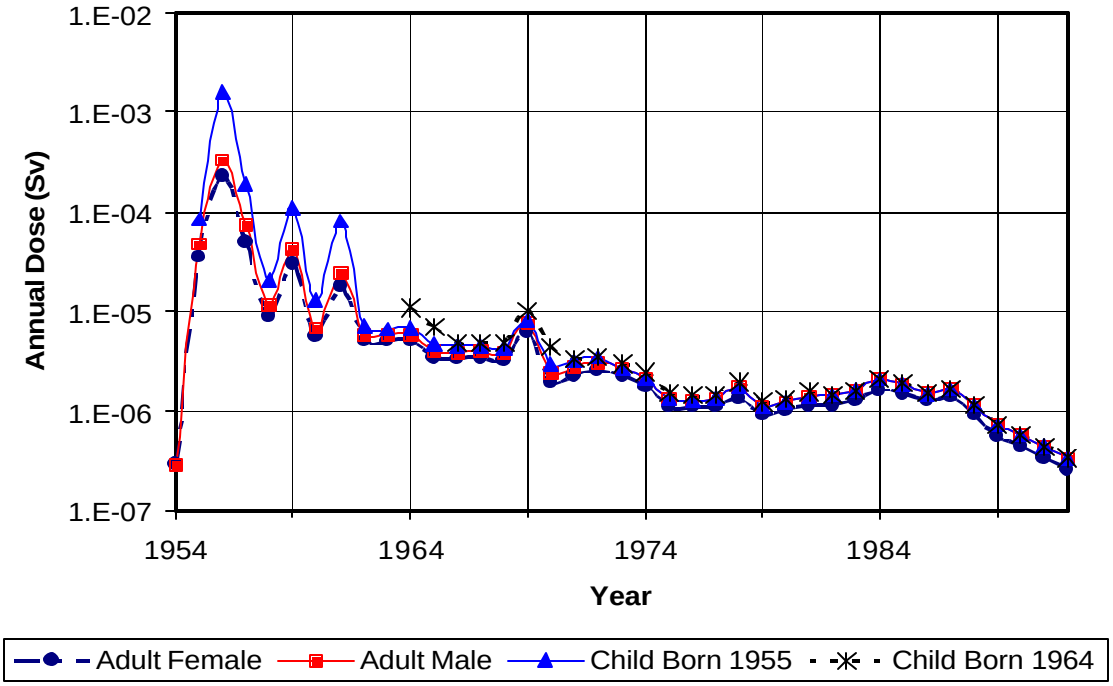


Figure 11-21 Annual Effective Dose (Sv) for Migrant Worker Family

Table 11-13 Annual Effective Dose (mSv) for Migrant Worker Family

	Adult Female		Adult Male		Child Born in 1955		Child Born in 1964	
Year	**Dose**	**%**	**Dose**	**%**	**Dose**	**%**	**Dose**	**%**
1954	$2.9x10^{-04}$	0.1	$2.9x10^{-04}$	0.0				
1955	0.036	8.0	0.049	7.8	0.084	3.8		
1956	0.236	52.2	0.34	54.3	1. 6	73.1		
1957	0.050	11.3	0.072	11.6	0.19	8.8		
1958	0.0090	2.0	0.012	1.9	0.021	1.0		
1959	0.031	6.9	0.043	6.9	0.11	5.1		
1960	0.0056	1.3	0.0068	1.1	0.013	0.6		
1961	0.018	4.0	0.024	3.9	0.083	3.8		
1962	0.0051	1.1	0.0060	1.0	0.0072	0.3		
1963	0.0050	1.1	0.0058	0.9	0.0067	0.3		
1964	0.0051	1.1	0.0060	1.0	0.0069	0.3	0.011	13.2
1965	0.0035	0.8	0.0041	0.7	0.0046	0.2	0.0068	8.2
1966	0.0034	0.8	0.0039	0.6	0.0046	0.2	0.0050	6.0
1967	0.0035	0.8	0.0040	0.6	0.0045	0.2	0.0049	5.9
1968	0.0032	0.7	0.0038	0.6	0.0044	0.2	0.0049	5.9
1969	0.0060	1.3	0.0078	1.3	0.0084	0.4	0.010	12.1
1970	0.0020	0.4	0.0025	0.4	0.0030	0.1	0.0044	5.2
1971	0.0023	0.5	0.0028	0.4	0.0032	0.1	0.0033	4.0
1972	0.0026	0.6	0.0031	0.5	0.0034	0.2	0.0035	4.2
1973	0.0023	0.5	0.0027	0.4	0.0027	0.1	0.0030	3.6
1974	0.0018	0.4	0.0021	0.3	0.0021	0.1	0.0024	2.9
1975	0.0011	0.2	0.0014	0.2	0.0014	0.1	0.0015	1.8
1976	0.0011	0.2	0.0013	0.2	0.0013	0.1	0.0014	1.7
1977	0.0011	0.2	0.0013	0.2	0.0013	0.1	0.0015	1.7
1978	0.0014	0.3	0.0017	0.3	0.0017	0.1	0.0019	2.3
1979	$9.3x10^{-04}$	0.2	0.0011	0.2	0.0011	0.1	0.0012	1.5
1980	0.0010	0.2	0.0012	0.2	0.0012	0.1	0.0014	1.6
1981	0.0011	0.3	0.0014	0.2	0.0014	0.1	0.0015	1.8
1982	0.0012	0.3	0.0014	0.2	0.0014	0.1	0.0014	1.7
1983	0.0013	0.3	0.0016	0.3	0.0016	0.1	0.0016	2.0
1984	0.0016	0.4	0.0021	0.3	0.0021	0.1	0.0021	2.5
1985	0.0015	0.3	0.0019	0.3	0.0019	0.1	0.0019	2.3
1986	0.0013	0.3	0.0015	0.2	0.0015	0.1	0.0015	1.8
1987	0.0014	0.3	0.0017	0.3	0.0017	0.1	0.0017	2.0
1988	$9.2x10^{-04}$	0.2	0.0012	0.2	0.0012	0.1	0.0012	1.4
1989	$5.5x10^{-04}$	0.1	$7.2x10^{-04}$	0.1	$7.2x10^{-04}$	<0.1	$7.2x10^{-04}$	0.9
1990	$4.5x10^{-04}$	0.1	$5.9x10^{-04}$	0.1	$5.9x10^{-04}$	<0.1	$5.9x10^{-04}$	0.7
1991	$3.3x10^{-04}$	0.1	$4.4x10^{-04}$	0.1	$4.4x10^{-04}$	<0.1	$4.4x10^{-04}$	0.5
1992	$2.6x10^{-04}$	0.1	$3.4x10^{-04}$	0.1	$3.4x10^{-04}$	<0.1	$3.4x10^{-04}$	0.4
Total	0.45	100	0.62	100	2.2	100	0.083	100

This 1964 dose was less than 1% of the largest annual dose for the Child Born in 1955. The pattern of annual dose is comparable to that seen for Rural Family One (Figure 11-3) and Rural Family Two (Figure 11-9).

11.2.4.3 Dominant Radionuclides, Exposure Routes, and Pathways

Figure 11-22 shows the radionuclides that were the largest contributors of dose over 39 years for each member of the Migrant Worker Family. The dominant radionuclides were generally the same as those for Rural Family One (Figure 11-4) and Rural Family Two (Figure 11-10). But there were small differences. For example, Pu-238 was somewhat more important for the Child Born in 1955 for the Migrant Worker Family than for Rural Family Two; and Ru-106 was somewhat more important for the Child Born in 1964 for the Migrant Worker Family than for Rural Family Two.

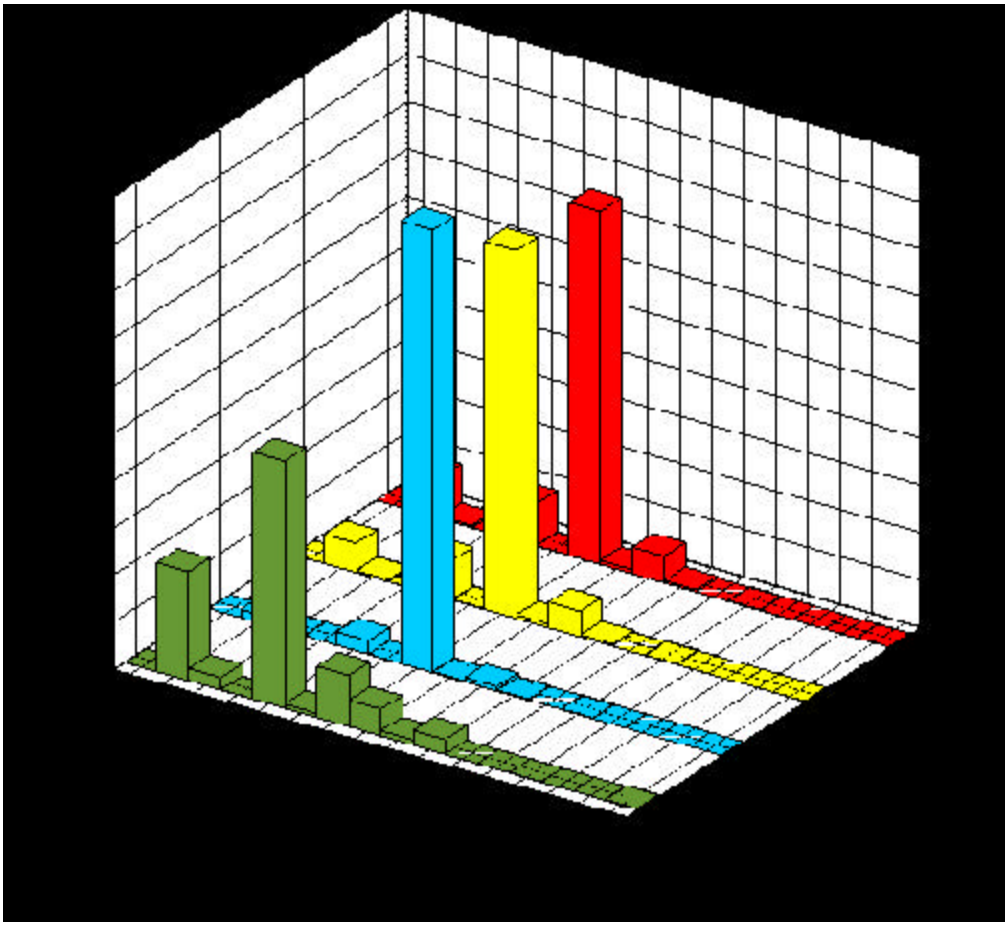


Figure 11-22 Percent of 39-Year Effective Dose by Dominant Isotopes for Migrant Worker Family

Most of the radiation dose received by this family came from eating food containing radionuclides (Figure 11-23). All family members received from 58 to 91 percent of their entire dose from ingestion. From 2 to 23 percent of their entire dose came from exposure to external radiation, and from 7 to 18 percent of their entire dose came from inhalation. This pattern of dose is similar to that seen for Rural Family One (Figure 11-5) and Rural Family Two (Figure 11-11).

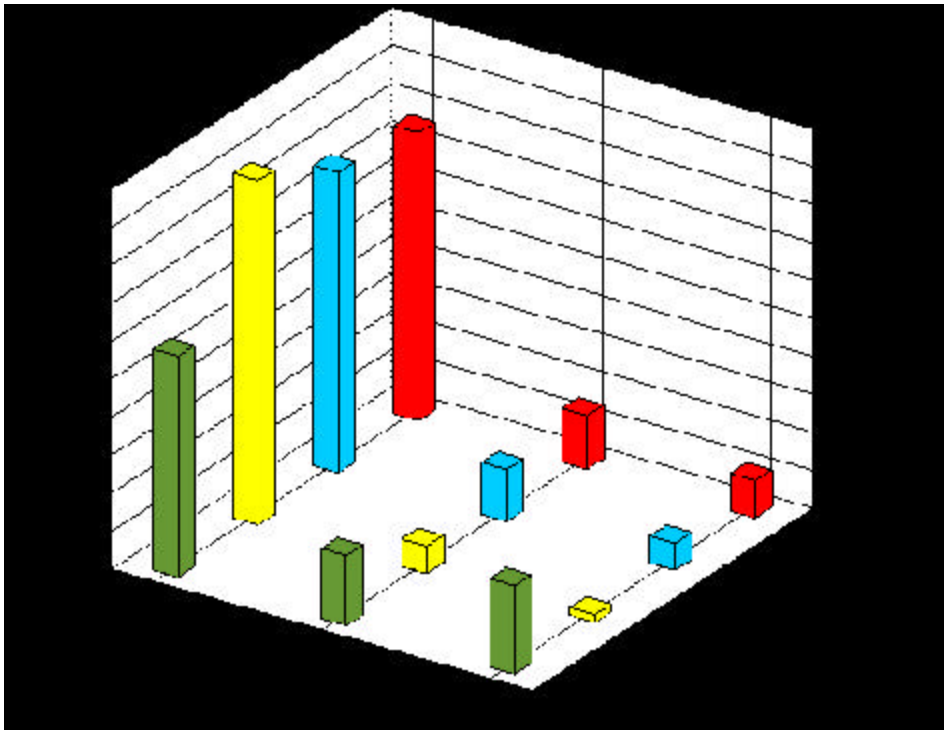


Figure 11-23 Percent of 39-Year Effective Dose by Exposure Route for Migrant Worker Family

Table 11-14 and Figure 11-24 show the effective dose, and percent of dose, by pathway and family member over 39 years. In general, the same pathways dominated radiation doses as those seen for Rural Family One (Table 11-5) and Rural Family Two (Table 11-8). Eating beef and drinking milk caused from 40 to 84 percent of their entire dose. Eating fruit and vegetables caused from 6 to 15 percent of their entire dose, and eating poultry, eggs, and grain caused from 1 to 3 percent of their entire dose. Inadvertently eating soil contributed no more than 0.0008% of any family member's entire dose.

Most external radiation doses came from immersion in a plume of contaminated air, rather than from radionuclides that had been deposited on the ground. Most inhalation doses came from breathing radionuclides directly from the plume of contaminated air, rather than breathing radionuclides that had been resuspended from soil.

Table 11-14 39-Year Effective Dose (mSv) by Exposure Pathway for Migrant Worker Family

		Adult Female		Adult Male		Child Born in 1955		Child Born in 1964	
Route	**Pathway**	**Dose**	**%**	**Dose**	**%**	**Dose**	**%**	**Dose**	**%**
External	Air Immersion	0.039	8.7	0.039	6.2	0.039	1.8	0.019	23.1
	Ground Contamination	0.0054	1.2	0.0058	0.9	0.0054	0.2	2.2×10^{-4}	0.3
Ingestion	Beef	0.23	52.1	0.37	58.7	1.0	48.2	0.015	17.8
	Eggs	0.0010	0.2	0.0017	0.3	0.0016	0.1	0.0010	1.2
	Fruit	0.015	3.2	0.014	2.3	0.064	2.9	0.0061	7.4
	Grain	0.0020	0.4	0.0024	0.4	0.0075	0.3	9.7×10^{-4}	1.1
	Leafy Vegetables	0.027	6.0	0.027	4.3	0.045	2.1	0.0012	1.5
	Milk	0.052	11.6	0.069	11.0	0.79	36.2	0.019	22.4
	Poultry	0.0011	0.3	0.0014	0.2	0.0015	0.1	9.0×10^{-4}	1.1
	Root Vegetables	0.0091	2.0	0.013	2.0	0.019	0.9	0.0049	5.9
	Soil*	1.1×10^{-6}	<0.1	1.1×10^{-6}	<0.1	1.7×10^{-5}	<0.1	1.8×10^{-7}	<0.1
Inhalation	Air Inhalation	0.054	12.1	0.073	11.6	0.15	6.9	0.013	16.2
	Resuspended Soil	0.0098	2.2	0.013	2.1	0.0091	0.4	0.0019	2.3
Total		0.45	100	0.62	100	2.29	100	0.083	100

* Doses from the soil ingestion pathway were no more than 0.0008% of any family member's entire 39-year dose.

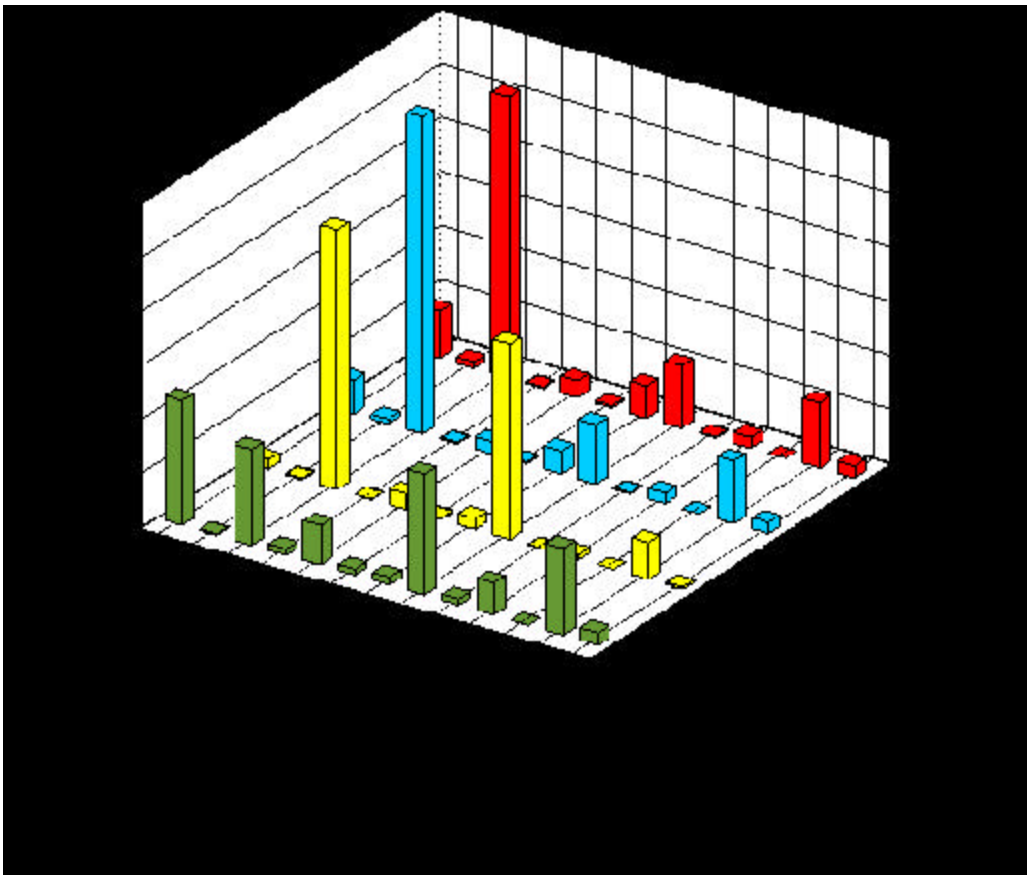


Figure 11-24 Percent of 39-Year Effective Dose by Exposure Pathway for Migrant Worker Family

11.2.5 Delivery Person Family

This hypothetical family lived in Barnwell, SC, where the children attended grade and high school. Because the Adult Male worked as a delivery driver for a bottling plant in Allendale, SC, he spent portions of his time in Allendale and onsite at SRS, where he made periodic deliveries. (When the children reached 18 they lived in Barnwell and became delivery drivers like the Adult Male.) The Adult Female worked at home. All family members attended religious services in Martin, SC, for a few hours per week. All family members swam, fished, and spent time along the shoreline at Lower Three Runs Creek near Martin. The Adult Male hunted deer and fowl in the Martin vicinity. The family boated in the Savannah River, catching fish in Smith Lake and spending time along its shoreline (Figure 11-25).

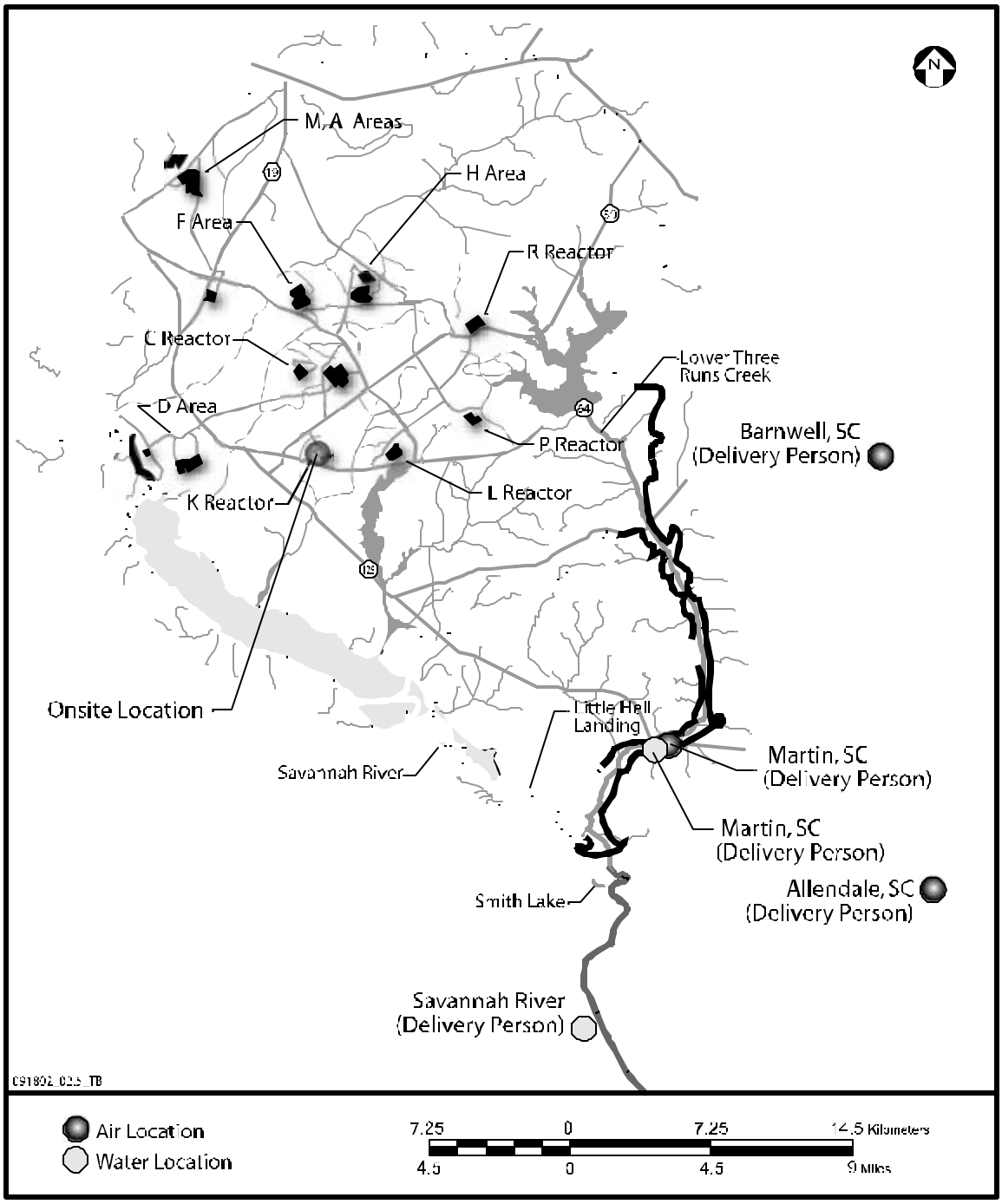


Figure 11-25 Exposure Locations for Delivery Person Family

Half the family's milk and eggs came from cows and hens located in Barnwell, and half from cows and hens located in Martin. 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 therefore possibly contained radionuclides from SRS), and half was acquired (e.g., by stores) from sources away from the SRS area.

Of the beef and poultry from Martin, 25% consisted of meat from hunting deer and wild fowl. [14] That is, 25% of the beef from Martin consisted of locally-hunted venison while

25% of the poultry from Martin consisted of locally-hunted wild fowl. Of the remaining 75% 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 SRS.[15]

Half the leafy vegetables, root vegetables, and fruit came from Barnwell and half from Martin. Half of this produce from Barnwell was locally-grown, as was half of this produce from Martin. [16] Half of the corn eaten by the family was grown in Barnwell and half was grown in Martin. Half of the fish was caught in Lower Three Runs Creek at Martin, and half was caught in Smith Lake.

11.2.5.1 Effective Dose and Total Risk

Table 11-15 lists the effective dose and cancer risks for each member of the Delivery Person Family over 39 years of SRS operation. The doses and risks included those from radionuclides released into surface water as well as radionuclides released into the air.

Table 11-15 39-Year Effective Dose and Risks for Delivery Person Family

Dose or Risk	Adult Female	Adult Male	Child Born in 1955	Child Born in 1964
Effective Dose (mSv)				
Air Pathways	0.40	0.57	2.1	0.12
Water Pathways	5.7	5.7	3.1	2.0
All Pathways	6.1	6.3	5.2	2.1
Cancer Incidence Risk (%)				
Air Pathways	0.0012	0.0017	0.022	0.0018
Water Pathways	0.027	0.027	0.048	0.031
All Pathways	0.028	0.029	0.070	0.033
Cancer Fatality Risk (%)				
Air Pathways	0.00050	0.00074	0.0038	0.0011
Water Pathways	0.020	0.020	0.032	0.021
All Pathways	0.020	0.021	0.036	0.022

The Adult Male received an effective dose of 6.3 mSv (630 mrem), the Adult Female received an effective dose of 6.1 mSv (610 mrem), and the Child Born in 1955 received an effective dose of 5.2mSv (520 mrem). The dose for the Child Born in 1964 was about one-half to one-third of the dose for the other

[14] Recall from Chapter 8 and Appendix D that consumption of game animals was modeled as consumption of additional beef and poultry.

[15] Combining the venison and wild fowl obtained from hunting with other beef and poultry obtained in Martin, it was assumed that 62.5% of all beef (including venison) obtained from Martin potentially contained radionuclides from SRS, as did 62.5% of all poultry (including wild fowl) eaten by the family.

[16] In other words, 50% of the vegetables and fruit obtained from Barnwell potentially contained radionuclides released by SRS, as did 50% of the vegetables and fruit obtained from Martin.

family members. The Child Born in 1955 had the largest cancer risks in this scenario; the Child Born in 1964 had the smallest.

Although the doses received from only the air pathways were comparable for most Delivery Family members to those received by Rural Family One members, the addition of the water pathways raised the overall doses received by the Delivery Family members to levels much larger than those received by Rural Family One members. The distribution of dose between all air pathways and all surface water pathways is shown in Figure 11-26. Except for the Child Born in 1955, surface water pathways caused at least 91% of the entire dose over 39 years. For that child, however, air pathways contributed 41% of his entire dose while water pathways contributed 59%.

In the previous four scenarios based on air pathways only, the Child Born in 1955 always received the largest dose. But here, when doses through all water pathways are added to those through all air pathways, the Adult Male received the largest dose. This dose resulted mainly from eating fish containing radionuclides (see below).

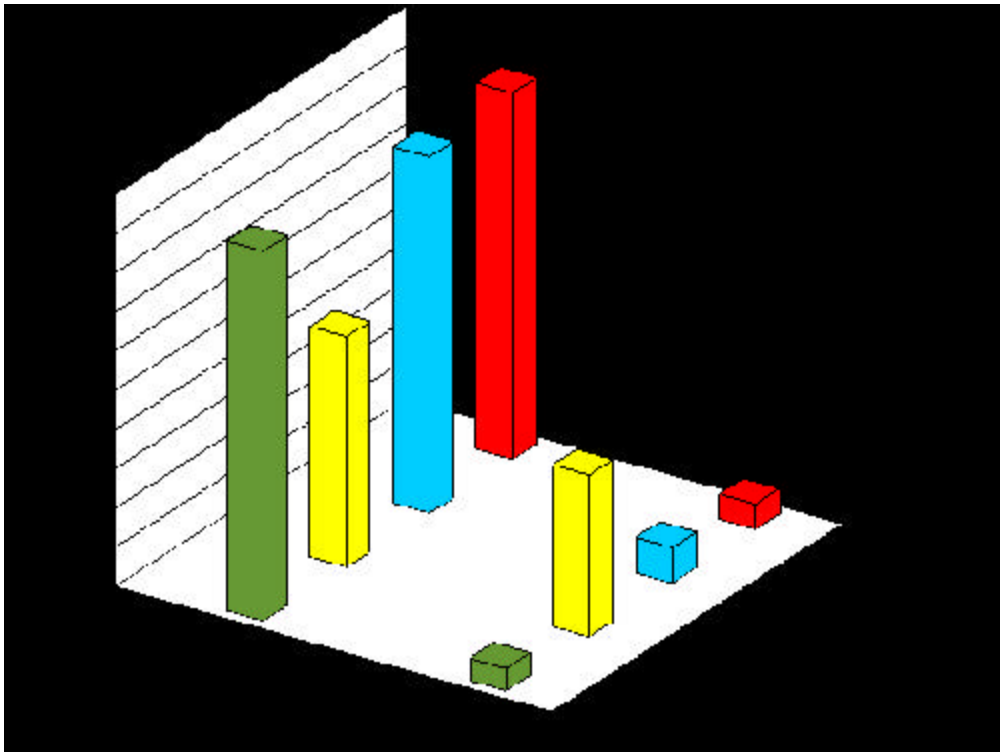


Figure 11-26 Distribution of 39-Year Effective Dose (%) Between Air and Water Pathways for Delivery Person Family

11.2.5.2 Effective Dose by Year

The percent of the entire dose contributed each year for each family member is shown in Figure 11-27, while Figure 11-28 shows the annual dose for each member of the Delivery Person Family. Table 11-16 lists the percent of the entire 39-year effective dose received each year by each family member, as well as their annual dose. These two figures and table include doses from all air and all water pathways.

The Child Born in 1955 received the largest annual dose of any family member: In 1956, he received 1.6 mSv (160 mrem), or 30% of his entire dose. In 1958, the Adult Female and Adult Male each received

their largest annual dose: the Adult Female received 1.0 mSv (100 mrem), or 17% of her entire dose, while the Adult Male also received 1.0 mSv (100 mrem), or 16% of his entire dose. The largest annual dose for the Child Born in 1964 occurred in 1964 when he received 0.55 mSv (55 mrem), or 15% of his entire dose.

Figure 11-29 shows the annual effective dose received by each family member from all air pathways. Annual doses from the air pathways followed a similar pattern as those for previous scenarios. Most doses were received during the early days of operation. During 1956, the Adult Female received 0.18 mSv (18 mrem), or 46% of her dose from all air pathways, the Adult Male received 0.26 mSv (26 mrem), or 46% of his dose from all air pathways, and the Child Born in 1955 received 1.5 mSv (150 mrem), or 71% of his dose from all air pathways. In 1964, the Child Born in 1964 received 0.017 mSv (1.7 mrem), or 15% of his dose from all air pathways.

Figure 11-29 shows that the annual doses received by the two children eventually merged with doses received by the Adult Male, when the children began work in Allendale and at SRS when each child reached age 18. The dose curves for the Adult Male and two children tended to "separate" from that for the Adult Female in later years, although the separation is not as pronounced as that seen Figure 11-15 for the Urban/Suburban Family. This occurred because the Adult Male and grown children of the Delivery Family spent much less time on the SRS site than did the Adult Male and grown children of the Urban/Suburban Family.[17]

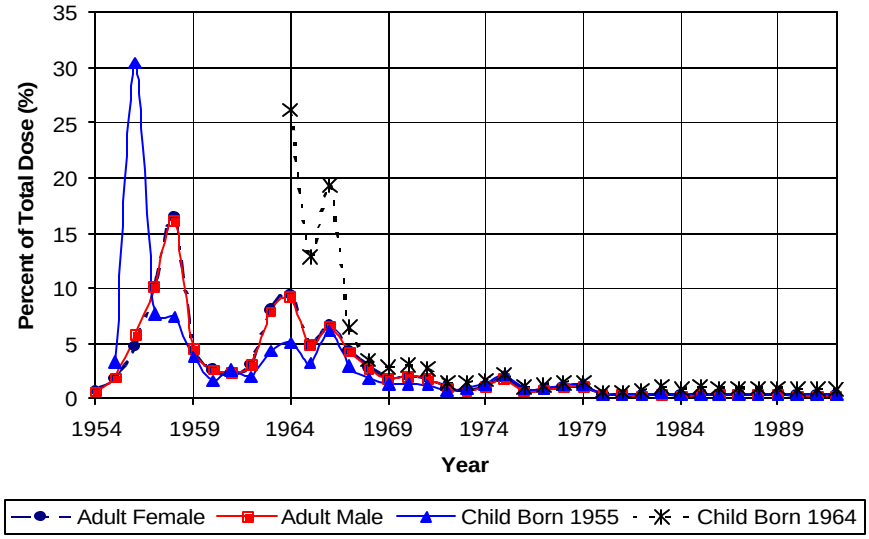


Figure 11-27 Percent of 39-Year Effective Dose by Year for Delivery Person Family – Air + Water Pathways

[17] For the Urban/Suburban scenario, the Adult Male (and two children when they each reached age 18) spent 2,000 hours per year on the SRS site. But for the Delivery Family Scenario, the Adult Male (and two children when they each reached age 18) spent only 400 hours per year on the SRS site.

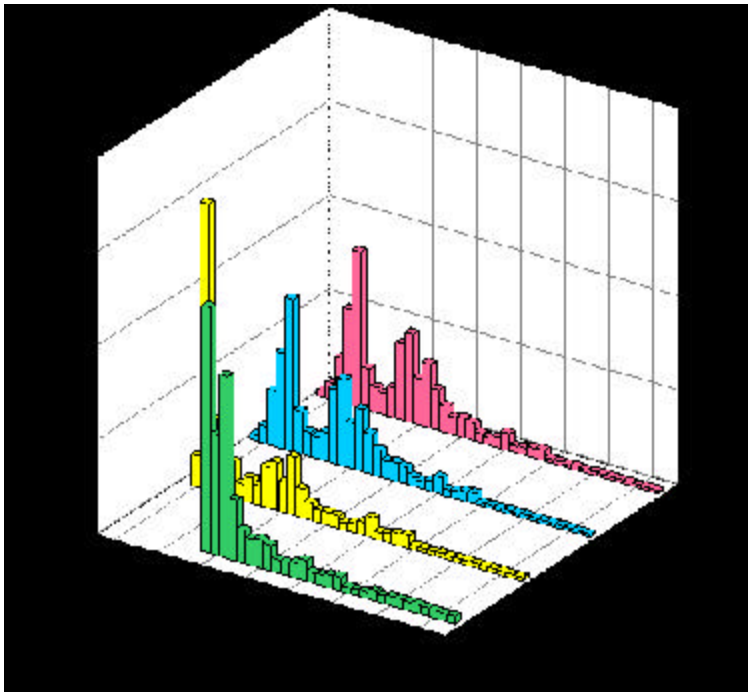


Figure 11-28 Annual Effective Dose (Sv) for Delivery Person Family – Air + Water Pathways

Table 11-16 Annual Effective Dose (mSv) for Delivery Person Family

	Adult Female		Adult Male		Child Born in 1955		Child Born in 1964	
Year	**Dose**	**%**	**Dose**	**%**	**Dose**	**%**	**Dose**	**%**
1954	0.040	0.6	0.040	0.6				
1955	0.11	1.7	0.12	1.8	0.17	3.3		
1956	0.29	4.7	0.37	5.8	1.58	30.4		
1957	0.62	10.2	0.64	10.2	0.40	7.7		
1958	1.0	16.5	1.0	16.1	0.39	7.5		
1959	0.27	4.4	0.28	4.5	0.20	3.8		
1960	0.16	2.6	0.16	2.6	0.088	1.7		
1961	0.14	2.3	0.15	2.3	0.13	2.6		
1962	0.19	3.1	0.19	3.1	0.10	2.0		
1963	0.49	8.0	0.50	7.9	0.22	4.3		
1964	0.57	9.4	0.58	9.2	0.26	5.0	0.55	26.2
1965	0.30	4.9	0.30	4.8	0.17	3.2	0.271	12.9
1966	0.41	6.7	0.41	6.6	0.32	6.1	0.40	19.3
1967	0.26	4.3	0.27	4.3	0.16	3.0	0.14	6.5
1968	0.17	2.8	0.17	2.8	0.092	1.8	0.073	3.5
1969	0.11	1.8	0.11	1.8	0.065	1.2	0.060	2.8
1970	0.12	2.0	0.12	2.0	0.069	1.3	0.064	3.0
1971	0.11	1.8	0.11	1.8	0.063	1.2	0.057	2.7
1972	0.059	1.0	0.060	1.0	0.034	0.6	0.030	1.5
1973	0.046	0.8	0.048	0.8	0.048	0.9	0.029	1.4

	Adult Female		Adult Male		Child Born in 1955		Child Born in 1964	
Year	**Dose**	**%**	**Dose**	**%**	**Dose**	**%**	**Dose**	**%**
1974	0.066	1.1	0.067	1.1	0.067	1.3	0.034	1.6
1975	0.11	1.8	0.11	1.7	0.11	2.1	0.046	2.2
1976	0.040	0.7	0.041	0.6	0.041	0.8	0.023	1.1
1977	0.049	0.8	0.050	0.8	0.050	1.0	0.024	1.2
1978	0.062	1.0	0.063	1.0	0.063	1.2	0.030	1.4
1979	0.067	1.1	0.067	1.1	0.067	1.3	0.032	1.5
1980	0.020	0.3	0.021	0.3	0.021	0.4	0.013	0.6
1981	0.020	0.3	0.021	0.3	0.021	0.4	0.013	0.6
1982	0.015	0.2	0.015	0.2	0.015	0.3	0.015	0.7
1983	0.022	0.4	0.023	0.4	0.023	0.4	0.023	1.1
1984	0.016	0.3	0.016	0.3	0.016	0.3	0.016	0.8
1985	0.020	0.3	0.021	0.3	0.021	0.4	0.021	1.0
1986	0.020	0.3	0.020	0.3	0.020	0.4	0.020	1.0
1987	0.019	0.3	0.020	0.3	0.020	0.4	0.020	0.9
1988	0.019	0.3	0.020	0.3	0.020	0.4	0.020	0.9
1989	0.019	0.3	0.019	0.3	0.019	0.4	0.019	0.9
1990	0.018	0.3	0.018	0.3	0.018	0.3	0.018	0.9
1991	0.017	0.3	0.017	0.3	0.017	0.3	0.017	0.8
1992	0.017	0.3	0.017	0.3	0.017	0.3	0.017	0.8
Total	6.1	100	6.3	100	5.2	100	2.1	100

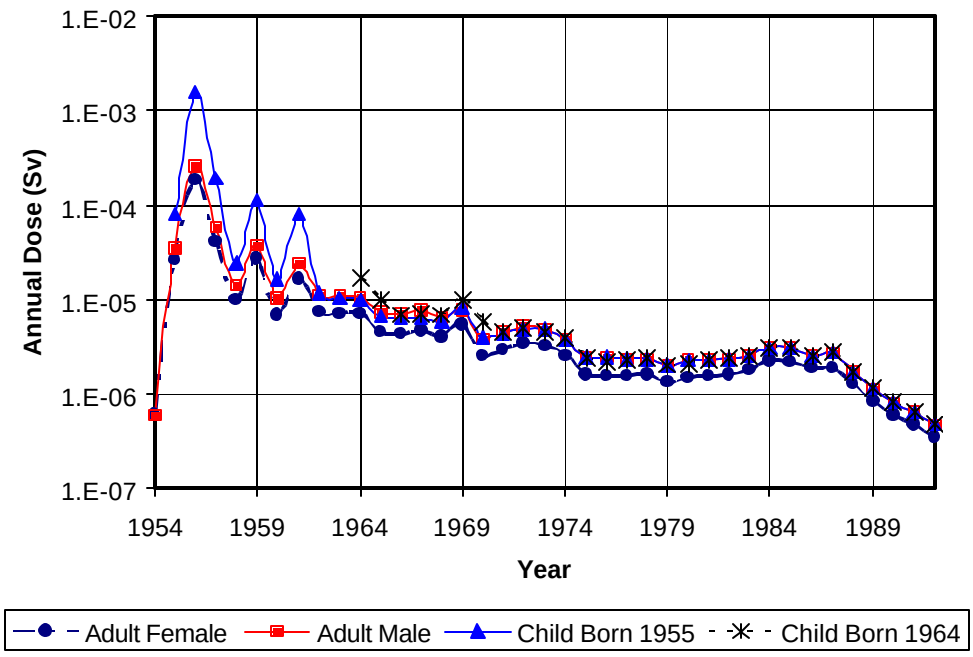


Figure 11-29 Annual Effective Dose (Sv) for Delivery Person Family – Air Pathways Only

Figure 11-30 shows the annual dose from all water pathways. The Adult Female, Adult Male, and Child Born in 1955 each received their largest annual doses from the water pathways in 1958, although doses received in 1964 and 1966 were also relatively large. Doses for these family members were, in 1958:

- Adult Female: 1.0 mSv (100 mrem) – 18% of her dose from all water pathways.
- Adult Male: 1.0 mSv (100 mrem) – 18% of his dose from all water pathways.

Child Born in 1955: 0.36 mSv (36 mrem) – 12% of his dose from all water pathways.The Child Born in 1964 received his largest annual dose – 0.53 mSv (53 mrem) -- from the water pathways in 1964. This dose was 27% of his dose from all water pathways. Another year of relatively large dose for this child was 1966.[18]

The annual doses from the water pathways for the Adult Male and Adult Female were nearly equivalent, mainly because the Adult Male and Adult Female each ate the same annual quantities of fish containing radionuclides.[19] When the children reached age 18, they each ate the same annual quantities of fish as did the two adults. Hence, the curve for the Child Born in 1955 merges with those for the two adults in 1973, and the curve for the Child Born in 1964 merges with those for the two adults in 1982.

The pattern for annual dose from all water pathways (Figure 11-30) is clearly different than the pattern from all air pathways (Figure 11-29). Whereas the annual dose received from the air pathways peaked during the 1950s and early 1960s, and thereafter declined significantly, the annual dose from the water pathways varies over a smaller range. Except for the earliest years, the annual dose from the water pathways were also larger than those from the air pathways. This point is illustrated in Figure 11-31 which shows the annual dose from all air pathways and all water pathways for the Child Born in 1955. Except for the years 1955, 1959, and 1961, annual doses from the water pathways were larger than those for the air pathways. Doses from the air pathways also dropped over the years more abruptly than did doses from the water pathways.

[18] Annual doses received by each family member through all water pathways are listed in Appendix I.
[19] The Adult Female curve on Figure 11.2.5.6 is not seen because the curve for the Adult Male is superimposed over that for the Adult Female.

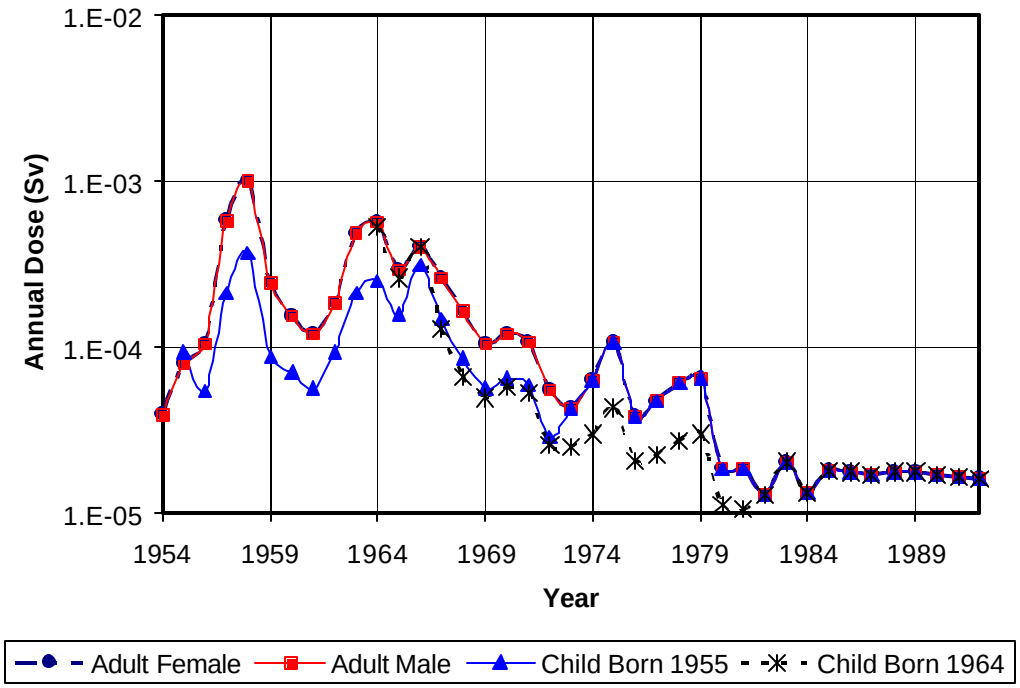


Figure 11-30 Annual Effective Dose (Sv) for Delivery Person Family – Water Pathways Only

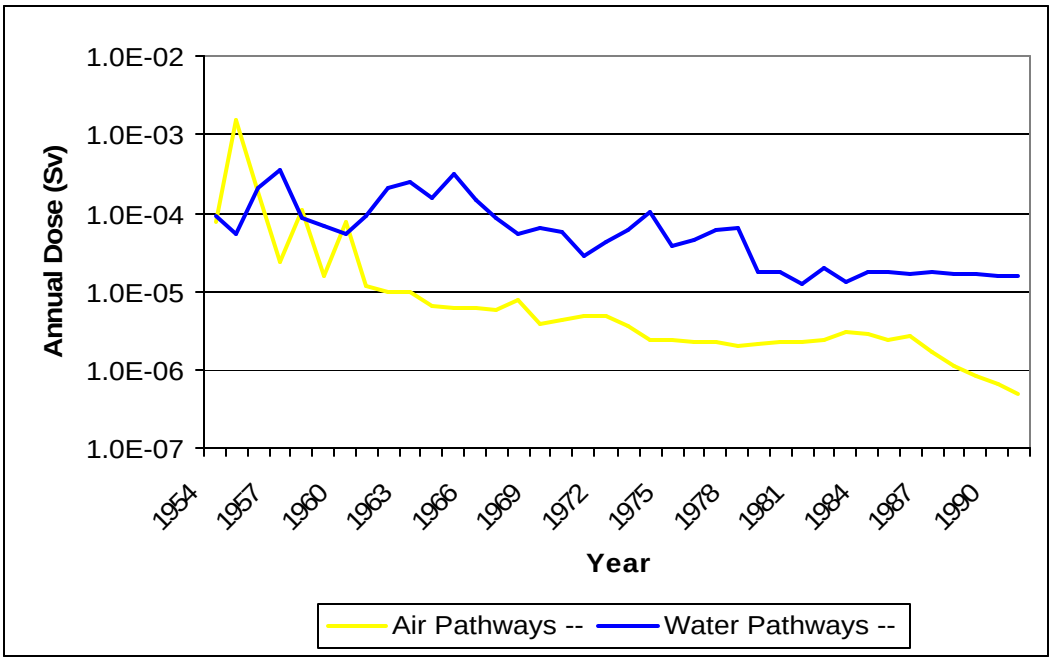


Figure 11-31 Annual Effective Dose (Sv) for Child Born in 1955, Delivery Person Family – Air vs. Water Pathways

11.2.5.3 Dominant Radionuclides, Exposure Routes, and Pathways

Figure 11-32 lists the radionuclides that caused the largest doses for each member of the Delivery Person Family. These radionuclides were different from those dominating dose for the previous scenarios.

For example, although I-131 caused most of the dose for the two adults and the Child Born in 1955 of the Urban/Suburban Family (Figure 11-16), Cs-137 caused most of the dose for these members of the Delivery Person Family. Although tritium (followed by Ar-41) caused most of the dose for the Child Born in 1955 of the Urban/Suburban Family, Cs-137 caused most of the dose for this member of the Delivery Person Family. For all Delivery Person Family members the doses from Cs-137, Sr-90, and P-32 came mainly from eating fish containing these radionuclides.

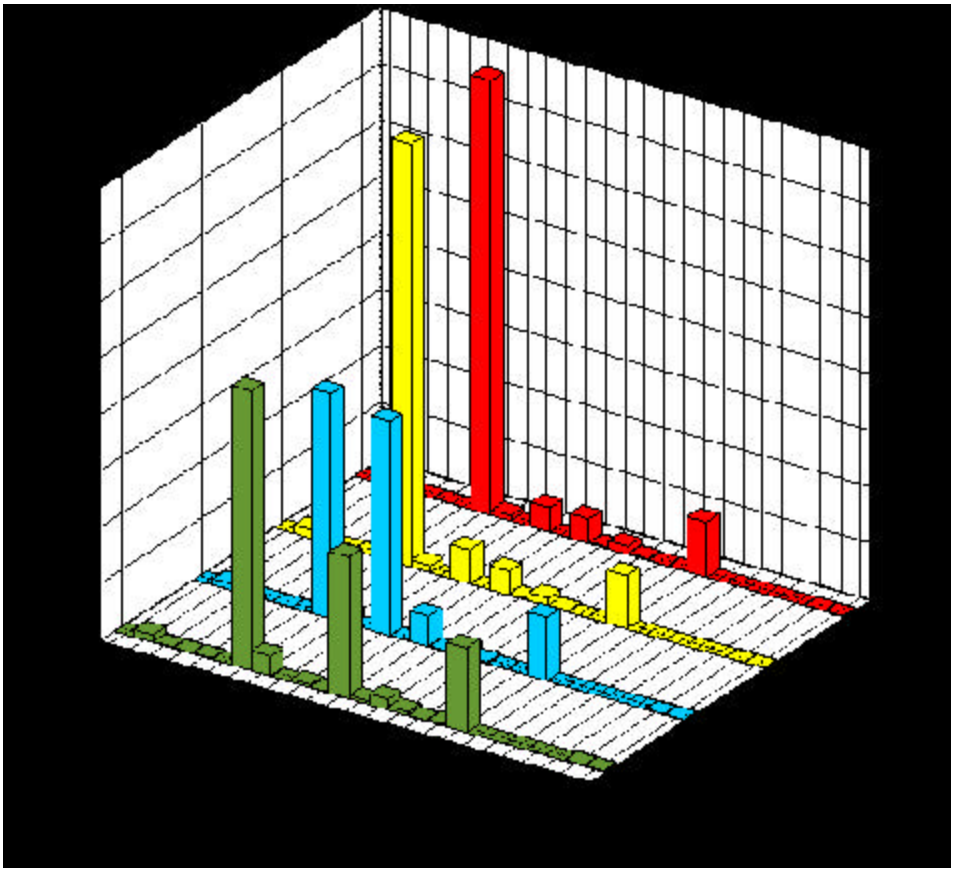


Figure 11-32 Percent of 39-Year Effective Dose by Dominant Isotopes for Delivery Person Family

As shown in Figure 11-33, at least 95% of the entire dose for any member of the Delivery Person Family came from ingestion. External exposure accounted for 2 to 3 percent of the entire dose; inhalation accounted for 1 to 3 percent of the entire dose.

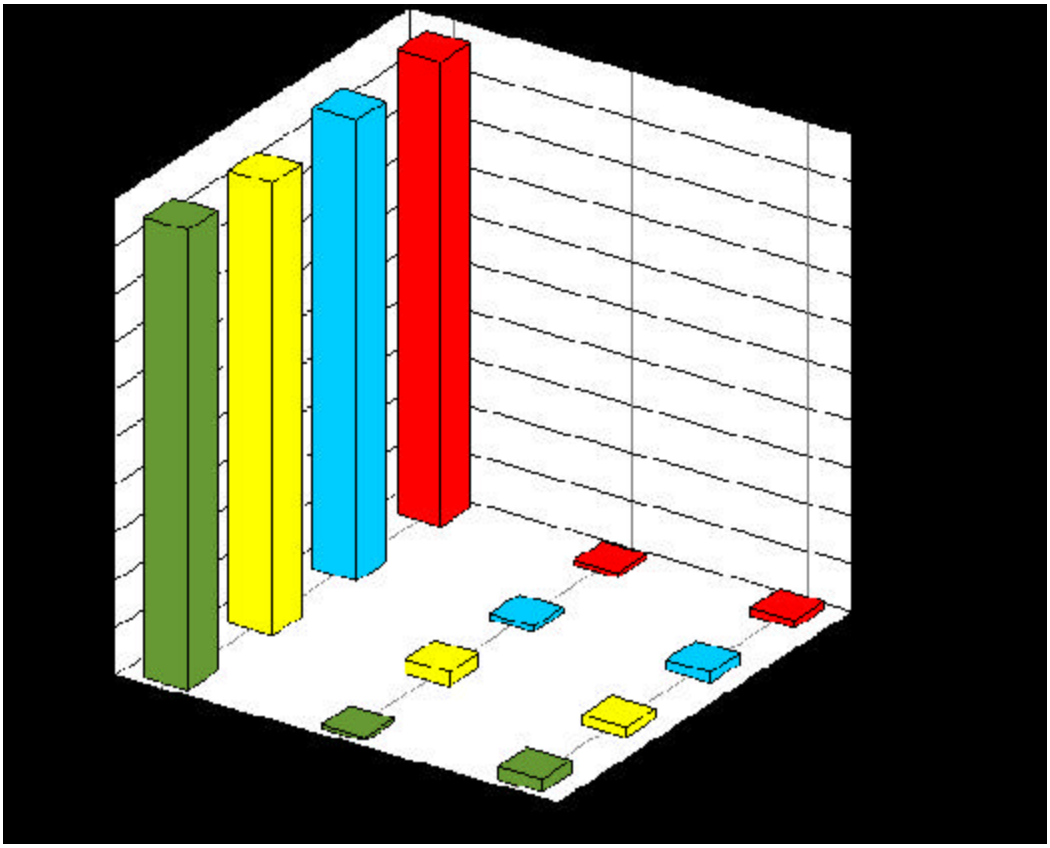


Figure 11-33 Percent of 39-Year Effective Dose by Exposure Route for Delivery Person Family

The dose from ingestion mainly came from eating fish, followed by beef and milk (Table 11-17 and Figure 11-34). At least 90% of the entire dose received by the two adults and the Child Born in 1964 came from eating fish, and from 3 to 6 percent of their dose came from eating beef and milk. Nearly 58% of the entire dose received by the Child Born in 1955 came from eating fish, while 13% of his dose came from eating beef and 22% of his dose came from drinking milk. For all family members, doses from eating vegetables, fruit, grain, eggs, and poultry were comparatively small. Combined doses from eating fruit and vegetables represented no more than 1.5% of any family member's entire dose, and combined doses from eating grain, eggs, and poultry represented no more than 0.2% of any family member's entire dose. Still smaller doses came from inadvertently drinking water while swimming: for all family members they represented less than 0.1% of the entire dose. Doses from inadvertently eating soil were again very small – contributing no more than 0.0003% of the entire dose of any family member over 39 years.

The dose from external radiation exposure primarily came from being immersed in a plume of air containing radionuclides. External doses from air immersion caused from 1 to 1.5 percent of the entire dose received by each family member. Also of interest were the doses caused by activities performed along a contaminated shoreline.[20] Shoreline external doses contributed roughly one percent of the entire dose received by each family member.

[20] Recall that this scenario is modeled in GENII as external exposure to radionuclides deposited from river or water onto shoreline sediments. The model used in GENII uses a transport rate constant of 35,400 L/m^2/y for all radionuclides, a value that was chosen for use in GENII based on river and sediment samples mostly obtained from the Columbia River. The model also took into account that exposures would occur from radionuclides deposited on a finite plane surface (the narrow width of the shoreline) as opposed to an large, semi-infinite plane surface.

Inhalation doses from breathing a cloud of air containing radionuclides were again much larger than the inhalation doses received from breathing radionuclides that had been resuspended from soil.

Table 11-17 39-Year Effective Dose (mSv) by Exposure Pathway for Delivery Person Family

		Adult Female		Adult Male		Child Born in 1955		Child Born in 1964	
Route	**Pathway**	**Dose**	**%**	**Dose**	**%**	**Dose**	**%**	**Dose**	**%**
External	Air Immersion	0.055	0.9	0.093	1.5	0.060	1.2	0.028	1.3
	Boating	$8.2x10^{-5}$	<0.1	$8.2x10^{-5}$	<0.1	$8.2x10^{-5}$	<0.1	$5.2x10^{-5}$	<0.1
	Ground Contamination	0.0047	0.1	0.0046	0.1	0.0047	0.1	$1.8x10^{-4}$	<0.1
	Shoreline	0.044	0.7	0.044	0.7	0.044	0.8	0.029	1.4
	Swimming	$5.9x10^{-5}$	<0.1	$5.9x10^{-5}$	<0.1	$5.8x10^{-5}$	<0.1	$2.6x10^{-5}$	<0.1
Ingestion	Beef	0.16	2.6	0.25	3.9	0.69	13.3	0.015	0.7
	Eggs	0.0023	<0.1	0.0038	0.1	0.0034	0.1	0.0023	0.1
	Fish	5.7	92.8	5.7	90.2	3.0	57.9	1.9	92.9
	Fruit	0.011	0.2	0.011	0.2	0.038	0.7	0.0069	0.3
	Grain	0.0016	<0.1	0.0019	<0.1	0.0031	0.1	$8.8x10^{-4}$	<0.1
	Inadvertent swimming ingestion	$7.7x10^{-4}$	<0.1	$7.7x10^{-4}$	<0.1	0.0011	<0.1	$8.0x10^{-4}$	<0.1
	Leafy Vegetables	0.016	0.3	0.016	0.2	0.025	0.5	0.0012	0.1
	Milk	0.080	1.3	0.11	1.7	1.14	21.9	0.041	2.0
	Poultry	0.0014	<0.1	0.0017	<0.1	0.0018	<0.1	0.0011	0.1
	Root Vegetables	0.0089	0.1	0.012	0.2	0.016	0.3	0.0056	0.3
	Soil*	$9.8x10^{-7}$	<0.1	$9.5x10^{-7}$	<0.1	$1.5x10^{-5}$	<0.1	$1.6x10^{-7}$	<0.1
Inhalation	Air Inhalation	0.059	1.0	0.077	1.2	0.16	3.1	0.017	0.8
	Resuspended Soil	$8.2x10^{-5}$	<0.1	$1.0x10^{-4}$	<0.1	$7.7x10^{-5}$	<0.1	$1.6x10^{-5}$	<0.1
Total		6.1	100	6.3	100	5.2	100	2.1	100

* Doses from the soil ingestion pathway were on the order of 10^{-7} to 10^{-5} mSv for each family member. These doses were no more than 0.0003% of any family member's entire 39-year dose.

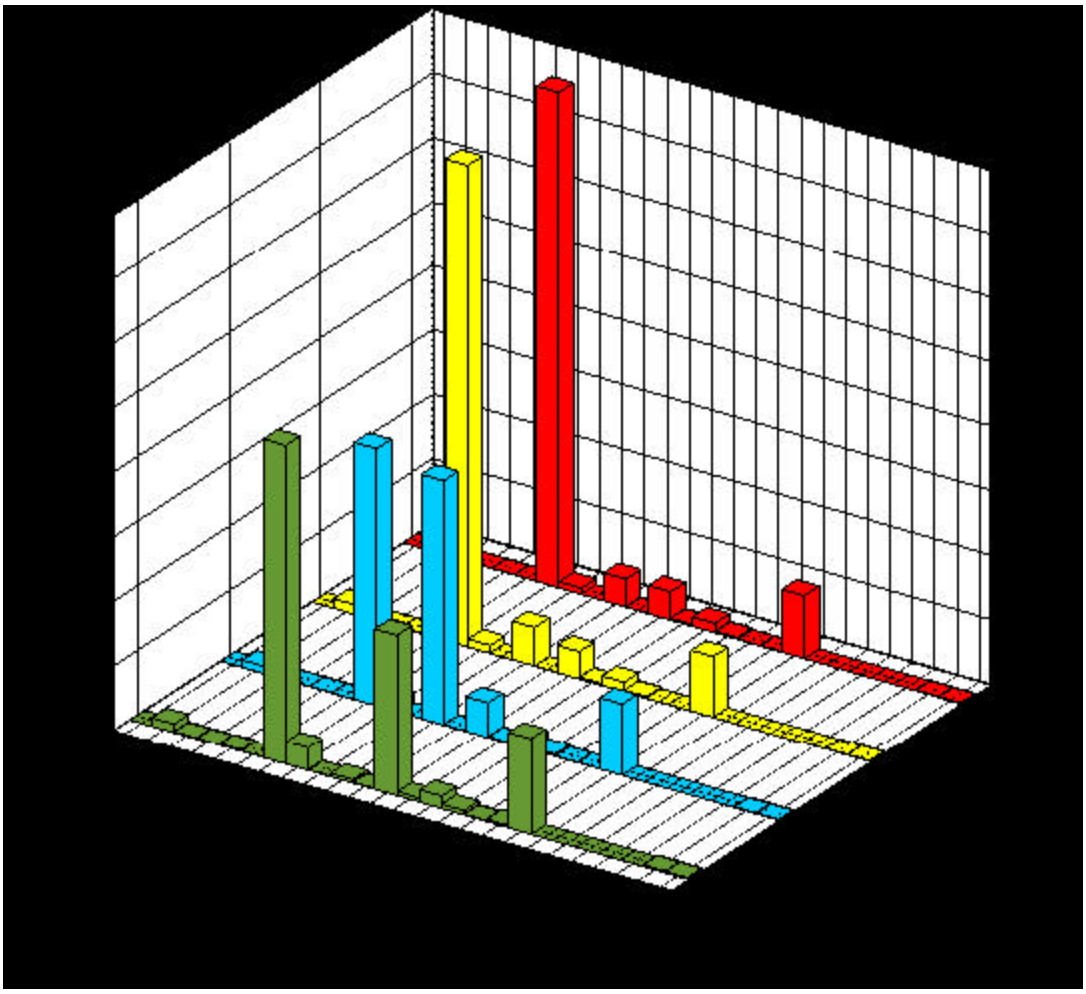


Figure 11-34 Percent of 39-Year Effective Dose by Exposure Pathway for Delivery Person Family

11.2.6 Outdoors Person Family

This hypothetical family lived in Jackson, SC, and all family members stayed there for most activities, including school and religious services. When the children grew up, they also lived in Jackson. The Adult Male worked onsite at SRS as a hunter, for 2000 hours out of each year, as did the children when they reached age 18. His job required him to spend 260 hours each year boating on the Savannah River. The Adult Male took game animals in the form of deer and birds, and caught fish from the Savannah River.[21] The children performed similar activities after they started work (Figure 11-35).

[21] It was assumed that he would be exposed to radionuclides discharged into the Savannah River from all surface water sources from SRS, including Lower Three Runs Creek. To determine exposures from air pathways, it was assumed a single onsite exposure location to represent all the locations that he might have occupied while working.

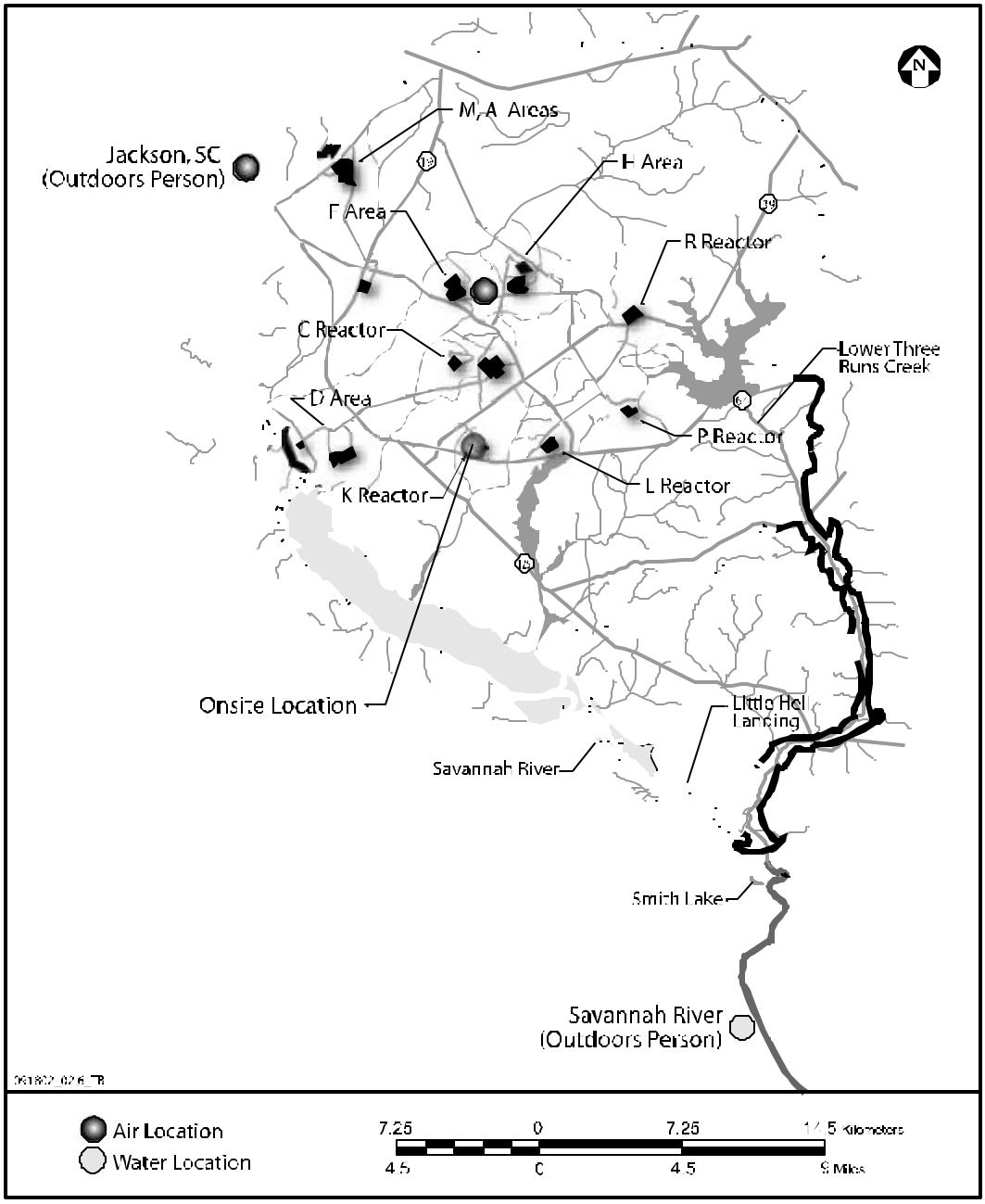


Figure 11-35 Exposure Locations for Outdoors Person Family

All family members (including the adult male) swam, camped, and fished on the Savannah River near the Jackson, SC, boat ramp (upstream of the site). They boated, however, in the Savannah River downstream of the discharge from SRS.

All milk and eggs came from cows and hens located in Jackson. Hence, it was assumed that all milk and eggs contained radionuclides released by SRS into the air. 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. All of this meat contained radionuclides from SRS operations. Their remaining beef and poultry came from other sources such as stores. Of this remaining 25%, half was produced in Jackson (and therefore contained radionuclides from SRS operations and half came from sources away from the SRS area. All fish taken from the Savannah River contained radionuclides from SRS operations.[22]

11.2.6.1 Effective Dose and Total Risks

Table 11-18 lists effective dose and cancer risks for the Outdoors Person Family over 39 years of SRS operation. These doses and risks included those from exposure to radionuclides released into the air as well as to radionuclides released into surface water. The Child Born in 1955 received the largest dose (9.4 mSv, or 940 mrem) and risks while the Child Born in 1964 received the smallest dose (1.8 mSv, or 180 mrem) and risks.

Table 11-18 39-Year Effective Dose and Cancer Risks for Outdoors Person Family

Total Dose or Risk	Adult Female	Adult Male	Child Born in 1955	Child Born in 1964
Effective Dose (mSv)				
Air Pathways	1.6	2.5	8.3	0.36
Water Pathways	1.5	1.7	1.2	1.5
All Pathways	3.0	4.2	9.4	1.8
Cancer Incidence Risk (%)				
Air Pathways	0.0042	0.0071	0.082	0.0053
Water Pathways	0.0063	0.0072	0.018	0.030
All Pathways	0.011	0.014	0.10	0.035
Cancer Fatality Risk (%)				
Air Pathways	0.0013	0.0025	0.012	0.0030
Water Pathways	0.0048	0.0055	0.011	0.020
All Pathways	0.0061	0.0080	0.024	0.023

Doses and risks from the air pathways were larger than those for the family members in any other scenario. The Child Born in 1955 received the largest doses from the air pathways: 8.3 mSv (830 mrem) over 39 years. The next largest doses were received by the Adult Male who received 2.5 mSv (250 mrem), and the Adult Female who received 1.6 mSv (160 mrem); the Child Born in 1964 received the smallest dose through the air pathways: 0.36 mSv (36 mrem).

One reason that the doses received by these family members through all air pathways were larger than those for comparable members of other scenarios, was because it was assumed that three-quarters of the meat eaten by these family members was venison obtained from the SRS site. The exposure location assumed for deer hunting was much closer to the assumed SRS airborne release points than any other

[22] To determine exposures from consumption of fish, it was assumed that the fish would be taken from areas below the confluence of the Savannah River with Lower Three Runs Creek, so that the fish would be affected by radionuclides discharged into the Savannah River from all SRS surface sources, including Lower Three Runs Creek.

exposure location assumed in this study. From about half to three-quarters of the entire 39-year dose from all air pathways received by any family member came from eating beef (see below). In addition, much of the remaining food eaten by the family came from Jackson, which is located close to (and west-north-west) of the assumed SRS airborne release points.

All family members received comparable doses from the water pathways. The Adult Male received the largest dose; his incremental increase was because he spent much more time than the other family members along the Savannah River shoreline and boating in the Savannah River. His dose from all water pathways was 1.7 mSv (170 mrem) over 39 years. The Adult Female and Child Born in 1964 each received 1.5 mSv (150 mrem), while the Child Born in 1955 received 1.2 mSv (120 mrem). These doses were smaller than those received from the water pathways by members of the Delivery Person Family (Table 11-15).

The percent distribution of dose between air and surface water pathways is shown in Figure 11-36 for the Outdoors Person Family. The water pathways caused a smaller percent of overall dose for members of the Outdoors Person Family than for members of the Delivery Person Family (Figure 11-26). The main difference is Lower Three Runs Creek.

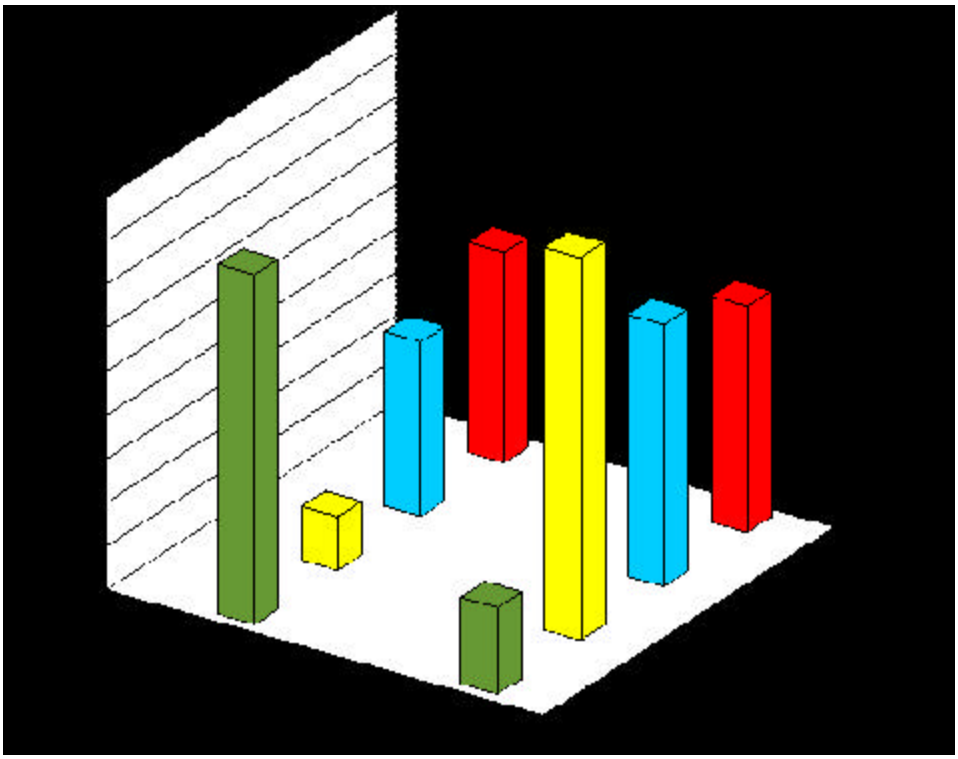


Figure 11-36 Percent Distribution of 39-Year Effective Dose (%) Between Air and Water Pathways for Outdoors Person Family

Members of the Delivery Person family swam in, spent time along the shoreline of, and ate fish taken from Lower Three Runs Creek and the Savannah River. But members of the Outdoors Person Family were not affected by radionuclides in Lower Three Runs Creek. They swam in the Savannah River upstream of SRS's discharge. The Adult Male received shoreline exposures (along the Savannah River) as part of work, as did the two children when they each reached age 18. (The Adult Female spent her entire time along the Savannah River shoreline upstream of SRS's discharge.) All family members

received exposures from boating in the Savannah River as well as exposures from eating fish taken from the Savannah River.

11.2.6.2 Effective Dose by Year

Figure 11-37 shows the percent of the entire dose received by each family member from all (air + water) pathways, while Figure 11-38 shows the percent annual effective dose received by each family member through all pathways. Table 11-19 lists the percent of the entire 39-year effective dose received each year by each family member, as well as their annual dose.

Two large peaks in dose are seen for the years 1956 and 1966, while two smaller peaks are seen for the years 1959 and 1961 (Figure 11-38). The Child Born in 1955 received his largest dose in 1956, when he received 5.9 mSv (590 mrem), or 63% of his entire dose over 39 years. The Adult Female and Adult Male also received their largest doses during this year. The Adult Female received 0.86 mSv (86 mrem), or 28% of her entire dose, while the Adult Male received 1.3 mSv (130 mrem), or 30% of his entire dose. The Child Born in 1964 received his largest dose in 1966, when he received 0.70 mSv (70 mrem), or 38% of his entire dose.

The patterns of annual dose and percent of dose are different from those seen for the Delivery Person Scenario (see Figure 11-27 and Figure 11-28).

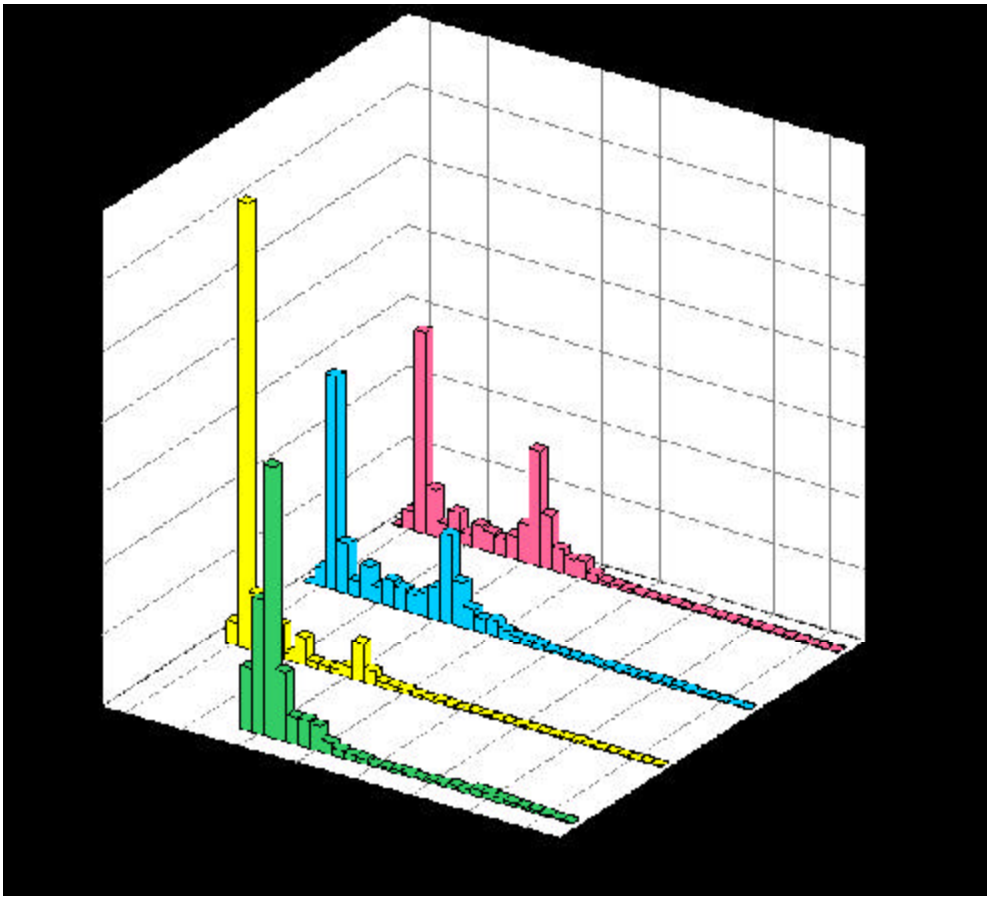


Figure 11-37 Percent of 39-Year Effective Dose by Year for Outdoors Person Family – Air + Water Pathways

Annual doses from all air pathways for the Outdoors Person Family are shown in Figure 11-39. The pattern is familiar. During 1956, the Child Born in 1955 received 5.9 mSv (592 mrem), or 72% of his dose from all air pathways, the Adult Female received 0.84 mSv (84 mrem), or 53% of her dose from all air pathways, and the Adult Male received 1.3 mSv (130 mrem), or 50% of his dose from all air pathways. In 1964, the Child Born in 1964 received 0.045 mSv (4.5 mrem), or 12% of his dose from all air pathways.

Figure 11-40 shows annual effective doses received by each member of the Outdoors Person Family through the water pathways. Annual doses rose to a peak in 1966, and then dropped. After the mid 1970s annual doses fluctuated for all family members between about 0.001 and 0.01 mSv per year. Annual doses through all water pathways were, during 1966:

- Adult Female: 0.48 mSv (48 mrem) -- 33% of her dose from all water pathways.
- Adult Male: 0.50 mSv (50 mrem) -- 30% of his dose from all water pathways.
- Child Born in 1955: 0.48 mSv (48 mrem) -- 42% of his dose from all water pathways.
- Child Born in 1966: 0.68 mSv (68 mrem) -- 47% of his dose from all water pathways.

The annual pattern of dose shown in Figure 11-40 for the water pathways is different than that for the Delivery Person Scenario (Figure 11-30). Whereas for the Delivery

Person Scenario the annual doses fluctuated over a range of about 0.01 to 1 mSv, the doses from the water pathways for the Outdoors Person Scenario built to a peak and varied over a larger range. Except for a few years on either side of 1966, annual doses from the water pathways tended to be smaller than those from the air pathways. This second point is illustrated in ~~Figure 11.2.6.7~~ Figure 11-41, which shows the annual dose from all air pathways and all water pathways for the Child Born in 1955 of the Outdoors Person Family. This pattern is clearly different from that seen for the Child Born in 1955 of the Delivery Person Family (Figure 11-31).

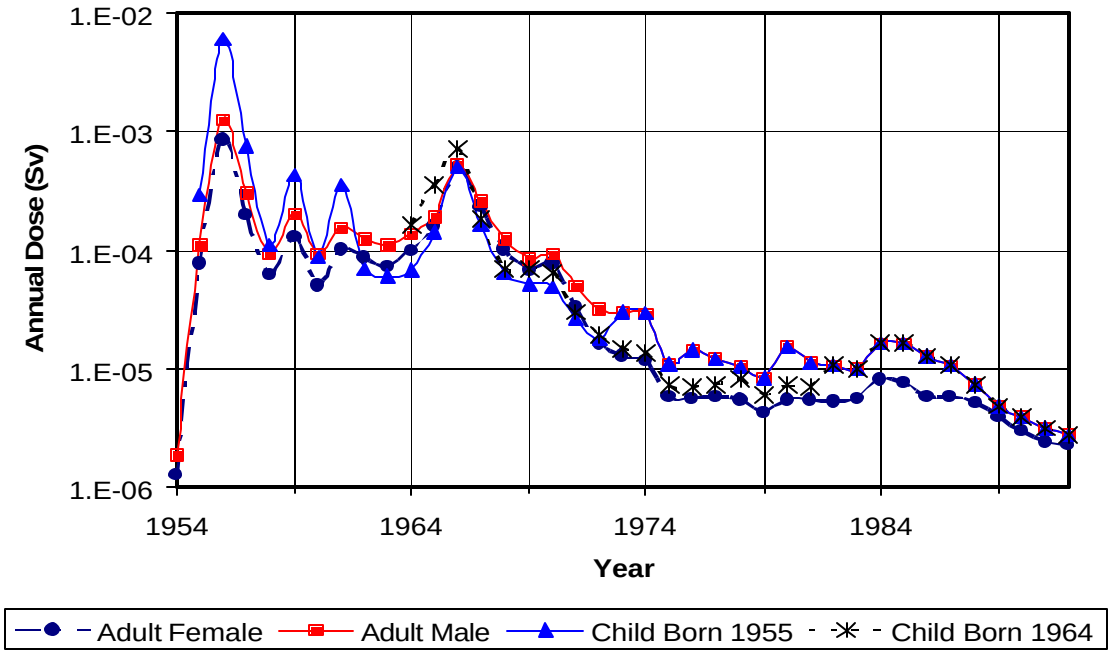


Figure 11-38 Annual Effective Dose (Sv) for the Outdoors Person Family – Air + Water Pathways

Table 11-19 Annual Effective Dose (mSv) for Outdoors Person Family

	Adult Female		Adult Male		Child Born in 1955		Child Born in 1964	
Year	Dose	%	Dose	%	Dose	%	Dose	%
1954	0.0013	0.0	0.0019	0.0				
1955	0.077	2.5	0.11	2.7	0.29	3.1		
1956	0.86	28.3	1.3	30.3	5.9	62.9		
1957	0.20	6.5	0.30	7.2	0.76	8.0		
1958	0.062	2.1	0.09	2.2	0.11	1.2		
1959	0.13	4.3	0.20	4.8	0.44	4.7		
1960	0.050	1.7	0.093	2.2	0.087	0.9		
1961	0.10	3.3	0.15	3.6	0.35	3.7		
1962	0.087	2.8	0.13	3.0	0.070	0.7		
1963	0.072	2.4	0.11	2.6	0.060	0.6		
1964	0.098	3.2	0.14	3.3	0.068	0.7	0.16	9.0
1965	0.16	5.3	0.19	4.5	0.14	1.5	0.35	19.1
1966	0.49	16.3	0.53	12.5	0.50	5.3	0.70	38.4
1967	0.23	7.5	0.26	6.3	0.17	1.8	0.18	9.8
1968	0.10	3.3	0.13	3.0	0.065	0.7	0.070	3.8
1969	0.067	2.2	0.084	2.0	0.052	0.5	0.071	3.9
1970	0.077	2.5	0.092	2.2	0.049	0.5	0.064	3.5
1971	0.033	1.1	0.050	1.2	0.027	0.3	0.030	1.7
1972	0.016	0.5	0.032	0.8	0.018	0.2	0.019	1.0
1973	0.013	0.4	0.030	0.7	0.030	0.3	0.015	0.8
1974	0.012	0.4	0.029	0.7	0.029	0.3	0.014	0.7
1975	0.0058	0.2	0.011	0.3	0.011	0.1	0.0071	0.4
1976	0.0056	0.2	0.014	0.3	0.014	0.2	0.0071	0.4
1977	0.0059	0.2	0.012	0.3	0.012	0.1	0.0074	0.4
1978	0.0056	0.2	0.010	0.2	0.010	0.1	0.0081	0.4
1979	0.0043	0.1	0.0084	0.2	0.0084	0.1	0.0059	0.3
1980	0.0055	0.2	0.015	0.4	0.015	0.2	0.0072	0.4
1981	0.0055	0.2	0.011	0.3	0.011	0.1	0.0071	0.4
1982	0.0054	0.2	0.011	0.3	0.011	0.1	0.011	0.6
1983	0.0057	0.2	0.010	0.2	0.010	0.1	0.010	0.6
1984	0.0082	0.3	0.016	0.4	0.016	0.2	0.016	0.9
1985	0.0076	0.3	0.016	0.4	0.016	0.2	0.016	0.9
1986	0.0058	0.2	0.013	0.3	0.013	0.1	0.013	0.7
1987	0.0058	0.2	0.011	0.3	0.011	0.1	0.011	0.6
1988	0.0052	0.2	0.0074	0.2	0.0074	0.1	0.0074	0.4
1989	0.0045	0.1	0.0055	0.1	0.0055	0.1	0.0055	0.3
1990	0.0030	0.1	0.0039	0.1	0.0039	<0.1	0.0039	0.2
1991	0.0024	0.1	0.0032	0.1	0.0032	<0.1	0.0032	0.2
1992	0.0022	0.1	0.0029	0.1	0.0029	<0.1	0.0029	0.2
Total	3.0	100	4.2	100	9.4	100	1.83	100

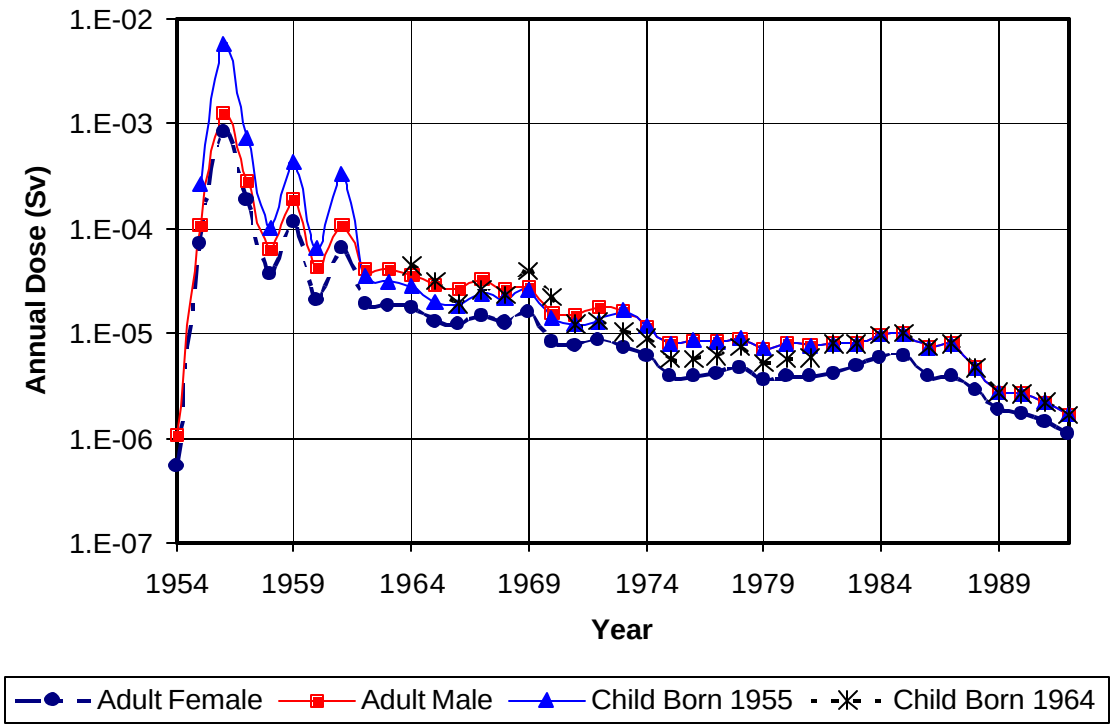


Figure 11-39 Annual Effective Dose (Sv) for the Outdoors Person Family – Air Pathways Only

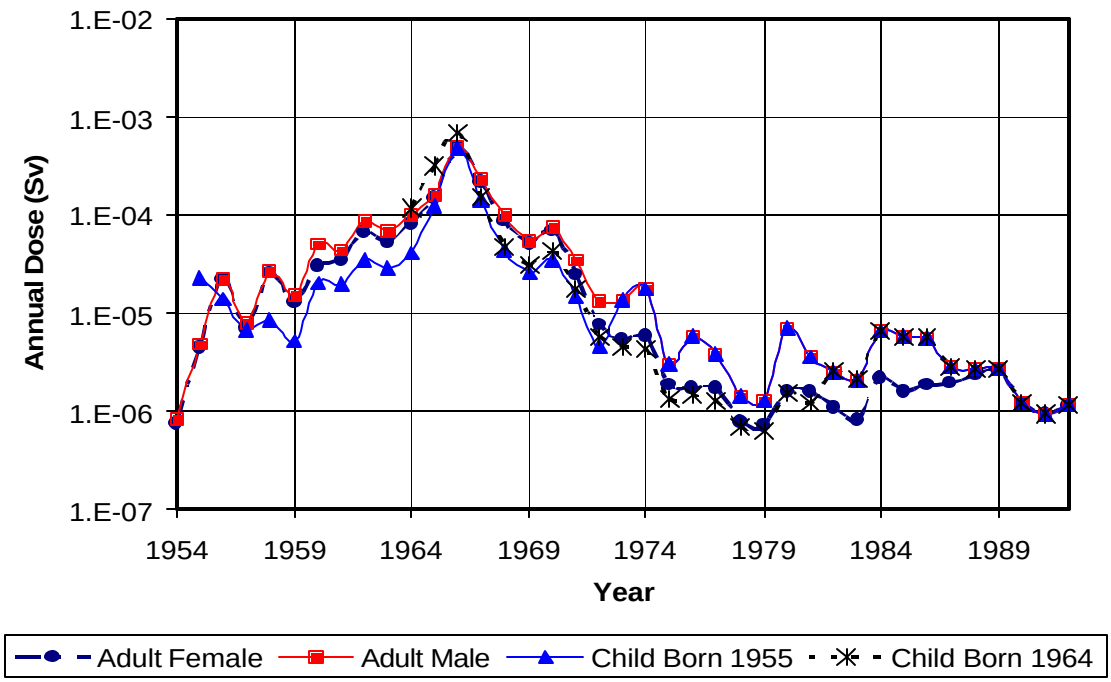


Figure 11-40 Annual Effective Dose (Sv) for Outdoors Person Family – Water Pathways Only

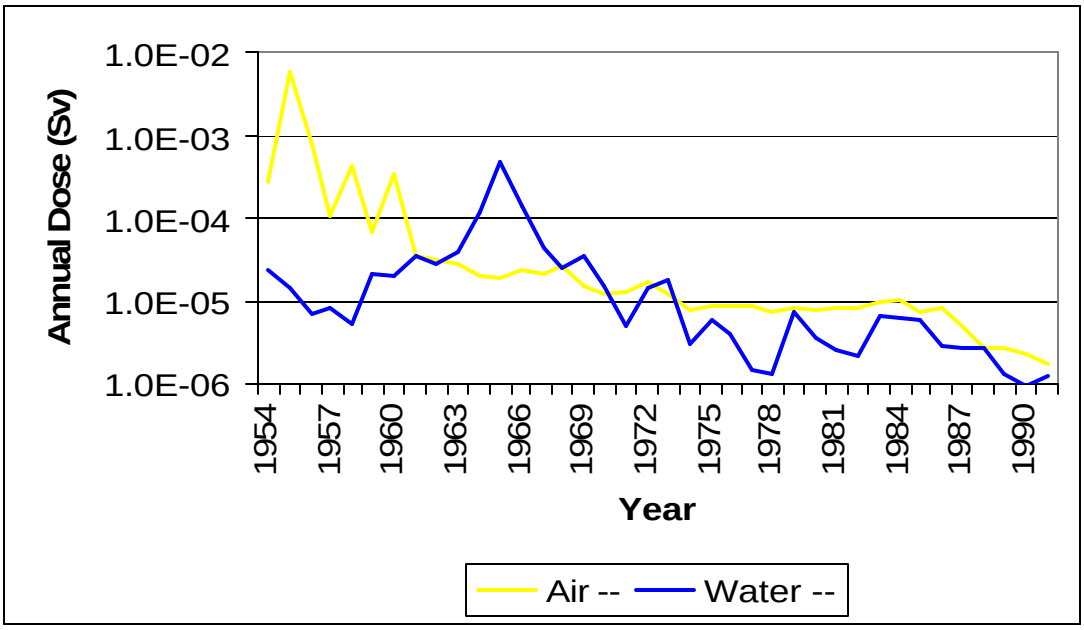


Figure 11-41 Annual Effective Dose (Sv) for Child Born in 1955, Outdoors Person Family – Air vs. Water Pathways

11.2.6.3 Exposure Pathways and Dominant Radionuclides

Figure 11-42 lists the radionuclides causing the largest doses over 39 years for each member of the Outdoors Person Family. For the two adults and the Child Born in 1955, the largest contributor to dose was I-131. This radionuclide caused radiation dose principally from eating foods such as beef and milk. The next two important radionuclides were generally Cs-137 and P-32, radionuclides that caused radiation dose principally from eating fish. For the Child Born in 1964, P-32 was the largest contributor to radiation dose. It again caused dose mostly from eating fish, as did Cs-137 and Sr-90. Tritium caused dose to this family member mainly from inhaling air and eating foods containing this radionuclide.

Each family member received most of their dose from ingestion (Figure 11-43). From 83 to 95 percent of the dose received by each family member came from ingestion, from 2 to 13 percent came from external exposure to radiation, and from 2 to 4 percent came from inhalation.

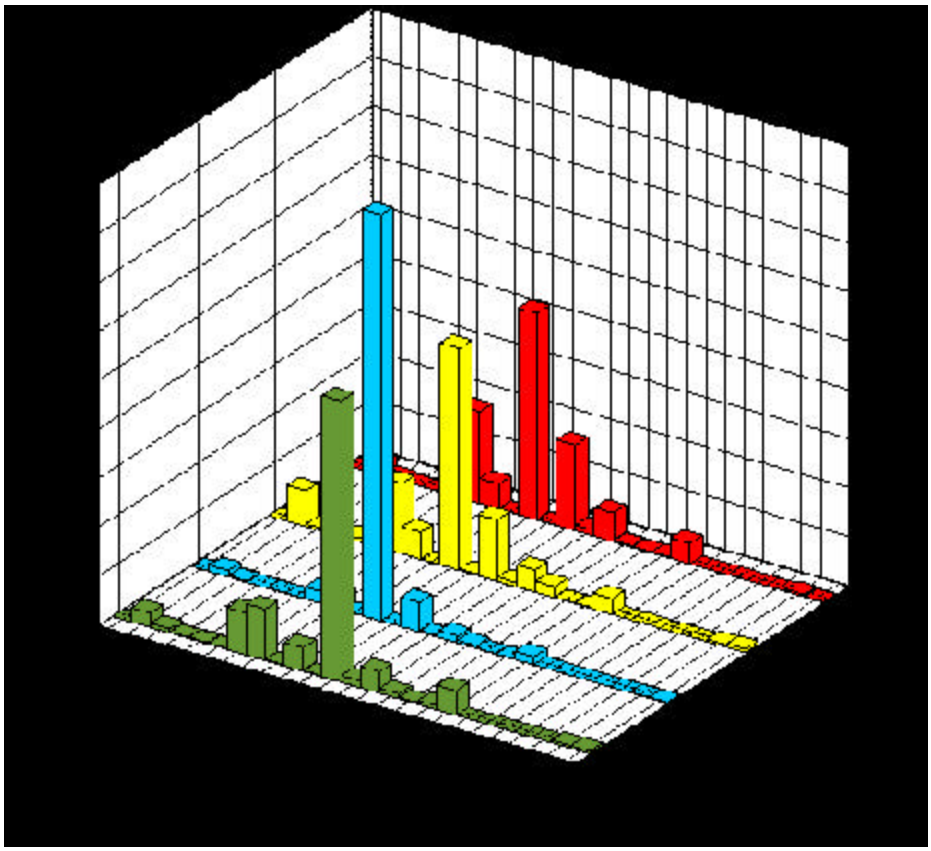


Figure 11-42 Percent of 39-Year Effective Dose by Dominant Isotopes for Outdoors Person Family

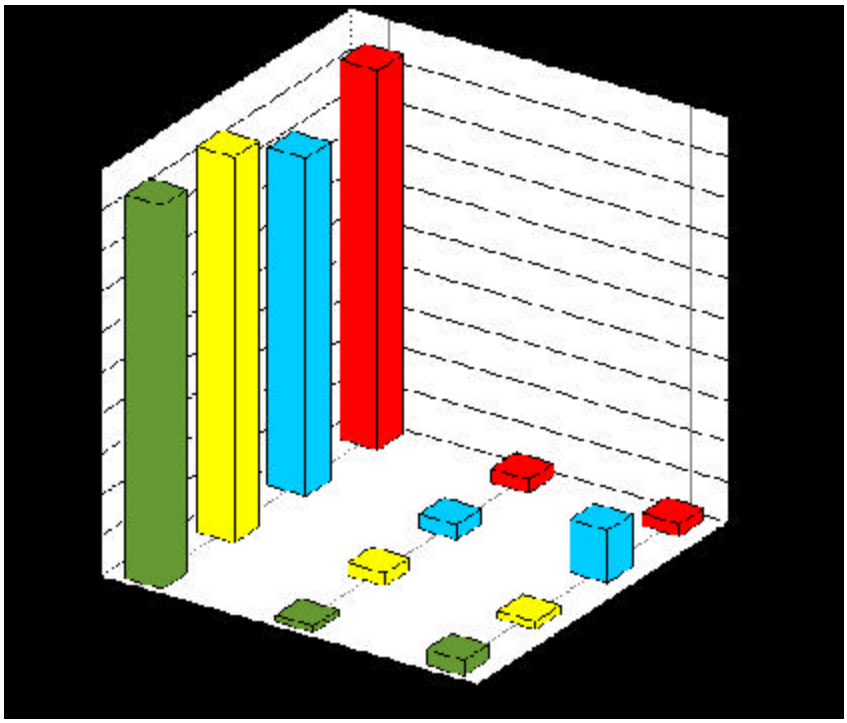


Figure 11-43 Percent of 39-Year Effective Dose by Exposure Route for Outdoors Person Family

As shown in Table 11-20 and Figure 11-44, eating fish was a significant contributor to dose for all family members – i.e., from 12 to 79 percent of any family member's entire dose. It was not, however, as significant as the dose received from eating fish by the members of the Delivery Person Family (Table 11-17). Doses to members of the Outdoors Person family from eating fish were smaller than doses to members of the Delivery Person Family by a factor of up to 3.9. Each member in the Outdoors Person Family ate the same amount of fish as the comparable member of the Delivery Person Family. The doses were different because members of the Delivery Person family ate fish from Lower Three Runs Creek and the Savannah River, while members of the Outdoors Person Family ate fish only from the Savannah River.

Eating beef and milk was a strong contributor to dose for members of the Outdoors Person Family, ranging from 13 to 80 percent of any member's entire dose. The beef and milk pathways were less important for the Child Born in 1964 than for the other family members because he missed the large radionuclide releases into the air during the 1950s and early 1960s. By comparison, doses from eating fruit and vegetables were small, ranging from 1 to 3 percent of any family member's entire dose. Doses from eating eggs, grain, and poultry contributed no more than 1% of any family member's entire dose. Doses from inadvertently eating soil contributed to no more than 0.0004% of any family member's entire dose.

Of interest is the external radiation dose received by the Adult Male (Table 11-20). He received a larger external dose from air immersion than did the Adult Male for the Urban/Suburban Family (Table 11-11). Although they both spent the same amount of time onsite at SRS, the Urban/Suburban Family home in Augusta was farther away from SRS than was the Outdoors Person home in Jackson. In addition, the Adult Male of the Outdoors Person Family received a relatively large dose from shoreline exposure (0.23 mSv, or 23 mrem), contributing about 5% of his entire dose over 39 years. This dose reflected the 260 hours per year he spent along the Savannah River shoreline while at work. By contrast, his doses from boating were relatively small despite the 356 hours per spent boating in the Savannah River.

External radiation doses for the three other members of the Outdoors Person Family ranged from 2 to 4 percent of their entire dose. Most of their external radiation dose came from immersion in a plume of radionuclides in air. Boating in the Savannah River contributed less than 0.1% of their entire dose. Doses from external exposure to radionuclides on the ground were larger, as were doses from shoreline exposures.[23] Still, doses from these pathways were smaller than air immersion doses.

Inhalation doses from breathing a plume of air containing radionuclides were again much larger than the inhalation doses received from breathing radionuclides that had been resuspended from soil.

[23] Except for the Adult Female, who did not experience any shoreline exposures to radionuclides.

Table 11-20 Effective Dose (mSv) by Exposure Pathway for Outdoors Person Family

		Adult Female		Adult Male		Child Born in 1955		Child Born in 1964	
Route	**Pathway**	**Dose**	**%**	**Dose**	**%**	**Dose**	**%**	**Dose**	**%**
External	Air Immersion	0.084	2.8	0.31	7.3	0.12	1.3	0.053	2.9
	Boating	8.2×10^{-5}	<0.1	3.1×10^{-4}	<0.1	1.3×10^{-4}	<0.1	7.2×10^{-5}	<0.1
	Ground Contamin-ation	0.010	0.3	0.012	0.3	0.011	0.1	4.2×10^{-4}	<0.1
	Shoreline	--	--	0.23	5.4	0.053	0.6	0.017	0.9
Ingestion	Beef	1.1	34.8	1.7	39.3	4.5	47.8	0.16	8.9
	Eggs	0.0041	0.1	0.0068	0.2	0.0062	0.1	0.0039	0.2
	Fish	1.5	48.2	1.5	34.6	1.1	11.8	1.4	79.3
	Fruit	0.028	0.9	0.028	0.7	0.12	1.3	0.012	0.7
	Grain	0.0038	0.1	0.0046	0.1	0.015	0.2	0.0018	0.1
	Leafy Vegetables	0.052	1.7	0.052	1.2	0.088	0.9	0.0024	0.1
	Milk	0.20	6.6	0.27	6.3	3.1	32.4	0.075	4.1
	Poultry	0.011	0.4	0.014	0.3	0.014	0.1	0.010	0.6
	Root Vegetables	0.018	0.6	0.025	0.6	0.037	0.4	0.0099	0.5
	Soil*	2.2×10^{-6}	<0.1	2.4×10^{-6}	<0.1	3.4×10^{-5}	<0.1	3.8×10^{-7}	<0.1
Inhalation	Air Inhalation	0.10	3.4	0.16	3.7	0.29	3.1	0.030	1.6
	Resuspend-ed Soil	1.9×10^{-4}	<0.1	2.6×10^{-4}	<0.1	1.8×10^{-4}	<0.1	3.7×10^{-5}	<0.1
Total		3.0	100	4.2	100	9.4	100	1.8	100

* Doses from the soil ingestion pathway were on the order of 10^{-7} to 10^{-5} mSv for each family member. These doses were no more than 0.0004% of any family member's entire 39-year dose.

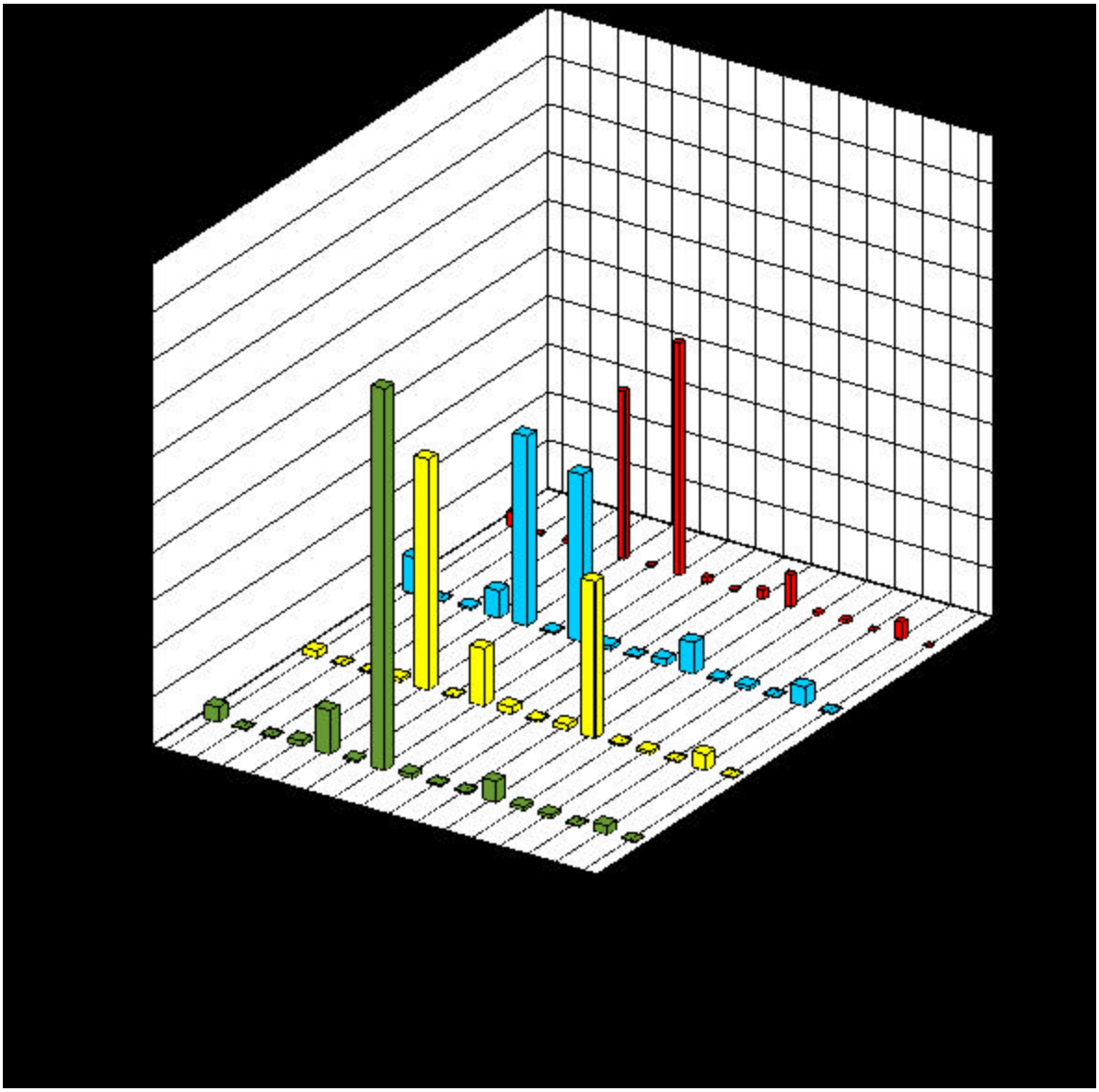


Figure 11-44 Percent of Effective Dose by Exposure Pathways for Outdoors Person Family

11.2.7 Near River Family

This hypothetical family lived in Martin, SC (Figure 11-45). 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. 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.[24] 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

[24] All boating, swimming, and shoreline activities took place below the confluence of the Savannah River with Lower Three Runs Creek.

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.

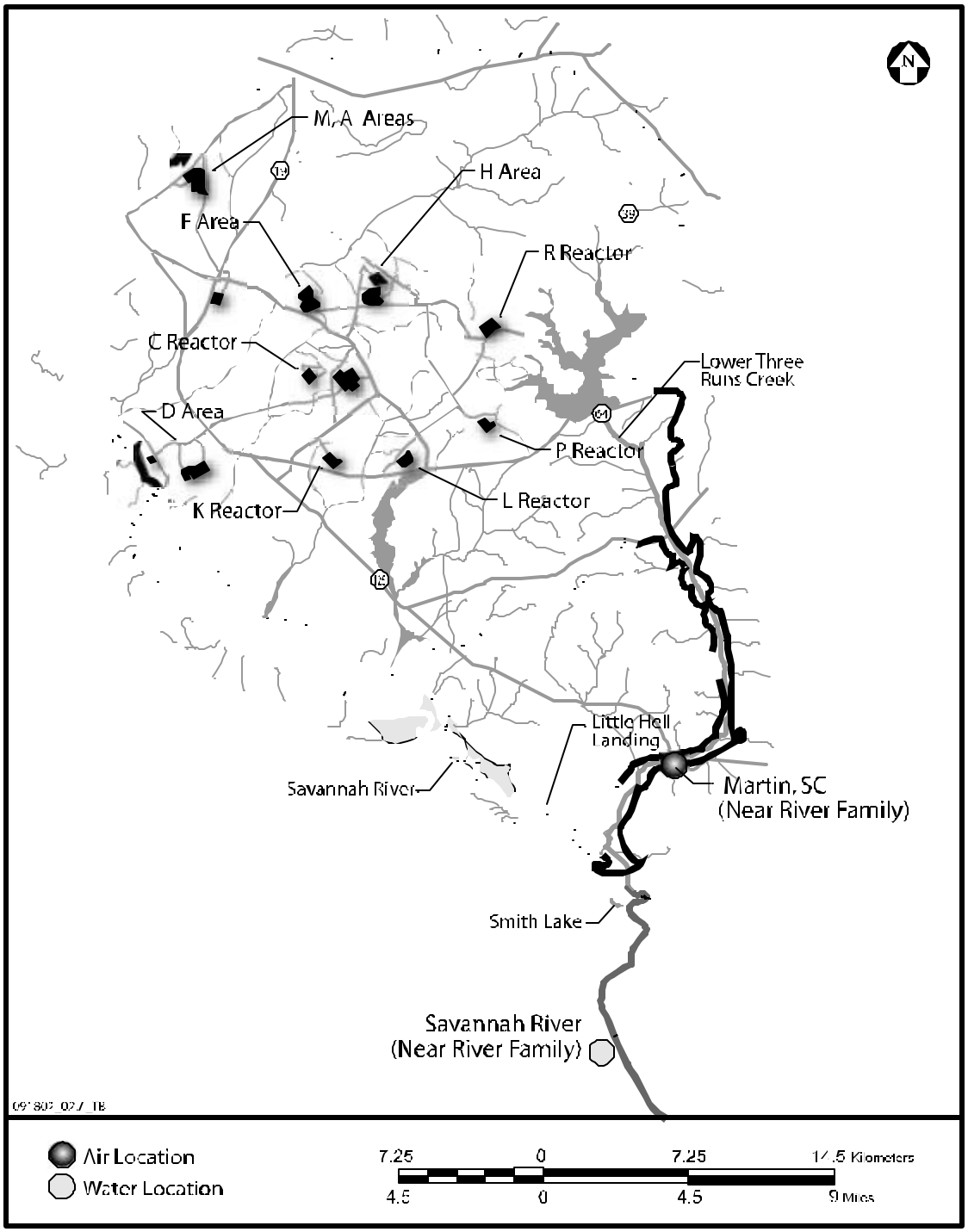


Figure 11-45 Exposure Location for Near Water Family

11.2.7.1 Doses and Total Risks

Table 11-21 lists effective dose and cancer risks for the Near River Family over 39 years of SRS operation. Doses and risks included those from exposure to radionuclides released into the air as well as to radionuclides released into surface water. The Child Born in 1955 received the largest doses and risks; the Child Born in 1964 received the smallest doses and risks.

Doses from all air pathways are similar to those received by members of Rural Family One (Table 11-3). Doses from all water pathways are only a little larger than those received by members of the Outdoors Person Family but much smaller than those received by members of the Delivery Person Family. The members of the Near River Family spent more time in contact with the Savannah River than did the Outdoors Person family, but did not spend time in nor eat fish taken from Lower Three Runs Creek.

Nonetheless, for the two adults and the Child Born in 1964, most radiation doses resulted from the water pathways as illustrated in Figure 11-46. For these family members the water pathways contributed from 81 to 95 percent of their entire dose over 39 years. For the Child Born in 1955, however, the water pathways contributed only 45% of his entire dose over 39 years.

Table 11-21 39-Year Effective Dose and Cancer Risks for Near River Family

Total Dose or Risk	Adult Female	Adult Male	Child Born in 1955	Child Born in 1964
Effective Dose (mSv)				
Air Pathways	0.31	0.42	1.7	0.088
Water Pathways	1.8	1.8	1.4	1.7
All Pathways	2.1	2.2	3.1	1.8
Cancer Incidence Risk (%)				
Air Pathways	0.00089	0.0012	0.017	0.0013
Water Pathways	0.0076	0.0076	0.021	0.033
All Pathways	0.0085	0.0088	0.038	0.034
Cancer Fatality Risk (%)				
Air Pathways	0.00036	0.00044	0.0028	0.00084
Water Pathways	0.0057	0.0057	0.014	0.021
All Pathways	0.0061	0.0062	0.017	0.022

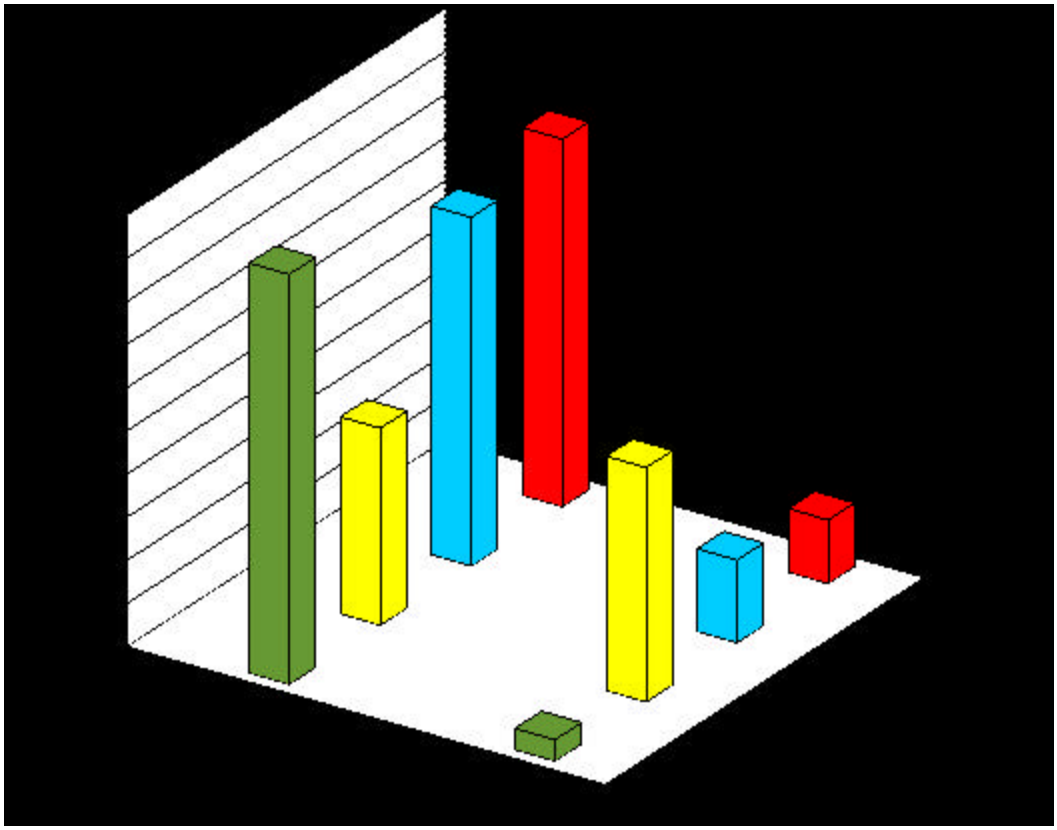


Figure 11-46 Distribution of 39-Year Effective Dose (%) Between Air and Water Pathways for Near River Family

11.2.7.2 Effective Dose by Year

Figure 11-47 shows the percent of the entire dose received by each family member, while Figure 11-48 shows the annual effective dose received by each family member. Table 11-22 lists the percent of the entire 39-year effective dose received each year by each family member, as well as their annual dose. Both the two figures and the table include combined doses from all (air + water) pathways.

Two large peaks in dose are seen for the years 1956 and 1966 (Figure 11-47 and Figure 11-48). These two figures appear similar to corresponding figures for annual dose and percent of entire dose for the Outdoors Person Family (Figure 11-37 and Figure 11-38). Largest dose for the Child Born in 1955 occurred in 1956, while the largest dose for the two adults and the Child Born in 1964 occurred in 1966. In 1956, the Child Born in 1955 received 1.2 mSv (120 mrem), or 40% of his entire dose. In 1966, the Adult Female received 24% (0.51 mSv, or 51 mrem) of her entire dose, the Adult Male received 23% (0.51 mSv, or 51 mrem) of his entire dose, and the Child Born in 1964 received 40% (0.71 mSv, or 71 mrem) of his entire dose.

Figure 11-49 shows the effective dose received by each receptor from only the air pathways. In 1956, the Adult Female received a dose of 0.15 mSv (15 mrem) from the air pathways, the Adult Male received a dose of 0.21 mSv (21 mrem), and the Child Born in 1955 received a dose of 1.2 mSv (120 mrem). After the 1950s, annual doses through all air pathways for these family members typically ranged from about 0.001 to 0.005 mSv per year. The Child Born in 1964 received his largest annual dose (0.013 mSv, or 1.3 mrem) in 1964. Annual doses thereafter fell -- by about a factor of ten by 1988.

As shown in Figure 11-50, annual doses from the water pathways followed a similar pattern to those shown in Figure 11-40 for the Outdoors Person Family. Annual doses from all water pathways built to a maximum in 1966 for all family members:

- Adult Female: 0.50 mSv (50 mrem) – 28% of her dose from all water pathways.
- Adult Male: 0.50 mSv (50 mrem) – 28% of her dose from all water pathways.
- Child Born in 1955: 0.51 mSv (51 mrem) – 35% of his dose from all water pathways.
- Child Born in 1964: 0.70 mSv (70 mrem) – 42% of his dose from all water pathways.

Unlike the situation for the Outdoors Person Family (Figure 11-40), however, after the early 1970s, each member of the Near River Family received essentially equivalent annual doses (Figure 11-50). This pattern of dose occurred because all members of the

Near River Family spent all their time in the Martin area, and all spent the same amount of time swimming and boating in the Savannah River, and spending time along its shoreline.[25]

The result of the combined doses from the air and water pathways was two large peak doses that occurred in 1956 for the air pathways and 1966 for the water pathways. After the early to mid 1960s, most of the doses for each family member were caused by the water pathways as illustrated in Figure 11-51 for the Child Born in 1955.

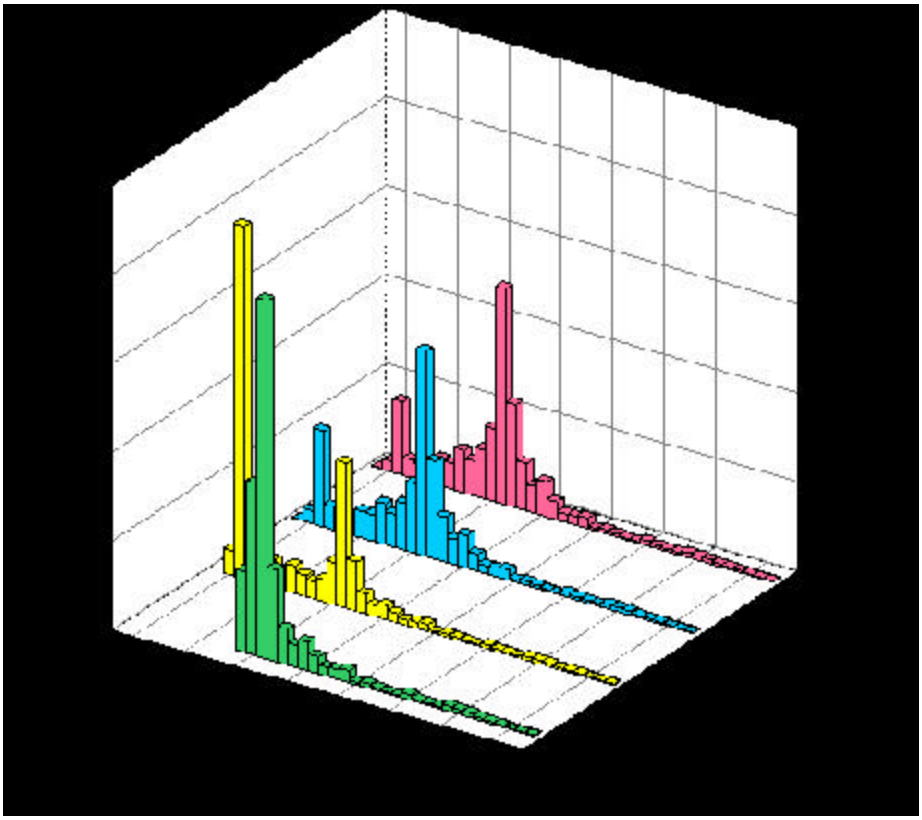


Figure 11-47 Percent of 39-Year Effective Dose for Near River Family – Air + Water Pathways

[25] By contrast, the children of the Outdoors Person Family, after they each reached age 18, worked on the SRS site. The Adult Female of the Outdoors Person Family always stayed at home.

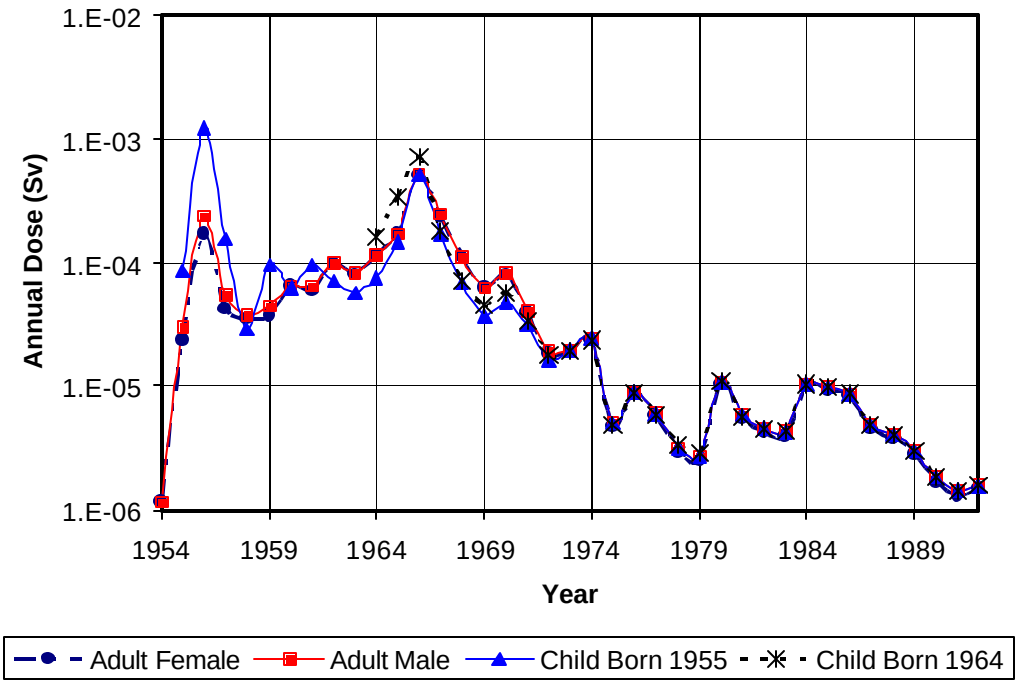


Figure 11-48 Annual Effective Dose (Sv) for Near River Family – Air + Water Pathways

Table 11-22 Annual Effective Dose (mSv) for Near River Family

	Adult Female		Adult Male		Child Born in 1955		Child Born in 1964	
Year	Dose	%	Dose	%	Dose	%	Dose	%
1954	0.0011	0.1	0.0011	0.1				
1955	0.024	1.1	0.031	1.4	0.084	2.7		
1956	0.17	8.2	0.24	10.7	1.24	39.6		
1957	0.041	2.0	0.055	2.5	0.16	5.0		
1958	0.035	1.7	0.037	1.7	0.030	0.9		
1959	0.037	1.8	0.045	2.0	0.095	3.0		
1960	0.064	3.1	0.065	3.0	0.063	2.0		
1961	0.060	2.8	0.064	2.9	0.095	3.0		
1962	0.099	4.7	0.10	4.5	0.071	2.3		
1963	0.080	3.8	0.081	3.7	0.058	1.8		
1964	0.11	5.4	0.11	5.2	0.076	2.4	0.16	9.1
1965	0.17	8.1	0.17	7.7	0.15	4.6	0.34	19.5
1966	0.51	24.3	0.51	23.0	0.51	16.3	0.71	40.4
1967	0.24	11.5	0.24	11.0	0.17	5.5	0.18	10.4
1968	0.11	5.2	0.11	5.0	0.067	2.1	0.071	4.0
1969	0.062	2.9	0.063	2.8	0.037	1.2	0.044	2.5
1970	0.080	3.8	0.081	3.7	0.048	1.5	0.057	3.2
1971	0.040	1.9	0.041	1.8	0.031	1.0	0.034	1.9
1972	0.018	0.9	0.019	0.9	0.017	0.5	0.018	1.0

	Adult Female		Adult Male		Child Born in 1955		Child Born in 1964	
Year	**Dose**	**%**	**Dose**	**%**	**Dose**	**%**	**Dose**	**%**
1973	0.019	0.9	0.019	0.9	0.019	0.6	0.019	1.1
1974	0.024	1.1	0.024	1.1	0.024	0.8	0.024	1.3
1975	0.0047	0.2	0.0049	0.2	0.0049	0.2	0.0048	0.3
1976	0.0087	0.4	0.0089	0.4	0.0089	0.3	0.0089	0.5
1977	0.0058	0.3	0.0060	0.3	0.0060	0.2	0.0059	0.3
1978	0.0029	0.1	0.0032	0.1	0.0032	0.1	0.0034	0.2
1979	0.0025	0.1	0.0027	0.1	0.0027	0.1	0.0029	0.2
1980	0.0105	0.5	0.011	0.5	0.0107	0.3	0.011	0.6
1981	0.0055	0.3	0.0058	0.3	0.0058	0.2	0.0057	0.3
1982	0.0043	0.2	0.0046	0.2	0.0046	0.1	0.0046	0.3
1983	0.0039	0.2	0.0043	0.2	0.0043	0.1	0.0043	0.2
1984	0.010	0.5	0.0105	0.5	0.011	0.3	0.011	0.6
1985	0.0093	0.4	0.0097	0.4	0.0097	0.3	0.0097	0.6
1986	0.0084	0.4	0.0087	0.4	0.0087	0.3	0.0087	0.5
1987	0.0045	0.2	0.0048	0.2	0.0048	0.2	0.0048	0.3
1988	0.0038	0.2	0.0040	0.2	0.0040	0.1	0.0040	0.2
1989	0.0034	0.2	0.0036	0.2	0.0036	0.1	0.0036	0.2
1990	0.0017	0.1	0.0018	0.1	0.0018	0.1	0.0018	0.1
1991	0.0013	0.1	0.0014	0.1	0.0014	<0.1	0.0014	0.1
1992	0.0015	0.1	0.0016	0.1	0.0016	<0.1	0.0016	0.1
Total	2.1	100	2.2	100	3.1	100	1.7586	100

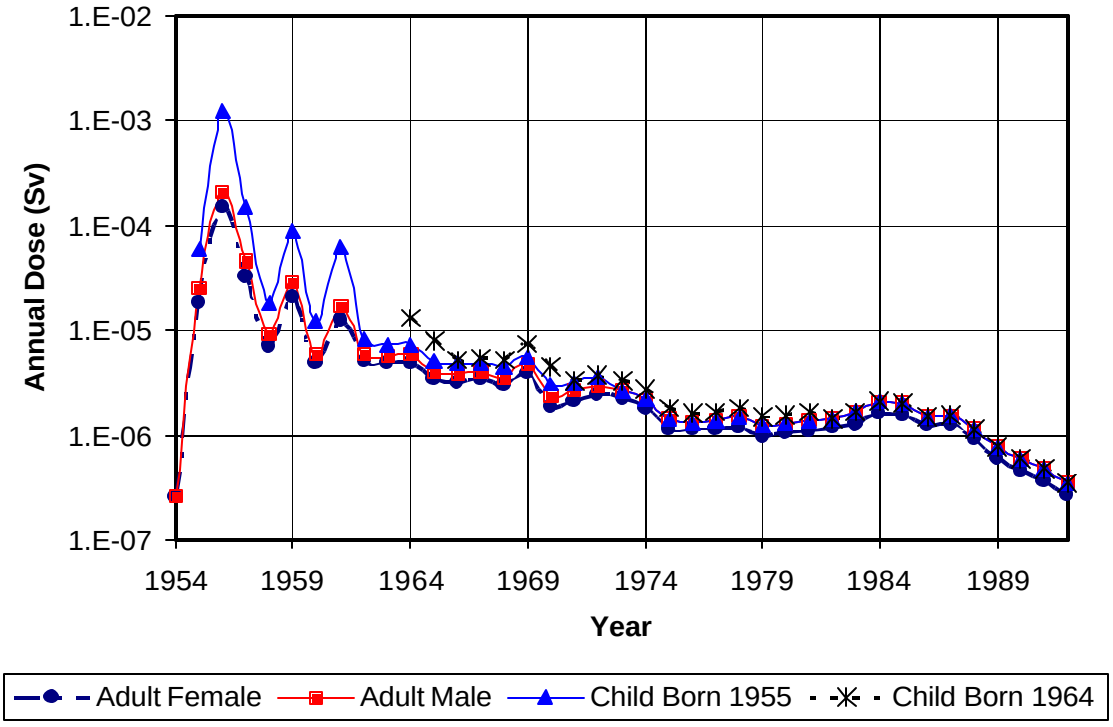


Figure 11-49 Annual Effective Dose (Sv) for Near River Family – Air Pathways Only

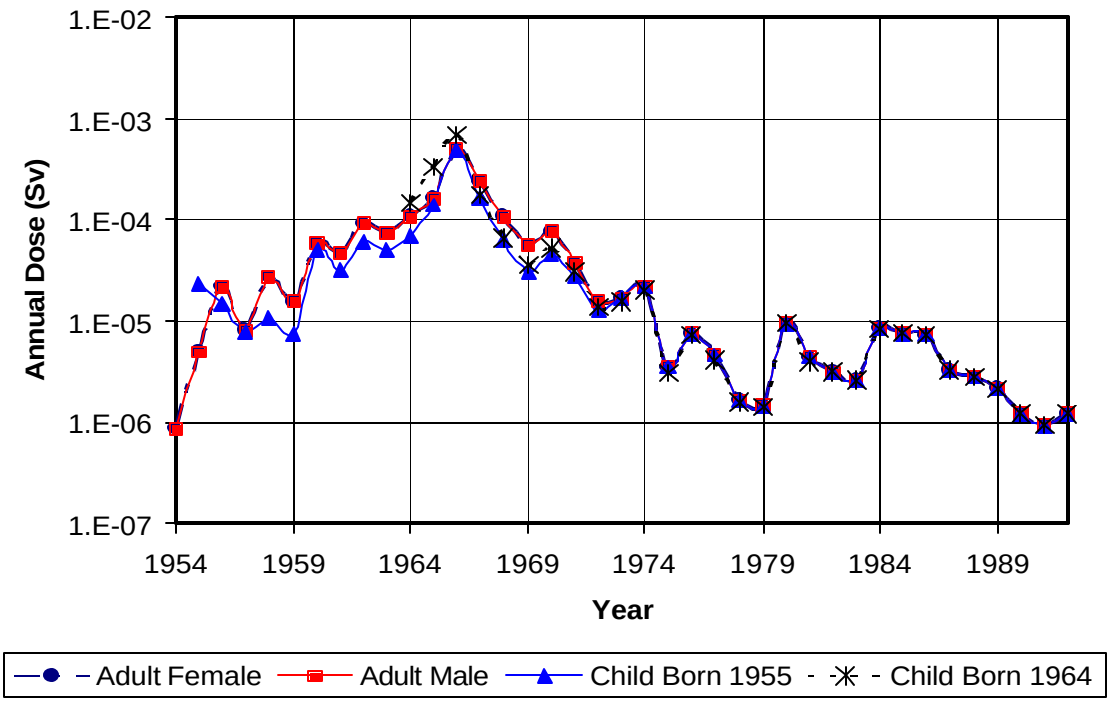


Figure 11-50 Annual Effective Dose (Sv) for Near River Family – Water Pathways Only

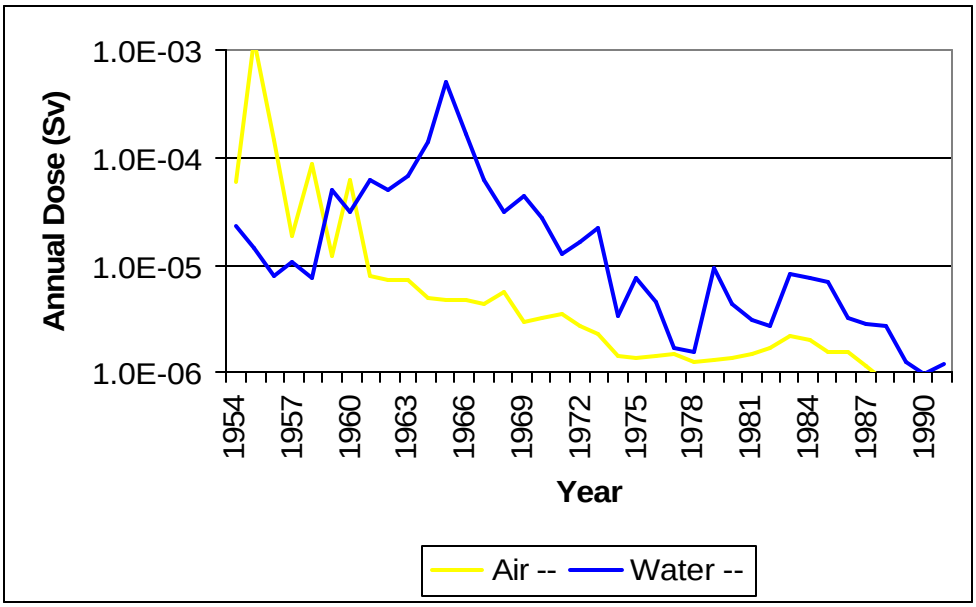


Figure 11-51 Annual Effective Dose (Sv) for Child Born in 1955, Near River Family – Air vs. Water Pathways

11.2.7.3 Dominant Radionuclides, Exposure Routes, and Pathways

Figure 11-52 shows the radionuclides that were the largest contributors of dose over 39 years for each family member. For the two adults, the dominant radionuclides were Cs-137 and P-32. The importance of these two radionuclides reflects the importance of the water pathways for the Near River Family. Doses from these two radionuclides mainly resulted from eating fish. For the Child Born in 1955, I-131 again caused most of his radiation dose. This dose was caused mainly by eating foods containing I-131, and occurred mostly during the 1950s and early 1960s. The Child Born in 1964 missed the large releases of iodine that occurred during the 1950s. Most of his dose was caused by eating fish containing P-32, Cs-137, and Sr-90.

Similar to previous scenarios, each family member received most of their dose from ingestion (Figure 11-53). From 81 to 86 percent of the dose received by each family member came from ingestion, from 12 to 17 percent came from external exposure to radiation, and from 1 to 3 percent came from inhalation.

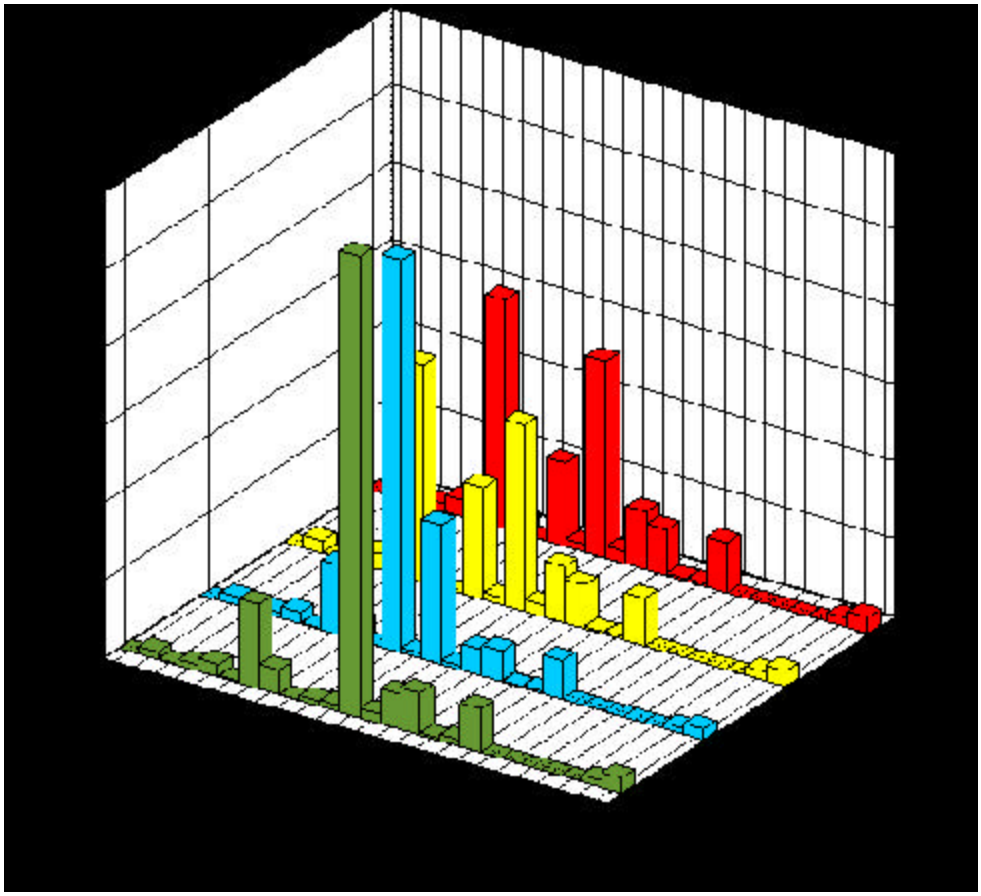


Figure 11-52 Percent of 39-Year Effective Dose by Dominant Isotopes for Near River Family

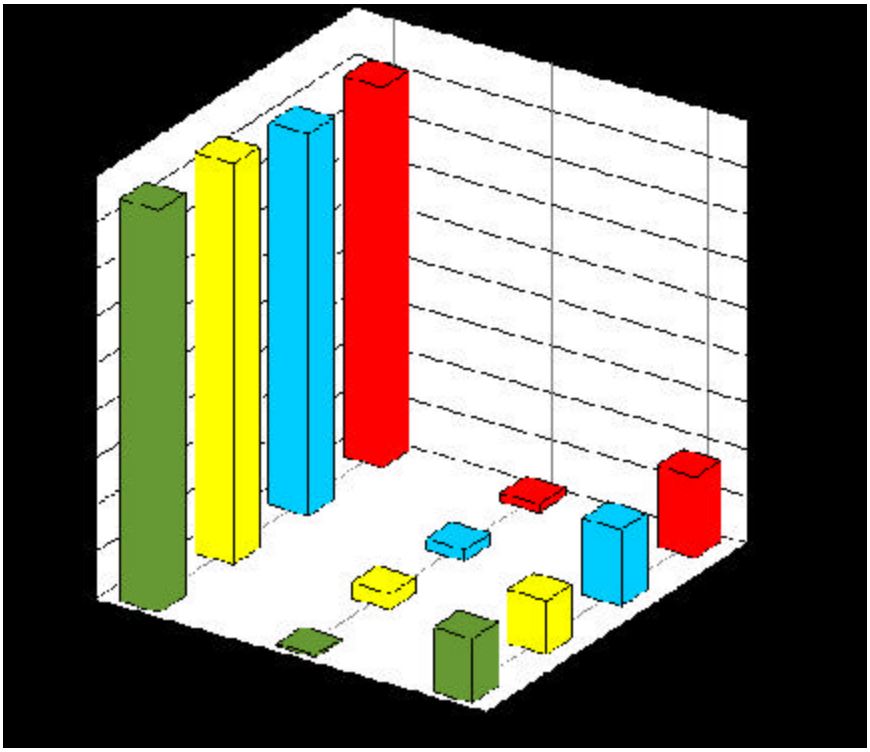


Figure 11-53 Percent of 39-Year Effective Dose by Exposure Route for Near River Family

All family members received most of their dose from eating fish, beef, and milk (Table 11-23 and Figure 11-54). Eating fish accounted for 35 to 82 percent of their entire dose over 39 years, eating beef accounted for 0.6 to 19 percent of their entire dose, and drinking milk accounted for about 2 to 28 percent of their entire dose. These three combined pathways caused from 79 to 85 percent of the entire dose received by any family member. Doses from eating vegetables and fruit were smaller: these combined pathways contributed from 0.7 to 2.4 percent of any family member's entire dose. Doses from eating poultry, eggs, and grain were smaller still, no more than 0.2% of any family member's entire dose. Doses from inadvertently consuming water while swimming in the Savannah River were about as large as those from eating poultry -- i.e., 0.1% of the entire dose. Doses from inadvertently eating soil contributed no more than 0.0003% of any family member's entire dose.

For all family members, most of the external dose came from exposure to radioactive material that had been deposited on the shoreline of the Savannah River. Each family member spent 365 hours per year along the shoreline, a larger time than members of other scenarios. Doses from shoreline exposure contributed from 10 to 16 percent of any family member's entire dose. In contrast, doses from other external radiation exposure pathways associated with boating and swimming accounted for less than 0.1% of any family member's entire dose. Doses from these two water pathways were, for the two adults and the Child Born in 1955, more than 10 times smaller than the doses received by these family members from external exposure to radionuclides that had been deposited from the air onto the ground. These latter doses still contributed no more than 0.1% of any family member's entire dose. Otherwise, external radiation doses from immersion in a plume of air containing radionuclides accounted for no more than about 2% of any family member's entire dose.

Doses from inhaling radionuclides showed a familiar pattern. For all family members, doses from breathing radionuclides from a contaminated plume were much larger than doses from breathing radionuclides after they had been resuspended after being deposited onto soil.

Table 11-23 39-Year Effective Dose (mSv) by Exposure Pathway for Near River Family

		Adult Female		Adult Male		Child Born in 1955		Child Born in 1964	
Route	**Pathway**	**Dose**	**%**	**Dose**	**%**	**Dose**	**%**	**Dose**	**%**
External	Air Immersion	0.036	<0.1	0.036	1.6	0.036	1.1	0.018	1.0
	Boating	$1.6x10^{-4}$	<0.1	$1.6x10^{-4}$	<0.1	$1.6x10^{-4}$	<0.1	$1.0x10^{-4}$	<0.1
	Ground Contamina-tion	0.0029	0.1	0.0029	0.1	0.0029	0.1	$1.2x10^{-4}$	<0.1
	Shoreline	0.32	15.6	0.32	14.6	0.32	10.2	0.22	12.7
	Swimming	$1.6x10^{-4}$	<0.1	$1.6x10^{-4}$	<0.1	$1.6x10^{-4}$	<0.1	$9.8x10^{-5}$	<0.1
Ingestion	Beef	0.13	6.5	0.21	9.5	0.59	18.8	0.011	0.6
	Eggs	0.0018	0.1	0.0030	0.1	0.0027	0.1	0.0018	0.1
	Fish	1.46	71.0	1.46	66.2	1.1	35.4	1.4	82.3
	Fruit	0.010	0.5	0.0098	0.4	0.037	1.2	0.0056	0.3
	Grain	$7.0x10^{-4}$	<0.1	$8.4x10^{-4}$	<0.1	0.0023	0.1	$4.0x10^{-4}$	<0.1
	Inadvertent swimming ingestion	0.0011	0.1	0.0011	0.1	0.0019	0.1	0.0017	0.1
	Leafy Vegetables	0.016	0.8	0.016	0.7	0.026	0.8	0.0010	0.1
	Milk	0.062	3.0	0.083	3.7	0.89	28.3	0.033	1.9
	Poultry	0.0010	<0.1	0.0013	0.1	0.0013	<0.1	$8.4x10^{-4}$	<0.1
	Root Vegetables	0.0070	0.3	0.0097	0.4	0.013	0.4	0.0045	0.3
	Soil*	$6.4x10^{-7}$	<0.1	$6.4x10^{-7}$	<0.1	$9.7x10^{-6}$	<0.1	$1.1x10^{-7}$	<0.1
Inhalation	Air Inhalation	0.039	1.9	0.052	2.4	0.10	3.3	0.012	0.7
	Resuspended Soil	$5.3x10^{-5}$	<0.1	$7.2x10^{-5}$	<0.1	$5.0x10^{-5}$	<0.1	$1.0x10^{-5}$	<0.1
Total		2.1	100	2.2	100	3.1	100	1.8	100

*Doses from the soil ingestion pathway were no more than 0.0003% of any family member's entire 39-year dose.

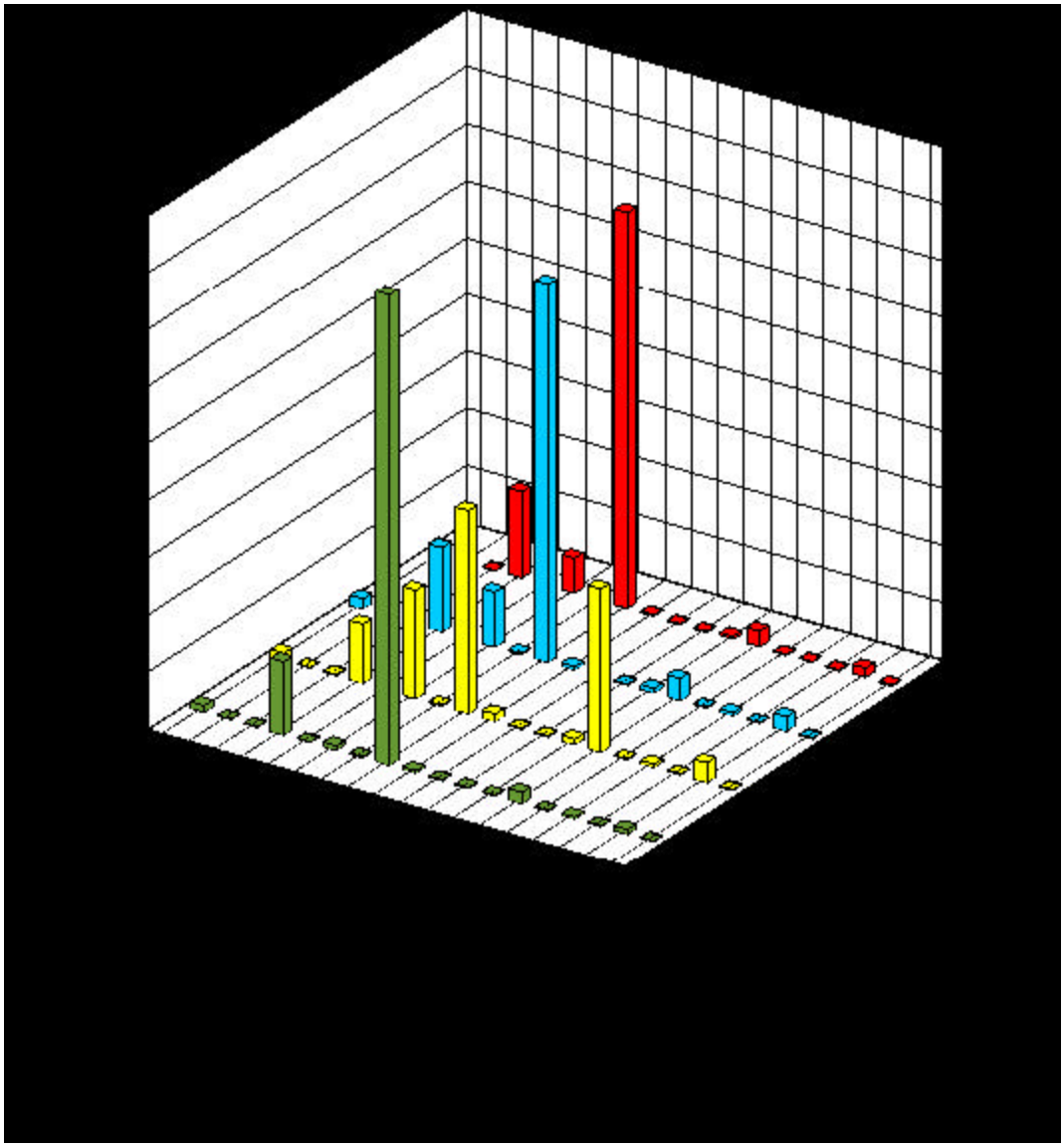


Figure 11-54 Percent of 39-Year Effective Dose by Exposure Pathway for Near River Family

12 UNCERTAINTY ANALYSIS AND RESULTS

12.1 Introduction

Chapter 11, *Point-Estimate Results*, provided the results of the base-case dose assessment. In that particular analysis, a single value of dose was determined for each member of 7 hypothetical 4-member families (a total of 28 receptors). Each family was subjected to a different exposure scenario. These doses were obtained based on point estimates (single representative values) assigned to the variables involved in the analyzed models. This point-estimate analysis is frequently referred to as a deterministic analysis.

While the single-point estimates used in a deterministic estimate of dose may be considered "representative" or "realistic," they do not capture the inherent uncertainty in the variables of interest. By nature, many of the natural processes and phenomena that investigators attempt to represent with equations and numbers will vary with time, space, and environmental conditions. Likewise, many of the variables used to represent or describe a natural process will change with time, space, and the environmental conditions.

In addition to the uncertainty in the natural phenomena, there is uncertainty associated with our understanding of how the phenomena used to represent natural processes are related (the conceptual models), their mathematical descriptions, and their computational implementation. When these uncertainties are considered, the reconstructed dose is uncertain; instead of a single-point estimate of dose for each receptor (as described in Chapter 11), multiple values (a probability distribution of dose) result. Simply, the uncertainty approach involves treating specified input variables as sets of values rather than as single values in the computation. The computation is repeated multiple times using various combinations of the input variable values. This results in a set of dose estimates rather than a single value. This set can then be used to describe the uncertainty associated with the result from the deterministic approach.

In the dose reconstruction for the Savannah River Site, the analysts focused on the uncertainty associated with the variables that are used to describe a particular process (e.g., the bio-uptake factors, consumption of foodstuffs, and particle size). This approach is the most common way to address uncertainty because it does not require development of alternative conceptual models or computational codes. In addition, this approach enables an analysis of the sensitivity (i.e., what changes in the results [dose] are produced by specific changes in the input variables). In this report, the term "uncertainty analysis" is used to describe three types of evaluation:

1. Description of the uncertainty in dose (i.e., how much variability is estimated for dose given uncertainty in the input variables).
2. Description of how the uncertainty in dose depends on the uncertainty for each uncertain input variable.
3. Description of the sensitivity of dose to variations in input variables.

Sometimes the terms "probabilistic" or "stochastic" analysis are used to describe these evaluations.

12.1.1 Overall Description of Uncertainty Analysis

Uncertainty analysis is sometimes referred to as probabilistic analysis or Monte Carlo analysis. It involves multiple computations that use the same code but change the values of the input variables with each computation. The input values are selected randomly from either sets of observations or distributions,

using observations and judgment based upon experience. Section 12.1.1.2 describes this selection process. The selected values for the input variables of interest are then used in the computation, and the value for each of the sampled variables changes with each computation. For example, if 10 values are selected for each variable, the computation is repeated 10 times. It should be noted that each individual computation is a deterministic analysis similar to the point-estimate case but with different values for the variables.

In this analysis, the effect of 14 variables on dose was investigated. This required a series of computations that changed the values of these variables with each computation. As explained below, each computation is called a realization and yields a dose estimate based on a particular choice of values for all the input variables.

In an uncertainty analysis, the aggregate results are generally of interest rather than the result from any one computation. This set of results can be described in terms of simple statistics to give the representative values (e.g., mean), range, and nature of the distribution. In exercises such as dose reconstruction or risk analysis, uncertainty analysis provides insight into the uncertainty associated with the results.

Uncertainty analysis can be approached in a variety of ways. The most common approach is the Monte Carlo approach, which is based on random selection of the variable values from specified distributions. Section 12.1.1.2 describes the details of the Monte Carlo approach.

12.1.1.1 Rationale – Why We Do It; What Are We Trying to Determine?

The primary task of this project was to estimate the dose to 28 hypothetical individuals resulting from exposure to releases from the Savannah River Site (SRS). This estimation was performed using two methods: a point-estimate analysis and an uncertainty analysis. The point-estimate analysis used a representative value for each of the model input variables and resulted in an estimate of dose, cancer incidence risk, and cancer fatality risk for each of the 28 hypothetical receptors specified in the 7 scenarios. The point-estimate analysis included all credible exposure pathways given the behaviors specified in the scenarios and the land-use, water-use, and agricultural practices in the region surrounding the SRS during the period studied. The point-estimate analysis included only those radionuclides that survived the Level 1 screening of the Phase II report. Chapter 11 describes the point-estimate results. The point-estimate results provided a very detailed picture of what caused the dose and risk to each receptor including:

- How doses and risks changed in time.
- What radionuclides contributed most to dose and risks for a particular receptor.
- What pathways contributed most to dose and risks for a particular receptor.
- How the behaviors specified in the various scenarios influenced doses and risks.

An uncertainty analysis was undertaken with the objective of quantifying the uncertainty associated with the estimated doses. To reduce the computational and data-handling burden, risks were not carried along as part of the calculation; however, risks can be estimated from the doses using adult risk factors. Because the uncertainty analysis involves repeating the dose assessments of the point-estimate analysis many times, a daunting amount of computation would be required if all input variables were considered in the uncertainty analysis. To reduce the effort associated with defining a distribution for each variable, the dose-assessment model used for the uncertainty analysis was simplified. Section 12.2 describes this simplification.

Because the results of the point-estimate analysis were used to guide these simplifications, the point-estimate analysis played the role of a screening analysis. As such, the point-estimate analysis was used to determine which pathways and radionuclides were very minor contributors to dose and could be excluded from the uncertainty analysis. In addition, the point-estimate results helped to determine which variables could be considered to be fixed, rather than uncertain, in the uncertainty analysis as described in Section 12.3.

12.1.1.2 Approach – Monte Carlo Sampling of Inputs to Provide Distributions of Dose

In uncertainty analysis, a randomly generated value selected from the probability distribution of each uncertain variable is assigned to that variable; other variables considered to be certain are assigned their nonrandom values. The values assigned to all variables comprise the set of values for one realization (i.e., one set of input variables for one computer run) that results in a random value as the outcome for that particular realization. Depending on the number of uncertain variables involved in the model and the sampling method adopted, the number of realizations required for good statistical estimates may range from a few to a few thousand. A distribution of dose would be obtained after estimating the dose for each of the realizations considered.

The process of random sampling falls into two categories: simple random sampling (Monte Carlo sampling [MCS]) and stratified sampling (e.g., Latin Hypercube Sampling [LHS]) (1). In MCS, each uncertain variable is assigned a range and probability distribution (mathematically described as a probability density function) that may be based on observations, judgment, or a combination of the two. The probability density functions for each of the uncertain variables of interest are then randomly sampled, resulting in a set of values for each of the input variables of interest. Generally, many thousands of samples are required to adequately represent the probability density function when using simple random sampling. A large number of samples is needed to obtain values over the entire range of the variable.

The LHS technique divides the probability density function associated with an uncertain variable into several strata ("bins") to ensure the probability of choosing a random value from each stratum is the same. Compared to the Monte Carlo sampling technique, LHS is more efficient and enables more complete sampling from the probability density function with a limited number of samples. This technique requires more computer memory because all samples are generated at once to ensure appropriate distribution and independence or correlation among the variables. In this analysis, the computation time for each realization was sufficiently long to make LHS the preferred sampling technique because fewer realizations are required.

12.2 Development of a Simplified Model

Uncertainty analyses can be very computationally intensive, requiring a number of individual computations (realizations) that is many times the number of input variables. Each realization requires another computation using the preprocessor, GENII v.2 Code, and postprocessor as described in Chapter 4. To make the problem more manageable, it was decided to focus the uncertainty analysis on those radionuclides and pathways that were most important in the determination of the point estimate. This simplification reduced the computation time and the amount of data handling.

All the various contributors to dose, as described in Chapter 11, were evaluated. These include specific pathways such as dose from eating vegetables or dose from a specific radionuclide such as Cs-137. Each pathway and/or radionuclide contribution was compared with the total dose for a particular receptor. The contributors to dose by pathway and radionuclide were arranged in order from least to greatest. The smallest contributor was eliminated, then the next smallest was eliminated, and the process was repeated

until the cumulative contribution of eliminated pathways and/or radionuclides to the total dose was just under 5 percent. This process was performed on all 28 receptors.

The set of radionuclides and pathways satisfying the 5-percent criterion for all receptors was chosen as the set for simplifying the analysis. Because the pathways and radionuclides were not mutually exclusive (e.g., removing both soil ingestion and uranium takes out uranium dose from soil ingestion only once, but it was counted twice for the cumulative percent), the actual reduction in total dose was always less than 3 percent. With the removal of a particular radionuclide or pathway, a number of input variables were also eliminated from the computation. This helped to reduce the number of variables that needed to be evaluated for inclusion in the uncertainty analysis.

It should be noted that eliminating radionuclides and pathways from the analysis of a particular scenario in effect changed the conceptual model that was evaluated for the scenario. The effect of this change in the conceptual model was evaluated by comparing the point estimate of total dose (all pathways and radionuclides) to the estimate of total dose from the simplified model (reduced set of pathways and radionuclides). The total dose (using the simplified model but using the exact same input variable values as the point estimate) is designated "Run 0."

Table 12-1 presents the comparison of dose for each receptor from both the original point estimate and from the simplified computation ("Run 0"). Because the simplified computation provides doses within 3 percent of the more complete model, this simplification was considered to be acceptable (Table 12-1 shows that the largest deviation is 2.6 percent for the Child Born in 1964 for the Migrant Family scenario).

Table 12-1 Comparison of Dose Estimates from Complete and Simplified Models

Scenario	Family Member	Point Estimate (millisieverts)	Run 0 (millisieverts)	Ratio, Run 0 over Point Estimate
Delivery Family	Adult Female	6.106	6.091	0.997
Delivery Family	Adult Male	6.283	6.266	0.997
Delivery Family	Child Born 1955	5.200	5.180	0.996
Delivery Family	Child Born 1964	2.090	2.081	0.996
Migrant Family	Adult Female	0.447	0.438	0.979
Migrant Family	Adult Male	0.624	0.614	0.983
Migrant Family	Child Born 1955	2.178	2.160	0.992
Migrant Family	Child Born 1964	0.083	0.081	0.974
Near Water Family	Adult Female	2.091	2.057	0.984
Near Water Family	Adult Male	2.205	2.170	0.984
Near Water Family	Child Born 1955	3.137	3.099	0.988
Near Water Family	Child Born 1964	1.759	1.734	0.986
Outdoor Family	Adult Female	3.030	3.001	0.990
Outdoor Family	Adult Male	4.216	4.169	0.989
Outdoor Family	Child Born 1955	9.435	9.383	0.994
Outdoor Family	Child Born 1964	1.826	1.810	0.991

Scenario	Family Member	Point Estimate (millisieverts)	Run 0 (millisieverts)	Ratio, Run 0 over Point Estimate
Rural Family One	Adult Female	0.303	0.299	0.985
Rural Family One	Adult Male	0.423	0.418	0.987
Rural Family One	Child Born 1955	1.589	1.580	0.994
Rural Family One	Child Born 1964	0.072	0.071	0.981
Rural Family Two	Adult Female	0.696	0.685	0.985
Rural Family Two	Adult Male	0.974	0.961	0.987
Rural Family Two	Child Born 1955	3.751	3.729	0.994
Rural Family Two	Child Born 1964	0.140	0.137	0.979
Urban Family	Adult Female	0.330	0.325	0.986
Urban Family	Adult Male	0.731	0.723	0.989
Urban Family	Child Born 1955	2.686	2.675	0.996
Urban Family	Child Born 1964	0.107	0.106	0.983

12.3 Input Variables and Realizations

As discussed in the previous sections, the input variables involved in the computational model for the uncertainty analysis fall into two categories: 1) input variables that are considered as uncertain and 2) input variables that are considered as certain or fixed. While all input variables have an inherent uncertainty, the analysis described in Section 12.4 identified those variables that have the largest effect on the uncertainty of the resultant dose. This analysis reduced the number of input variables that will be considered as uncertain in the uncertainty analysis to 14, leaving the remaining input variables to be considered as certain (fixed) and thus treated as point estimates or fixed values.

Certain and uncertain input variables are introduced to the computational model differently. Certain input variables are represented by a single value, whereas an uncertain input variable is represented by a probability distribution and its associated statistics. Because an uncertain input variable cannot be represented by a single value, a set of values sampled from the variable's probability distribution is used to represent the variable of interest. The degree of representativeness depends on the sampling technique and the number of samples taken from the probability distribution.

As noted in Section 12.1.1.2, random sampling techniques fall into two categories: 1) simple random sampling (SRS), also known as MCS, and 2) the stratified sampling, also known as the LHS. The MCS technique does the sampling completely at random with each sample taken sequentially, whereas the LHS technique performs the sampling by a constraining value selection based on previously constructed realizations. By not allowing samples to be drawn from previously sampled intervals for a variable, LHS provides a more representative sampling of the distributions with a smaller sample size.

MCS is a computationally time-intensive sampling technique. The samples are chosen completely at random within the range of the probability distribution. This necessitates large numbers of random samples for highly skewed or long-tailed probability distributions to reasonably represent the uncertain nature of the variable under consideration.

LHS is more efficient than MCS because it is designed to accurately recreate the input distribution with fewer samples than the MCS method. However, LHS is a memory-intensive technique because the entire set of samples for all variables is collected at once.

All input values (fixed and sampled) are collected together in a matrix format. One set of input values from this collection, with a single value for each variable, is referred to as a realization. Each realization, when used in the computer code, results in a single value for the output variable (e.g., dose). When an uncertainty analysis is performed, the computer code is run iteratively, each time using a different combination of input variable values as determined by the sampling. For an uncertainty analysis involving n uncertain variables, 3n realizations (computer runs) are generally considered to be adequate when using LHS sampling.

12.3.1 Description

LHS was adopted as the sampling technique for the uncertainty analysis. After examining two general-purpose commercial software packages for risk analysis? Crystal Ball 2000 (2) and @RISK (3), it was decided to use the LHS computer code developed by Sandia National Laboratories for the U.S. Nuclear Regulatory Commission (4). This decision was based on the need to be able to define correlations among the uncertain variables. The LHS computer code requires each uncertain variable to be identified by its probability density function (probability distribution) and two quantiles for that distribution: the 0.001 quantile (0.1 percentile) and the 0.999 quantile (99.9 percentile).

Table 12-2 provides the 14 variables that were considered to be uncertain for the uncertainty analysis. For each variable, Table 12-2 contains the type of probability distribution and some of the statistics for that distribution, including the 0.001 and 0.999 quantiles. These quantiles were obtained from built-in functions of Microsoft Excel.

The 14 uncertain variables involved in the uncertainty analysis were considered to be independent of one another. Therefore, during the preparation of the input data file for the LHS code (discussed in the previous section), a particular "flag" was used to indicate that no correlation existed among the variables involved. This flag resulted in small correlation coefficients (less than 0.2) when the correlation coefficient matrix associated with the 40 X 14 output matrix (the output matrix with 40 realizations) was examined.

12.4 Overall Description of the Simplification Approach

This section describes the process by which 14 variables were selected for uncertainty/sensitivity analysis from an initial list of 331 possible variables.

12.4.1 Reasons for Limiting the Scope

A standard reference on radiological assessment (Till and Meyer, 1983) states:

> "The first step in an uncertainty analysis is to limit the scope. This requires an explicit statement of the objectives of the assessment and a determination of relevant radionuclides, exposure pathways, and model parameters. Limiting the scope of an uncertainty analysis avoids exhausting financial, physical, and human resources on aspects of assessment models that are not significant."

For this analysis, the scope was limited to focus attention on variables with the greatest potential for affecting variation in the dose to receptors. This avoided unnecessary use of resources for insignificant aspects of the models.

Table 12-2 The Fourteen Uncertain Variables Considered for Uncertainty Analysis

Variable	Description	Units	Dist. Type	Pt. Estimate	Log Mean	Log Std. Dev.	Median	0.001 Quantile	0.999 Quantile
Water Pathway									
CLBFF, Cs-137	Bioconcentration in fish	L/kg	Lognormal	4,700	8.46	1.20	4.70E+03	116	1.90E+05
CLBFF, Sr-90	Bioconcentration in fish	L/kg	Lognormal	450	6.11	2.03	4.50E+02	0.849	2.39E+05
CLBFF, P-32	Bioconcentration in fish	L/kg	Lognormal	50,000	10.82	0.89	5.00E+04	3.15E+03	7.93E+05
Air Pathway									
LEAFRS, RESFAC;1	Soil resuspension factor? farm	1/m	Lognormal	0.00001	-11.51	2.62	1.00E-05	3.03E-09	3.30E-02
RADIUS	Particle radius	µm	Lognormal	0.5	-0.69	0.41	5.00E-01	0.143	1.75
WTIM	Weathering rate constant from plant	d	Lognormal	14	2.64	1.40	1.40E+01	0.183	1.07E+03
DPVRES	Deposition velocity from air to plant surfaces	m/s	Lognormal	0.001	-6.91	1.26	1.00E-03	2.07E-05	4.84E-02
DEPFR1, 2	Deposition retention fraction for plants	Fraction	Lognormal	0.25	-1.39	0.59	2.50E-01	4.07E-02	1.54
GRWPA, 5&6	Growing period for animal forage	d	Lognormal	30	3.40	0.44	3.00E+01	7.65	118
CLFMT, I-131	Cattle intake-to-beef transfer factor	d/kg	Lognormal	0.04	-3.22	0.50	4.00E-02	8.49E-03	0.188
F	Release factor		Lognormal	1	0.00	0.20	1.00E+00	0.539	1.86
CONSUM, 5	Animal feed consumption rate? beef animal forage	kg/d	Normal	36	36.00*	8.63*		9.33	62.7
CLFMK, I-131	Cow intake-to-milk transfer factor	d/L	Lognormal	0.01	-4.61	0.91	1.00E-02	6.06E-04	0.165
BIOMA2, 5&6	Animal forage standing biomass (wet)	kg/m^2	Lognormal	0.3	-1.20	0.08	3.00E-01	0.233	0.386

* Mean and standard deviation for normal probability distribution.

By limiting the analysis scope to those radionuclides, pathways, and input variables most influencing dose and dose variation, the computational burden was focused on the most important model aspects (some of this simplification is described in Section 12.2). By screening the input variables to select those influencing variations in dose most, the development of probability distributions was focused on the most important variables.

12.4.2 Variable Selection Process? Overview

The point estimates provided in Chapter 11 are based on a single value chosen for each input variable. All input variables were considered to be fixed, or "certain," even though a range of values may have been considered in determining the single representative value for each variable. These representative values were chosen to be consistent with the specified scenarios, and site characteristics. When a range of values was available for a variable, the representative value was chosen in such a way that it did not intentionally underestimate or overestimate the dose.

In the uncertainty analysis, all of the "certain" input variables used to generate the point estimates could be considered as uncertain variables with their own probability distributions because, in fact, all input variables are uncertain. However, in most examples of environmental analysis, only a few input variables dominate the results. This variable selection process is intended to reduce the number of variables treated as uncertain to focus attention on those that appear to have the most effect on variations in dose.

Two categories of input variables were categorically excluded from consideration as uncertain:

1. The variable values representing the behavior of the receptors (e.g., the amount of milk consumed at a particular age) were derived from the scenario specifications. Because the scenarios were hypothetical and specified by the CDC and the SRSHES, and because the specified behaviors represented a range of plausible variation, these variable values were considered to be fixed for the purposes of this study.
2. This study has used a set of dose and risk factors established by national and international radiation protection organizations over many decades. These factors were treated as fixed because the uncertainty in these factors was considered small compared to that in other input variables and the uncertainty in these variables would be similar for any dose estimate.

Figure 12-1 shows the sequence of steps used by the variable selection approach to reduce the number of input variables considered in the uncertainty analysis.

At the beginning of the selection process, all input variables except those categorically excluded were considered to be candidates for treatment as uncertain variables. This stepwise process was intended to eliminate variables as candidates for the "uncertain" category based on a defined and defensible criterion at each step in the process. The following criteria were used at the six steps of the selection process:

1. Eliminate variables concerned with exposure pathways that are not used for modeling the SRS.
2. Eliminate variables that are only used for radionuclides and pathways that are minor contributors to dose.
3. Eliminate variables that are only used for radionuclides and pathways whose fractional contribution to dose squared is small.
4. Eliminate any remaining variables in categories already determined as fixed, such as variables associated with scenario specifications or dose and risk coefficients.

5. Combine input variables that may be specified separately but are more appropriately considered the same for this study.
6. Eliminate variables with small contributions to variance.

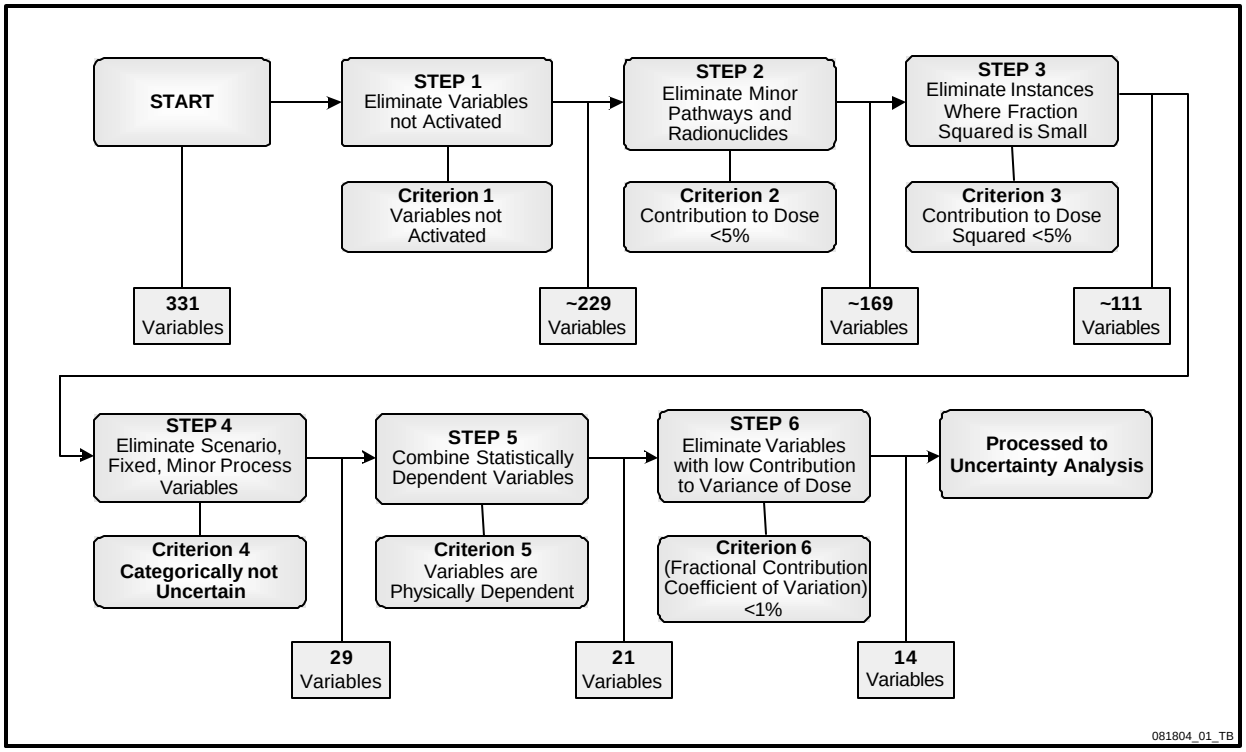


Figure 12-1 Steps Involved in Variable Reduction and Uncertainty Model Simplification

Each of these steps is described in more detail below. In accounting for the number of variables, Appendix F provides tables that list 331 separate variables. These lists are taken as the starting point of this process to reduce the number of variables considered as uncertain. However, there is a subjective element in counting the variables. For example, the variable "ARMETFILE" is the name of the file containing the 20-year average meteorological data that is read into GENII. These meteorological data were not counted among the input variables required to be specified because 1) they were computed separately and not included in the variable tables and 2) they were kept constant for all computations.

The main reason for performing the uncertainty analysis is to estimate the confidence interval for the estimated dose to each receptor. The confidence interval is a commonly used measure to describe the uncertainty in a variable. A key factor in determining the confidence interval is the variance of the dose (or equivalently the standard deviation of the dose, which is the square root of variance). Some of the screening steps are based on the fact that even though a variable may be important in determining the value of dose, it may have little influence on the variance of the dose.

12.4.2.1 Start

The 331 variables were specified to obtain the point estimate of dose for each receptor. Although each variable was carefully evaluated and specified, counting them is somewhat subjective. As stated in Section 12.4.2, some variables are just the name of a file containing extensive but fixed values? these variables were not included in the count. Other variables were indexed by exposure location or radionuclide and were specified for each location and radionuclide with potentially different values. In

this description, they were counted as a single variable if a single value was used for every instance. Additional inputs to the dose modeling that were not counted as variables include 1) air releases by year, isotope, and source; 2) computer grid coordinates; and 3) water concentrations by year, isotope, and location. In addition to the variable lists in Appendix F, a variable "F" was added to the lists which accounts for uncertainty in radionuclide releases.

12.4.2.2 Step 1? Eliminate Unused Variables

Because of the scenario specifications and the assumptions made for modeling, the point-estimate analysis did not use all the input variables employed by GENII to model the transport and exposure processes. For example, Appendix F shows that food chain transport variables associated with irrigation are not used due to the lack of evidence that the Savannah River had ever been used for irrigation in the region. Variables such as irrigation time (IRTIMA, IRTIMR, IRTIMT) and irrigation rate (RIRR, RIRRA, RIRRR) are not specified for the point-estimate analysis and need not be considered in the uncertainty analysis. As part of the scenario implementation, beef cattle were assumed to consume no contaminated feed (beef cattle consumed contaminated forage-grass); therefore, about 30 food chain variables were eliminated. Also note that cerium, technetium, niobium, zinc, cobalt, sulphur, phosphorus, yttrium (a decay product of niobium), and zirconium are only released to water, so their terrestrial uptake factors may be eliminated; this eliminates eight variables for each element. Approximately 102 variables were eliminated in this step, leaving approximately 229 potential uncertain variables.

12.4.2.3 Step 2? Screen Out Minor Contributors to Dose

As described in detail in Section 12.2, a simplified model was obtained by screening out radionuclides and pathways whose combined contribution to total dose was less than 5 percent. The actual reduction in dose was always less than 3 percent for any receptor. The following radionuclides and pathways were eliminated from the model on this basis:

1. Air Release:
    a. Radionuclides: americium-241, cesium-137, iodine-129, strontium-89, strontium-90, and all isotopes of uranium.
    b. Pathways: ground contamination, grain, and soil ingestion.
2. Water Release:
    a. Radionuclides: iodine-129, niobium-95, strontium-89, and all isotopes of uranium.
    b. Pathways: Boating, swimming immersion, and swimming inadvertent ingestion.

By eliminating these pathways and isotopes, it was unnecessary to consider about 60 associated variables as uncertain. For example, terrestrial uptake factors for various forms of vegetation and animals, and for the isotopes americium-241, cesium-137, iodine-129, strontium-89, strontium-90, and all uranium isotopes, could be eliminated from consideration as uncertain variables. Because uptake factors are generally element-specific and not isotope-specific, the uptake factors for iodine remained because iodine-131 was not screened out. Therefore, 8 terrestrial uptake factors for each of the elements americium, cesium, strontium, thorium (a decay product of uranium), and uranium were eliminated, thereby reducing the number of potential uncertain variables by 40. In addition, six variables related to grain and eight variables associated with direct exposure to contaminated soil were reclassified. Another six variables related to grain and aquatic uptake were eliminated. Approximately 60 variables were eliminated in this step, leaving approximately 169 potential uncertain variables.

12.4.2.4 Step 3? Screen Out Instances Where Fraction Squared Is Small

Appendix L discusses a mathematical approach in which the dose for any receptor is considered to be approximated by a linear function of each of the input variables, expanded about their nominal values (i.e., the point-estimate values). Quite a bit is known about the point-estimate dose, including the fractional contribution to the total dose from each radionuclide and through each pathway. Mathematically, the fraction of dose F(ij) is known for each pathway (i) and each radionuclide (j). This information has been used in the variable selection process described in Section 12.2 to eliminate pathways and radionuclides from the model.

The approach discussed in Appendix L shows that the variance of the dose is proportional to the square of the sum of the fractional contributions to dose, where the sum is taken over all pathways and all radionuclides for which the variable has an impact on dose. Note that a particular variable may not have an impact on the dose resulting from a particular radionuclide or pathway. For example, the variable characterizing the uptake of cesium-137 by fish does not have any impact on the dose from iodine from drinking milk. As an approximation, it was assumed that if the sum of the squares of the fractions for all isotopes of a given pathway were small, then the pathway and its associated variables would not contribute significantly to the variance of dose. Similarly, it was assumed that if the sum of the squares of the fractions for all pathways of a given isotope were small, then the radionuclide and its associated variables would not contribute significantly to the variance of dose.

For air releases, four receptors were used as indicators to test for these conditions. The receptors were the Adult Female and Child Born in 1964 for Rural Family #2 and for the Migrant Worker Family. As discussed in Chapter 11, for air releases, the two adults and Child Born in 1955 had similar contributors to total dose; however, the Child Born in 1964 was different because that receptor missed the large iodine releases early in the SRS history. Consequently, fractional dose contributions to both the Adult Female and Child Born in 1964 were examined for this step of the variable reduction. Rural Family #2 was selected because it had fractional contributions to dose typical for most of the scenarios receiving doses from air releases only; however, the Migrant Family was somewhat of an outlier and was included for that reason. From these instances, certain radionuclides and pathways were found to be insignificant contributors to the variance of dose. The incremental contribution to total dose by every radionuclide-pathway pair was computed and then renormalized by the total dose from the pathways and radionuclides remaining after the model simplification described in Section 12.2. (As shown by the ratios in Table 12-1, this adjustment in fractional contribution was small when compared to the fractional contributions stated in Chapter 11.) These renormalized fractional values were then squared, and the squared fractional values were renormalized by the largest value. The renormalized squared fractions were then summed over pathways and radionuclides. In general, if any of the resulting sums were smaller than 0.01, then the variables associated with those radionuclides and pathways were eliminated. On this basis the variables associated with the following pathways or radionuclides were thus eliminated:

- Cesium-14.
- Plutonium-238,239.
- Ruthenium-106.
- Resuspended soil inhalation.
- Poultry ingestion.
- Eggs ingestion.
- Fruit ingestion.
- Root vegetable ingestion.

For the Child Born in 1964 for Rural Family #2, the sum for root vegetable ingestion slightly exceeded the 0.01 criterion.

Two receptors included in water exposure scenarios were used as indicators to test for these conditions. These were the Adult Female and Child Born in 1964 for the Delivery Family. The Delivery Family was chosen because it had the largest doses from water releases; the Adult Female and Child Born in 1964 were chosen for the reasons stated previously. From these instances in which water release doses dominated, the following pathways and radionuclides were found to be insignificant contributors (as stated above) to the variance of dose:

- Shoreline direct exposure.
- Cesium-144.
- Cobalt-60.
- Cesium-134.
- Hydrogen-3.
- Iodine-131.
- Plutonium-238,239.
- Ruthenium-106.
- Zinc-65.
- Zirconium-95.

By eliminating variables associated with these pathways and radionuclides that are insignificant contributors to the variance of dose, approximately 58 variables were reclassified as fixed. For example, 7 uptake factors each for the elements plutonium and ruthenium were eliminated, thereby reducing the number of potential uncertain variables by 14. Elimination of the egg and poultry pathways reduced the number of variables by about 22. Elimination of water-release radionuclides reduced the number of uncertain variables by nine. Elimination of variables associated with ingestion of fruit and root vegetables reduced the variable count by about 12. This left about 111 potential uncertain variables.

12.4.2.5 Step 4? Eliminate Health Effects Variables and Scenario-Based Variables

A number of the remaining potential uncertain variables were reclassified as variables to be considered certain or fixed for a variety of reasons. The following represent some of the important reasons for these categorical reassignments:

- Holdup times are unimportant for long-lived radionuclides; the dose from phosphorus-32 could be affected because it has a relatively short half-life (14.5 days), but it is a relatively small contributor.
- Holdup times for food delivery and processing were assigned as part of completion of the scenario specifications; because the scenarios are mandated, these variables are considered to be certain.
- It was independently determined that, for these scenarios, radionuclide uptake by vegetation from soil is small compared to radionuclide uptake by vegetation from direct deposition; therefore, all variables associated with modeling soil uptake are considered fixed. Approximately 48 variables were reclassified on this basis.
- Variables associated with household use of river water were considered to be fixed; although volatilization of radionuclides was considered for the Near Water Family, it accounted for a very small fraction of the total dose.

The variables that relate to these points were considered fixed and therefore were eliminated at this step. Approximately 82 variables were thus eliminated, thereby leaving approximately 29 potentially uncertain variables.

12.4.2.6 Step 5? Combine Variables that May be Considered Together

Further reduction in the number of variables considered to be uncertain was accomplished by noting that for three pairs of variables only one value, albeit an uncertain value, need be assigned to the pair:

1. BIOMA2, 5 and BIOMA2, 6.
2. GRWPA, 5 and GRWPA, 6.
3. DEPFR1 and DEPFR2.

For the first two pairs, the variables referred to values for milk and beef animal forage. Because the same grass was used for both milk and beef animal forage, these variables could be assumed to be equal. For the third pair of variables, dry- and wet-deposition fractions were assumed to be equal.

In the following two cases, the value of one variable in a pair was derived from the sampled value of the other variable in the pair by multiplying the first variable by a constant; essentially, the pair of variables is assumed to be different by a multiplicative constant and perfectly correlated as explained in the following:

1. CONSUM,5? the consumption rate of forage by beef cattle was assumed to be the fraction 36/29 the value of CONSUM,6? the consumption rate of forage by milk cattle. This is the ratio of the point estimate values. The assumption means that whatever causes the beef cattle to eat more, it will have the same effect on dairy cows.

2. RESFAC,1? the resuspension factor for rural locations is assumed to be 100 times the value of RESFAC,2? the resuspension factor for urban locations. It is essentially assumed that whatever forces produce more resuspension in the city and suburbs (e.g., higher wind) will do the same on the farm. For the point-estimate case, it was assumed that the resuspension factor in the rural areas was 100 times that in the city due to plowing and other agricultural activities. LEAFRS is essentially the same variable as RESFAC, so those variables were set equal to the corresponding values for RESFAC.

Both particle radius and density are factors in determining deposition of radionuclides, but the equation uses radius squared. Because radius should have a more significant effect if varied, it was chosen as the uncertain variable, and density was considered fixed.

The net effect of these various consolidations was to eliminate 8 variables and leave 21 independent candidates for variables to be treated as uncertain. These variables are listed in Table 12-3.

Table 12-3 Characteristics of Input Variable Distributions

	Variable	Description	Units	Type	p1*	p2*
Water Pathway						
1	CLBFF, Cs-137	Bioconcentration in fish	L/kg	Lognormal	8.4553	1.1975
2	CLBFF, Sr-90	Bioconcentration in fish	L/kg	Lognormal	6.1092	2.0300
3	CLBFF, P-32	Bioconcentration in fish	L/kg	Lognormal	10.8198	0.8945
Air Pathway						
4	CLFMK, I-131	Cow intake-to-milk transfer factor	d/L	Lognormal	-4.6051702	0.9069765
5	CLFMT, I-131	Cattle intake-to-beef transfer factor	d/kg	Lognormal	-3.2188758	0.5015594
6	ABSHUM	Absolute Humidity	kg/m^3	Normal	0.01125	0.00053
7	BIOMA2, 5&6	Animal feed standing biomass (wet)-beef & milk animal forage	kg/m^2	Lognormal	-1.20397	0.0813929
8	BIOMA2, 3	Animal feed standing biomass (wet)-Milk animal feed	kg/m^2	Lognormal	1.43156†	0.02909†
9	BIOMAS, 1	Standing biomass (wet) - Leafy vegetables	kg/m^2	Lognormal	0.03486‡	
10	WTIM	Weathering rate constant from plant	d	Lognormal	2.63906	1.40311
11	CONSUM, 5&6§	Animal feed consumption rate-Beef & milk animal forage	kg/d	Normal	36.0000	8.6300
12	CONSUM, 3	Animal feed consumption rate-Milk animal feed	kg/d	Lognormal	1.71†	0.262†
13	DRYFAC, 1	Dry/wet ratio - Leafy vegetables	fraction	Lognormal	0.10875†	0.00218†
14	GRWP, 1	Growing period - Leafy vegetables	d	Lognormal	0.16861‡	
15	GRWPA, 5&6	Growing period for animal feed - Beef & milk animal forage	d	Lognormal	3.40119738	0.4423365
16	GRWPA, 3	Growing period for animal feed - Milk animal feed	d	Lognormal	0.05103‡	
17	DEPFR1,2	Dry & wet deposition retention fraction to plants	fraction	Lognormal	-1.3862944	0.5873942
18	LEAFRS, RESFAC;1§	Resuspension factor from soil to plant surfaces - farm	1/m	Lognormal	-11.512925	2.6214129
19	DPVRES	Deposition velocity from soil to plant surfaces	m/s	Lognormal	-6.9077553	1.2555349
20	RADIUS	Particle Radius	µm	Lognormal	-0.6931	0.4055
21	F	Release Factor		Lognormal	0	0.2

§ Related by a constant factor.

* p1 and p2 are the log mean and log standard deviation of their corresponding lognormal distributions, respectively, except for variables No. 6 and 11 that they are the arithmetic mean and the arithmetic standard deviation of the normal distribution, respectively.

†Arithmatic mean and arithmetic standard deviation.

‡Ratio of arithmetic standard deviation over arithmetic mean.

12.4.2.7 Step 6 – Retain Only Variables Contributing Substantially to Variance

The final step in reducing the number of input variables to be used in the uncertainty analysis was based on a factor (Column D in Table 12-4) that is the squared product of 1) the coefficient of variation for the variable (Column A in Table 12-4 and 2) the fractional contribution to dose from all pathways and radionuclides (Column B in Table 12-4) for which the variable is involved.

The coefficient of variation is equal to the standard deviation of the distribution describing the variable divided by the arithmetic mean of the distribution. The coefficient of variation is a relative measure of the variability of a random variable with respect to its mean value. Because the coefficient of variation (CV) measures relative variability, it allows comparison of variability across variables with different units and different absolute magnitudes. A variable with a small CV is very repeatable and reliable, experiencing little relative change from one measurement to another. A variable with a large CV is much more uncertain.

The data used to determine probability distributions for the 21 variables remaining at this step were gathered from a variety of published sources (with the exception of one case for which a personal communication was used). Appendix M provides details of the development of these probability distributions.

Table 12-4 shows the 21 variables, the coefficient of variation, the fractional contribution, the product of these squared, and the rank of the variable based on the combined factor. The following observations are based on this table:

- For the water-release variables, the range in the determining factor (Column D) is less than two orders of magnitude between the largest and smallest value; therefore, all three variables were retained.
- For the air-release variables, the highest ranked variable was the resuspension factor (the determining factor is 664) because the fractional contribution was relatively large and the coefficient of variation was over 31. This is an extremely large value that ranges over several orders of magnitude.
- Consider eliminating any variable with a determining factor less than 0.01: For the air release, the determining factor value falls off rapidly, and if the criterion of less than 0.01 was used, all variables of rank less than 10 would be excluded.
- The cutoff for rank was chosen to be 10. However, the variable of rank 11 was also included because it participated in dose from milk and meat as well as the companion variables? growing period (GRWPA,5) and forage consumption (CONSUM,5).

Based on these considerations, a final number of 14 variables were considered to be uncertain. Table 12-2 provides the statistical characteristics of these 14 variables, and Section 12.3 discusses how they were used.

Appendix N provides the input data used for the computations (LHS and GENII computer codes).

Table 12-4 Final Screening Step

		Variable	Coefficient of Variation (Standard Deviation /Mean)	Fractional Contribution to Total for Medium	Approximate Contribution to Variance	Square of Contribution to Variance	Rank for Medium
Water Pathway			***A***	***B***	***C***	***D***	
✓	1	CLBFF, Cs-137	1.788E+00	5.25E-01	9.38E-01	8.79E-01	2
✓	2	CLBFF, Sr-90	7.786E+00	1.59E-01	1.24E+00	1.53E+00	1
✓	3	CLBFF, P-32	1.107E+00	2.68E-01	2.96E-01	8.79E-02	3
Air Pathway							
✓	4	CLFMK, I-131	1.130E+00	1.38E-01	1.56E-01	2.43E-02	10
✓	5	CLFMT, I-131	5.348E-01	5.09E-01	2.72E-01	7.41E-02	7
	6	ABSHUM	4.711E-02	6.05E-01	2.85E-02	8.12E-04	13
✓	7	BIOMA2, 5&6	8.153E-02	6.93E-01	5.65E-02	3.19E-03	11
	8	BIOMA2, 3	2.032E-02	3.45E-01	7.01E-03	4.91E-05	16
	9	BIOMAS, 1	3.486E-02	6.09E-02	2.12E-03	4.50E-06	17
✓	10	WTIM	2.482E+00	8.16E-01	2.03E+00	4.10E+00	3
✓	11	CONSUM, 5	2.397E-01	6.93E-01	1.66E-01	2.76E-02	9
	12	CONSUM, 3	1.532E-01	3.45E-01	5.28E-02	2.79E-03	12
	13	DRYFAC, 1	2.000E-02	6.09E-02	1.22E-03	1.48E-06	18
	14	GRWP, 1	1.686E-01	6.09E-02	1.03E-02	1.05E-04	15
	15	GRWPA, 5&6	4.649E-01	6.93E-01	3.22E-01	1.04E-01	6
	16	GRWPA, 3	5.103E-02	3.45E-01	1.76E-02	3.10E-04	14
✓	17	DEPFR1,2	6.419E-01	8.16E-01	5.24E-01	2.74E-01	5
✓	18	LEAFRS, RESFAC;1	3.104E+01	8.30E-01	2.58E+01	6.64E+02	1
✓	19	DPVRES	1.959E+00	8.16E-01	1.60E+00	2.55E+00	4
✓	20	RADIUS	2.913E+00	1.00E+00	2.91E+00	8.49E+00	2
✓	21	F	2.000E-01	1.00E+00	2.00E-01	4.00E-02	8

✓ = retain for final analysis

12.5 Results of Uncertainty Analysis

The computer runs provided 40 dose values (corresponding to 40 realizations) for each receptor, as provided in Appendix O. In other words, the dose for each receptor was computed 40 times as a function of 40 (random) realizations of the variables considered to be uncertain plus all the other input variables considered to be fixed. Each set of 40 output values was examined statistically to determine an empirical

probability distribution and values representative of the central tendency (e.g., mean and median) for the dose to each receptor.

12.5.1 Description of Dose Distributions

The lognormal probability distribution was assumed to be a potentially good fit to the 40 random dose values associated with each receptor. This was assumed because all except 1 of the 14 probability distributions for the 14 uncertain input variables considered were lognormal (see Table 12-2). Also, the point-estimate value for each of these 14 variables from the deterministic analysis had been set equal to the median of the distribution for the corresponding variable in the uncertainty analysis. For this reason, the medians of the 28 distributions (1 for each receptor) were expected to be "close" to those point estimates found in the deterministic analysis contained in Chapter 11. In addition, the following is a well-known property of lognormal distributions: If a random variable is defined as the product of two or more independent random variables and each of these is described by a lognormal distribution, then the product will also be described by a lognormal distribution.

Using the computer software "Crystal Ball" (1), the best fit to the probability distributions for the total dose to 14 out of the 28 receptors was determined to be lognormal. The lognormal distribution was the second or third best fit to the dose distributions for the remaining receptors. However, even when the lognormal distribution was not the first choice, the best-fit distributions were similar to the lognormal. The fact that the dose distributions for all the receptors are not lognormal is attributed to the fact that the dose is computed by a complex mathematical model of the uncertain input variables involved in the uncertainty analysis. Except for very simple functions of random variables (e.g., multiplication by a constant), the function of several random variables is seldom characterized by the same probability distribution as the underlying input variables, even if they are all the same. For example, for the Adult Female member of the Delivery Family, the best fit to the distribution of dose from only air releases and the best fit to the distribution of dose from only water releases are gamma distributions; however, the best fit to the total dose from all releases, which is the sum of these air and water doses, is a lognormal distribution.

Table 12-5 displays descriptive statistics for the sample of 40 total dose realizations for each of the 28 receptors. The table lists the mean, median, minimum, maximum, and the standard deviation of total dose for each receptor. Note that the mean dose is larger than the median dose for every receptor. Because we have a sample of 40 values of dose, there are 20 values smaller than the median and 20 values larger than the median. If we had a symmetric distribution of dose, the smaller values and larger values would extend about equally on either side of the median value. In our case, however, the lower values are limited by zero because dose cannot be negative and the higher values extend out to relatively high values. For example, for the Child Born in 1955 for the Urban Family, the difference between the maximum value of dose (30.8 millisieverts) and the median dose (2.55 millisieverts) is 28.3 millisieverts; however, the difference between the median dose (2.55 millisieverts) and the minimum dose (0.345 millisieverts) is only 2.20 millisieverts. Figure 12-2 and Figure 12-3 show this skewing toward higher values, depicting as examples the dose distributions for the Adult Female in the Rural Family 2 and the Delivery Family, respectively. The distributions are displayed both as histograms and as a fitted lognormal distribution. Because the distribution is not symmetrical and is skewed toward higher values, the mean dose is larger than the median dose.

The range of the distribution of dose depends on the choice of both the scenario and family member. For example, for the Child Born in 1955 for the Urban Family, the ratio of maximum dose to minimum dose is over 89; for the Child Born in 1964 for the same family, the ratio of maximum dose to minimum dose is only about 4. Similarly, the ratio by which the mean dose exceeds the median dose depends on both the scenario and family member. The minimum value of this ratio is 1.07 for the Child Born in 1964 for the

Urban Family, and the maximum value of this ratio is 1.69 for the Child Born in 1955 for the same family.

Table 12-5 Statistics on Total Effective Dose Equivalent for Different Receptors*

Family	Family Member	Mean (mSv)‡	Median (mSv)‡	Minimum† (mSv)‡	Maximum† (mSv)‡	Standard Deviation (mSv)
Delivery Family	Adult Female	12.812	9.072	1.813	60.911	0.01223
Delivery Family	Adult Male	13.001	9.281	1.737	61.183	0.01226
Delivery Family	Child Born 1955	10.164	7.993	1.767	35.010	0.00776
Delivery Family	Child Born 1964	4.498	3.159	0.712	15.146	0.00373
Migrant Family	Adult Female	0.793	0.562	0.138	4.615	0.00090
Migrant Family	Adult Male	1.117	0.756	0.184	6.770	0.00129
Migrant Family	Child Born 1955	3.676	2.489	0.417	24.269	0.00445
Migrant Family	Child Born 1964	0.127	0.093	0.043	0.732	0.00013
Near Water Family	Adult Female	3.431	2.738	1.138	9.896	0.00204
Near Water Family	Adult Male	3.574	2.929	1.183	10.084	0.00206
Near Water Family	Child Born 1955	4.815	4.311	1.293	18.333	0.00303
Near Water Family	Child Born 1964	2.850	2.290	0.867	14.090	0.00231
Outdoor Family	Adult Female	4.687	4.263	1.272	11.751	0.00246
Outdoor Family	Adult Male	6.055	5.546	2.026	14.246	0.00295
Outdoor Family	Child Born 1955	13.331	10.988	2.529	60.270	0.01021
Outdoor Family	Child Born 1964	2.951	2.309	0.893	14.158	0.00231
Rural Family One	Adult Female	0.502	0.387	0.090	3.005	0.00053
Rural Family One	Adult Male	0.712	0.538	0.120	4.406	0.00076
Rural Family One	Child Born 1955	2.681	1.697	0.281	17.410	0.00334
Rural Family One	Child Born 1964	0.093	0.077	0.037	0.340	0.00006
Rural Family Two	Adult Female	1.174	0.890	0.199	7.162	0.00128
Rural Family Two	Adult Male	1.655	1.198	0.267	10.502	0.00185
Rural Family Two	Child Born 1955	6.362	4.006	0.642	41.579	0.00798
Rural Family Two	Child Born 1964	0.190	0.153	0.072	0.796	0.00014
Urban Family	Adult Female	0.447	0.284	0.083	2.204	0.00039
Urban Family	Adult Male	0.895	0.698	0.263	3.276	0.00055
Urban Family	Child Born 1955	4.314	2.551	0.345	30.820	0.00557
Urban Family	Child Born 1964	0.115	0.107	0.054	0.215	0.00003

* The number of decimal places for values in the table are to allow easy display; the values should be considered to have a precision no greater than two significant digits.
† These minimum and maximum values are for this sample; another set of realizations will likely have different values. However, any sample minimum value is greater than or equal to the population minimum value, while any sample maximum value is less than or equal to the population maximum value.
‡ mSv = millisieverts.

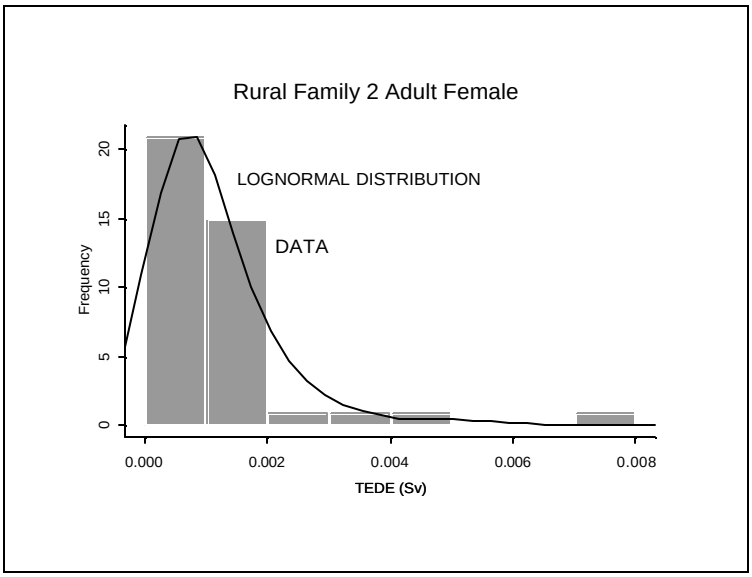


Figure 12-2 Histogram and Fitted Distribution for Dose to Adult Female, Rural Family 2

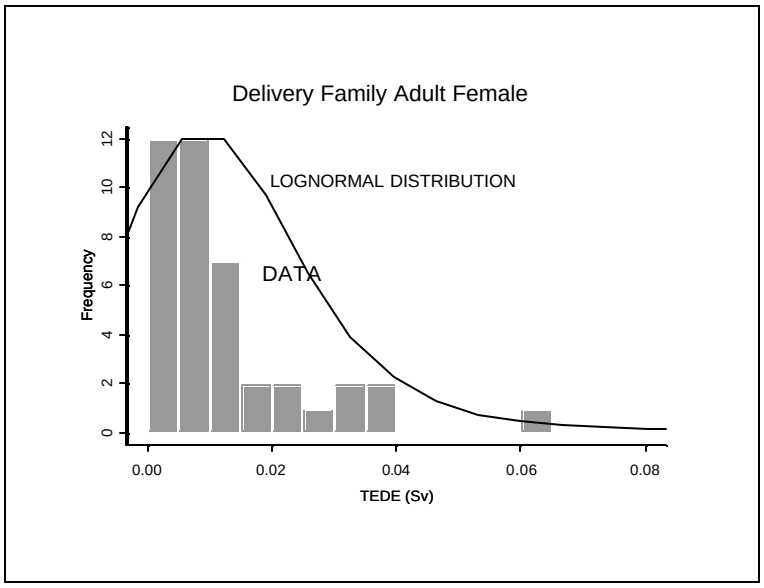


Figure 12-3 Histogram and Fitted Distribution for Dose to the Adult Female, Delivery Family

12.5.2 Quantified Confidence Bands for Doses

A primary motivation for the uncertainty analysis is to quantify the uncertainty associated with the dose to each receptor. One way to characterize this uncertainty is to state the confidence limits around the mean dose. Confidence limits define an interval around a parameter (e.g., the mean) so that the parameter is expected to be within the interval to a specified probability. Another way of looking at this is that the mean is estimated based on a finite set of values randomly sampled from a continuous distribution (i.e., in our case, we have a sample of 40 doses for each receptor out of an infinite number of possible values of

dose). The estimated parameter has two sources of uncertainty: 1) the underlying variability of the distributed values and 2) the finite sample size.

A standard statistical text (2) states the following:

$$\overline{X} - t_{1-\alpha/2}(n-1)\frac{S}{\sqrt{n}} \le \mu \le \overline{X} + t_{1-\alpha/2}(n-1)\frac{S}{\sqrt{n}} \qquad (12\text{-}1)$$

where, μ is the population mean

$\overline{X}$ is the sample mean

$t_{1-\alpha/2}(n-1)$ is the Student's t-distribution with (n-1) degrees of freedom for a 100(1-a)% total confidence level [100(a/2)% and 100(1-a/2)% confidence limits on the left and right sides of the distribution, respectively]

S is the unbiased estimator of the standard deviation

n is the number of observations (sample size).

If the sample variance is computed by the formula:

$$\hat{\sigma}^2 = \sum_{i=1}^{n} \frac{(X_i - \overline{X})^2}{n} \qquad (12\text{-}2)$$

then the unbiased estimator for the population variance is given by:

$$S^2 = \frac{n}{n-1}\hat{\sigma}^2 \qquad (12\text{-}3)$$

and the standard deviation, of either the sample or population, may be found by taking the square root of the corresponding variance.

For our computations, n=40. Then the fraction in equation (12-3) is 40/39 = 1.0256; if we take the square root to find S, then the fraction becomes $1.0256^{1/2}$= 1.0127. This relates the unbiased estimator to the sample standard deviation. This is a small correction, but it is made due to its ease of accomplishment.

Table 12-6 shows the values for t distribution for some typical confidence levels (1-a) and the 40 realizations.

Table 12-6 Values for t Distribution for Some Typical Confidence Intervals

a	Lower Bound	Upper Bound	Confidence Level	t(40-1)
0.1	5%	95%	90%	1.684875315
0.05	2.50%	97.50%	95%	2.022688932
0.02	1%	99%	98%	2.425840648

Since n=40, $40^{1/2}$ = 6.32455532. Then for a = 0.05,

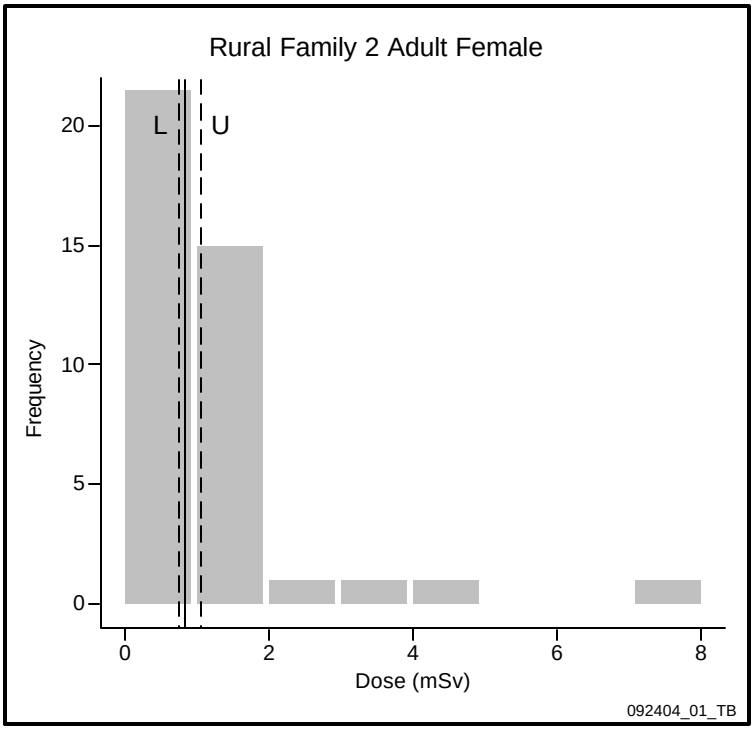
$$\overline{X} - 0.319815 \cdot S \le \mu \le \overline{X} + 0.319815 \cdot S \qquad (12\text{-}4)$$

Or the actual mean of dose is between the sample mean plus and minus about 1/3 of the sample standard deviation with a 95-percent confidence level. For example, for the Adult Female of the Delivery Family,

the sample mean dose is 0.012812 sievert; the actual mean dose is expected to be between 0.008899 sievert and 0.016724 sievert with a confidence level of 95 percent.

The median dose is closer to the point-estimate dose than to the mean dose because the medians of the lognormal distributions of input variables were set equal to the point-estimate values for those input variables. One way to make the same type of confidence statements about the median dose that have been made about the mean dose is to assume that the total dose distribution for each receptor is described by a lognormal distribution. A special property of the lognormal distribution is that the mean of the natural logarithm of the sampled doses is equal to the natural logarithm of the median dose. Therefore, equation 12-4 may be used to establish confidence limits around the ln (ln is used to represent the natural logarithm) median; by taking the inverse logarithm, one obtains the median and its confidence limits (i.e., raising e (the base of the natural logarithms) to the ln median and to the ln confidence limits provides the median and its associated confidence limits).

Table 12-7 displays the mean and median for all 28 receptors and also gives the upper and lower confidence bounds for each statistic at the 95-percent level. Figure 12-4 shows the confidence intervals around the median for one receptor (the Adult Female for Rural Family 2) overlaid on the histogram of dose.



U= Upper Bound
L= Lower Bound

Figure 12-4 Confidence Intervals Overlaid on Histogram of Dose

For the mean values, the confidence bounds are almost symmetrical; the confidence intervals on either side of the mean range from 9- to 41-percent of the mean value depending upon the scenario and family member. For the median values, assuming a lognormal distribution, the confidence bounds are skewed toward higher values (i.e., the difference between the upper bound and the median is generally a higher fraction of the median than the difference between the median and the lower bound). The lower bound of the confidence interval ranges from 9- to 26-percent of the median value; the upper bound of the confidence interval ranges from 9- to 36-percent of the median value.

Table 12-7 95% Confidence Intervals for Mean and Median of Total Effective Dose Equivalent for Each Receptor

Family	Family Member	Mean (mSv)‡	Lower Limit of 95% CI* for Mean (mSv)‡	Upper Limit of 95% CI for Mean (mSv)‡	Median † (mSv)‡	Lower Limit of 95% CI for Median (mSv)‡	Upper Limit of 95% CI for Median (mSv)‡
Delivery Family	Adult Female	12.812	8.899	16.724	8.662	6.464	11.608
Delivery Family	Adult Male	13.001	9.081	16.921	8.872	6.643	11.849
Delivery Family	Child Born 1955	10.164	7.681	12.646	7.826	6.173	9.923
Delivery Family	Child Born 1964	4.498	3.305	5.691	3.290	2.541	4.259
Migrant Family	Adult Female	0.793	0.504	1.082	0.554	0.431	0.713
Migrant Family	Adult Male	1.117	0.705	1.529	0.770	0.595	0.997
Migrant Family	Child Born 1955	3.676	2.252	5.100	2.465	1.871	3.246
Migrant Family	Child Born 1964	0.127	0.086	0.167	0.102	0.085	0.122
Near Water Family	Adult Female	3.431	2.778	4.083	2.953	2.480	3.517
Near Water Family	Adult Male	3.574	2.916	4.232	3.103	2.618	3.677
Near Water Family	Child Born 1955	4.815	3.846	5.784	4.150	3.493	4.932
Near Water Family	Child Born 1964	2.850	2.113	3.588	2.326	1.913	2.826
Outdoor Family	Adult Female	4.687	3.900	5.475	4.129	3.505	4.865
Outdoor Family	Adult Male	6.055	5.113	6.997	5.434	4.676	6.316
Outdoor Family	Child Born 1955	13.331	10.065	16.596	10.688	8.640	13.222
Outdoor Family	Child Born 1964	2.951	2.214	3.688	2.437	2.017	2.945
Rural Family One	Adult Female	0.502	0.332	0.672	0.367	0.289	0.465
Rural Family One	Adult Male	0.712	0.470	0.954	0.521	0.410	0.662
Rural Family One	Child Born 1955	2.681	1.612	3.750	1.765	1.333	2.337
Rural Family One	Child Born 1964	0.093	0.074	0.113	0.083	0.072	0.096
Rural Family Two	Adult Female	1.174	0.767	1.582	0.841	0.658	1.076

Family	Family Member	Mean (mSv)‡	Lower Limit of 95% CI* for Mean (mSv)‡	Upper Limit of 95% CI for Mean (mSv)‡	Median † (mSv)‡	Lower Limit of 95% CI for Median (mSv)‡	Upper Limit of 95% CI for Median (mSv)‡
Rural Family Two	Adult Male	1.655	1.064	2.246	1.166	0.905	1.501
Rural Family Two	Child Born 1955	6.362	3.808	8.915	4.150	3.121	5.519
Rural Family Two	Child Born 1964	0.190	0.144	0.236	0.164	0.141	0.192
Urban Family	Adult Female	0.447	0.322	0.572	0.349	0.281	0.433
Urban Family	Adult Male	0.895	0.718	1.073	0.784	0.670	0.918
Urban Family	Child Born 1955	4.314	2.532	6.096	2.659	1.955	3.616
Urban Family	Child Born 1964	0.115	0.104	0.125	0.111	0.101	0.121

* CI = confidence interval.
† Calculated based on the natural log values of total effective dose equivalent.
‡ mSv = millisievert.

Although the confidence intervals may be a substantial fraction of the central tendency value (the mean or the median), the upper confidence limits are not larger than the central tendency value (i.e., the confidence interval is always smaller than the interval 0 to twice the mean). This may seem counterintuitive to many who consider the dose estimates of this kind to be accurate only to an order of magnitude, if that. However, these confidence intervals reflect only the uncertainty in the input variables to the models and do not reflect the uncertainty in the models themselves or the approximations made in applying the models. In a sense, it is more correct to characterize these confidence bounds as a measure of precision rather than as a measure of accuracy.

For the dose distributions, the largest value of the coefficient of variation is approximately 1.3. This value is much smaller than the largest value of the coefficient of variation for the input variables, which was approximately 31 for the resuspension factor. The reason the uncertainty in resuspension factor is attenuated when processed by the dose models is that resuspension does not cause much dose for these scenarios. Inhalation of resuspended contamination has already been shown to be a minor pathway (see Section 12.2). In addition, resuspended contamination can cause dose by depositing on growing vegetation and becoming incorporated into the food chain. For the scenarios analyzed, however, direct deposition of contamination is always much more effective in causing dose than resuspended deposition.

12.5.3 Comparison of Results from Point Estimate and Uncertainty Analyses

Table 12-8 and Table 12-9 show for each receptor from the deterministic analysis the point-estimate dose compared to the results of the uncertainty analysis? the run 0 dose, the mean dose, and the median dose. As discussed previously in Section 12.2, the point-estimate dose is very close to the run 0 dose for each receptor -- as would be expected because the same values for the input variables are used. However, the mean dose from the uncertainty analysis is generally larger (and in some cases, substantially so) than the point-estimate dose for each receptor. The ratio of the mean dose to the point-estimate dose ranges from a high value of 2.15 (115 percent higher) for the Delivery Family Child Born in 1964 to a low value of 1.07 (7 percent higher) for the Urban Family Child Born in 1964. The median dose from the uncertainty analysis is generally higher than the point-estimate dose, but usually by a smaller amount than the corresponding mean dose. However, for the Urban Family receptors, the median doses are smaller than the point-estimate dose. The ratio of the median dose to the point-estimate dose ranges from a high value of 1.54 (54 percent higher) for the Delivery Family Child Born in 1955 to a low value of 0.86 (14 percent smaller) for the Urban Family Adult Female.

As discussed in Section 12.4.1, for the dose distributions obtained from the uncertainty analysis, it is not surprising that the median doses are generally smaller than the mean doses. However, it was somewhat surprising that the median doses were mostly larger (sometimes substantially so) than the point-estimate doses. After all, the point estimates of dose were developed using “representative” values for all the input variables, and a selected set of input variables were represented by distributions. All but one of the input distributions were chosen to be lognormal distributions (the other was a normal distribution). The median of each lognormal distribution was set equal to the point-estimate value of the corresponding input variable. Then the distribution of doses was generated based on 1) the distributions of input variables for those chosen to be uncertain and 2) the point-estimate values for those input variables chosen to be fixed. Because the medians of the input distributions were the point-estimate values, it could be expected (in a very approximate fashion) that the medians of the uncertain doses would be closer to the point-estimate values than the means of the uncertain doses. In some cases, however, they are greater than the point estimates by over 50 percent.

To examine this result, some additional analysis was performed. The dose to the Adult Female for the Delivery Person Family has been a focus of consideration because the water release dose (water dose) for

the point estimates is known to be 94 percent of the total dose. This receptor was chosen for closer scrutiny because it has dose dominated by this single release mode and because the median of the uncertain dose? 9.072 millisieverts? is 1.486 times the point-estimate dose of 6.106 millisieverts.

An initial conjecture is that the air doses add to the water doses in a random fashion and provide a "floor" for the total dose. This more-or-less average addition could cause the low values of the total doses to be elevated and therefore increase the median. This conjecture does not seem to be confirmed by the data. The median for just the water doses is 8.539 millisieverts. This implies that only 5.9 percent of the median dose is contributed by the air releases. Therefore, the air releases hardly seem capable of elevating the median of the dose. To look at it another way, the mean value of the air release dose is 0.469 millisieverts. If this mean value of air dose is added to the water doses, it will not substantially affect the median total dose. Although the fraction of the air dose increases substantially for lower total doses, the highest it ever gets is a little over 0.4. For most values, the fraction is less than 0.1 and for many it is less than 0.05. This is not the answer.

Table 12-8 Statistics on Total Effective Dose Equivalent for Different Receptors

Family	Family Member	Point Estimate (mSv)*	Run 0 (mSv)*	Mean (mSv)*	Median (mSv)*
Delivery Family	Adult Female	6.106	6.091	12.812	9.072
Delivery Family	Adult Male	6.283	6.266	13.001	9.281
Delivery Family	Child Born 1955	5.200	5.180	10.164	7.993
Delivery Family	Child Born 1964	2.090	2.081	4.498	3.159
Migrant Family	Adult Female	0.447	0.438	0.793	0.562
Migrant Family	Adult Male	0.624	0.614	1.117	0.756
Migrant Family	Child Born 1955	2.178	2.160	3.676	2.489
Migrant Family	Child Born 1964	0.083	0.081	0.127	0.093
Near Water Family	Adult Female	2.091	2.057	3.431	2.738
Near Water Family	Adult Male	2.205	2.170	3.574	2.929
Near Water Family	Child Born 1955	3.137	3.099	4.815	4.311
Near Water Family	Child Born 1964	1.759	1.734	2.850	2.290
Outdoor Family	Adult Female	3.030	3.001	4.687	4.263
Outdoor Family	Adult Male	4.216	4.169	6.055	5.546
Outdoor Family	Child Born 1955	9.435	9.383	13.331	10.988
Outdoor Family	Child Born 1964	1.826	1.810	2.951	2.309
Rural Family One	Adult Female	0.303	0.299	0.502	0.387
Rural Family One	Adult Male	0.423	0.418	0.712	0.538
Rural Family One	Child Born 1955	1.589	1.580	2.681	1.697
Rural Family One	Child Born 1964	0.072	0.071	0.093	0.077
Rural Family Two	Adult Female	0.696	0.685	1.174	0.890
Rural Family Two	Adult Male	0.974	0.961	1.655	1.198
Rural Family Two	Child Born 1955	3.751	3.729	6.362	4.006
Rural Family Two	Child Born 1964	0.140	0.137	0.190	0.153
Urban Family	Adult Female	0.330	0.325	0.447	0.284
Urban Family	Adult Male	0.731	0.723	0.895	0.698
Urban Family	Child Born 1955	2.686	2.675	4.314	2.551
Urban Family	Child Born 1964	0.107	0.106	0.115	0.107

Table 12-9 Comparison of Mean Dose and Median Dose with Point-Estimate Dose for each Receptor

Family	Family Member	Pt. Estimate (mSv)*	Mean (mSv)*	Ratio, Mean over Point Estimate	Median (mSv)*	Ratio, Median over Point Estimate
Delivery Family	Adult Female	6.106	12.812	2.098	9.072	1.486
Delivery Family	Adult Male	6.283	13.001	2.069	9.281	1.477
Delivery Family	Child Born 1955	5.200	10.164	1.955	7.993	1.537
Delivery Family	Child Born 1964	2.090	4.498	2.153	3.159	1.512
Migrant Family	Adult Female	0.447	0.793	1.773	0.562	1.255
Migrant Family	Adult Male	0.624	1.117	1.790	0.756	1.211
Migrant Family	Child Born 1955	2.178	3.676	1.688	2.489	1.143
Migrant Family	Child Born 1964	0.083	0.127	1.524	0.093	1.119
Near Water Family	Adult Female	2.091	3.431	1.641	2.738	1.309
Near Water Family	Adult Male	2.205	3.574	1.621	2.929	1.328
Near Water Family	Child Born 1955	3.137	4.815	1.535	4.311	1.374
Near Water Family	Child Born 1964	1.759	2.850	1.621	2.290	1.302
Outdoor Family	Adult Female	3.030	4.687	1.547	4.263	1.407
Outdoor Family	Adult Male	4.216	6.055	1.436	5.546	1.316
Outdoor Family	Child Born 1955	9.435	13.331	1.413	10.988	1.165
Outdoor Family	Child Born 1964	1.826	2.951	1.616	2.309	1.264
Rural Family One	Adult Female	0.303	0.502	1.656	0.387	1.277
Rural Family One	Adult Male	0.423	0.712	1.683	0.538	1.270
Rural Family One	Child Born 1955	1.589	2.681	1.687	1.697	1.067
Rural Family One	Child Born 1964	0.072	0.093	1.295	0.077	1.067
Rural Family Two	Adult Female	0.696	1.174	1.688	0.890	1.279
Rural Family Two	Adult Male	0.974	1.655	1.700	1.198	1.231
Rural Family Two	Child Born 1955	3.751	6.362	1.696	4.006	1.068
Rural Family Two	Child Born 1964	0.140	0.190	1.362	0.153	1.094
Urban Family	Adult Female	0.330	0.447	1.353	0.284	0.859
Urban Family	Adult Male	0.731	0.895	1.224	0.698	0.954
Urban Family	Child Born 1955	2.686	4.314	1.606	2.551	0.950
Urban Family	Child Born 1964	0.107	0.115	1.068	0.107	0.996

*mSv = millisieverts.

The components of the water dose seem to provide a more plausible explanation of the behavior of uncertain doses. For each realization, the doses resulting from cesium-137, strontium-90, and phosphorus-32 were listed as well as their sum. The median of the "sum" is 8.419 millisieverts. This sum accounts for most of the water-dose median (8.419/8.539 = 0.986) and most of the total-dose median (8.419/9.072 = 0.928). The median of doses for each isotope were found separately, and the sum of these medians is 5.857 millisieverts. This is much closer to the point-estimate dose of 6.106 millisieverts. This appears to suggest that if the three isotopic components of dose were summed separately, they would correspond closely to the base case. However, because these doses are summed for each realization, the sum is, on average, larger than the point estimate. Because the uptake factors for these three isotopes vary

independently and randomly, the total dose can be considered approximately to be the sum of three lognormal distributions. The smaller, but substantial, doses from strontium-90 and phosphorus-32 essentially make a "floor" on the dose from cesium-137 and boost the median (as shown) by a factor of about 50 percent over what would occur if the uptake factors were correlated.

In summary, it appears that the confidence intervals do not include the point estimates. This appears to be a result of both the assumptions regarding the input variable distributions and the mathematical form of the dose model. This also shows the utility of performing an uncertainty analysis, which may give a different perspective on the problem than a point estimate.

12.6 Secondary Results

The primary result of the overall uncertainty analysis was to establish distributions of dose estimates that incorporated uncertainty in the input variables and to establish the statistical confidence intervals about the mean values of those distributions. However, the large amount of data generated in performing this uncertainty analysis can be used to provide additional insights into how doses and the uncertainties in doses depend on the uncertain variables analyzed. This additional information can be useful in determining how to refine the modeling approaches or how to prioritize the need for additional site data.

In Chapter 11 dose to various receptors was explored by identifying important factors such as radionuclides, year of exposure, exposure pathways, and exposure routes. These results provided information on the structure of the model. These point estimate dose results and the conclusions drawn from them also depended on the choices made for the value of each input variables, i.e., one value for each input variable. In this Chapter the dependence of dose on the distributions chosen to describe each uncertain input variable is explored; i.e., the attention here is on the dependence of dose on the uncertain input variables. These analyses are based upon the sampled input variables and results of the uncertainty analysis described in previous sections. By aligning the input variable values with the respective resultant dose values, several statistical techniques can be used to evaluate how a change in an input variable changes the output (dose).

The dependence of dose on the uncertain input variables can be considered to have two components: (1) how effective a change in an input variable is in producing a change in dose and (2) how widely a particular input variable changes. Big variations in dose may be produced in three ways: (1) dose may be very sensitive to a particular variable, so even modest variations in that input variable produce substantial variations in dose; (2) dose may be moderately sensitive to a particular variable, but the variable is very uncertain, so large variations in dose are produced; (3) dose may be very sensitive to a highly variable input, so extremely large variations in dose are produced. The two components describing the dependence of dose on uncertain input variable are sometimes characterized by two coefficients: (1) a sensitivity coefficient and (2) a variance or uncertainty coefficient. Broadly speaking, the sensitivity coefficient is the ratio of the fractional change in dose to the fractional change of an input variable. The variance or uncertainty coefficient is the fraction of uncertainty in dose attributable to the uncertainty in an input variable. Both of these aspects are explored in the Sections that follow.

Sections 12.6.1 and 12.6.2 discuss how some general statistical methods can be used to describe the relationships between dose and input variables. Scatter plots are used to give a graphical assessment of the input-dose relationship. The correlation coefficient (assuming a linear relationship) was used to quantify the relationship between dose and input variables. Section 12.6.3 describes how the variability in dose depends on input variables (i.e., variance or uncertainty considerations); Section 12.6.4 describes how the dose depends on input variables (i.e., sensitivity considerations). Only a few examples were analyzed and described here. An extensive analysis of this type is beyond the scope of the current study. More extensive analyses of this type may be appropriate in the future. The limited analyses described

here generally reinforce the understanding of the generation of doses by SRS releases obtained from the modeling and results described in previous Chapters.

The names and characteristics of the uncertain variables analyzed are described in Table 12-2. However, to facilitate this discussion, the variable names and their physical meaning are repeated in Table 12-10 here.

Table 12-10 Names of Uncertain Variables and Their Physical Meaning

Variable Name	Physical Meaning
Water Pathway	
CLBFF, Cs-137	Bioconcentration factor for Cs-137 in fish
CLBFF, Sr-90	Bioconcentration factor for Sr-90 in fish
CLBFF, P-32	Bioconcentration factor for P-32 in fish
Air Pathway	
LEAFRS	Soil resuspension factor; determines the amount of radioactivity deposited on the ground that is resuspended; affects urban and rural scenarios.
RADIUS	Radius of particles that can deposit on the soil and plant surfaces.
WTIM	Weathering rate constant determines the rate at which deposited radioactivity is removed by weathering processes from crop surfaces.
DPVRES	Deposition velocity from air to plant surfaces for resuspended activity.
DEPFR1, 2	Dry and wet deposition fraction; how much of the radioactivity deposited on plant surfaces is retained and absorbed by the plant.
GRWPA, 5&6	Growing period for animal forage; the longer the growing period, the more exposure the plant has to air deposition of radionuclides.
CLFMT I-131	Uptake of I-131 by beef muscle; transfer to meat from cattle food.
F	Release factor characterizes the uncertainty in air and water releases of radionuclides from the SRS.
CONSUM, 5	Animal forage consumption rate; scales forage consumption by milk and beef animals.
CLFMK I-131	Uptake of I-131 by milk; transfer to milk from cow food.
BIOMA2	Animal forage standing biomass (wet) describes how much grass is in the field per unit area.

12.6.1 Scatter Plots

Figure 12-5 shows examples of scatter plots for the Delivery Family Adult Female. Simple scatter plots of the dose versus a sampled input variable (e.g., CLBFF-Cs, the bioconcentration of cesium in fish) can give a quick visual display of the importance of a particular variable in affecting the dose. For example, the left and right plots are, respectively, the plot of dose versus the cesium-bioconcentration in fish and the plot of dose versus the suspended particle radius. The pattern in the left plot resembles that of a line, indicating a strong linear relationship between the uptake of cesium in fish and the resultant dose to the Delivery Family Adult Female. The much more random “snow” pattern in the right plot indicates that the dose to the Delivery Family Adult Female is not significantly affected by the resuspended soil-particle radius.

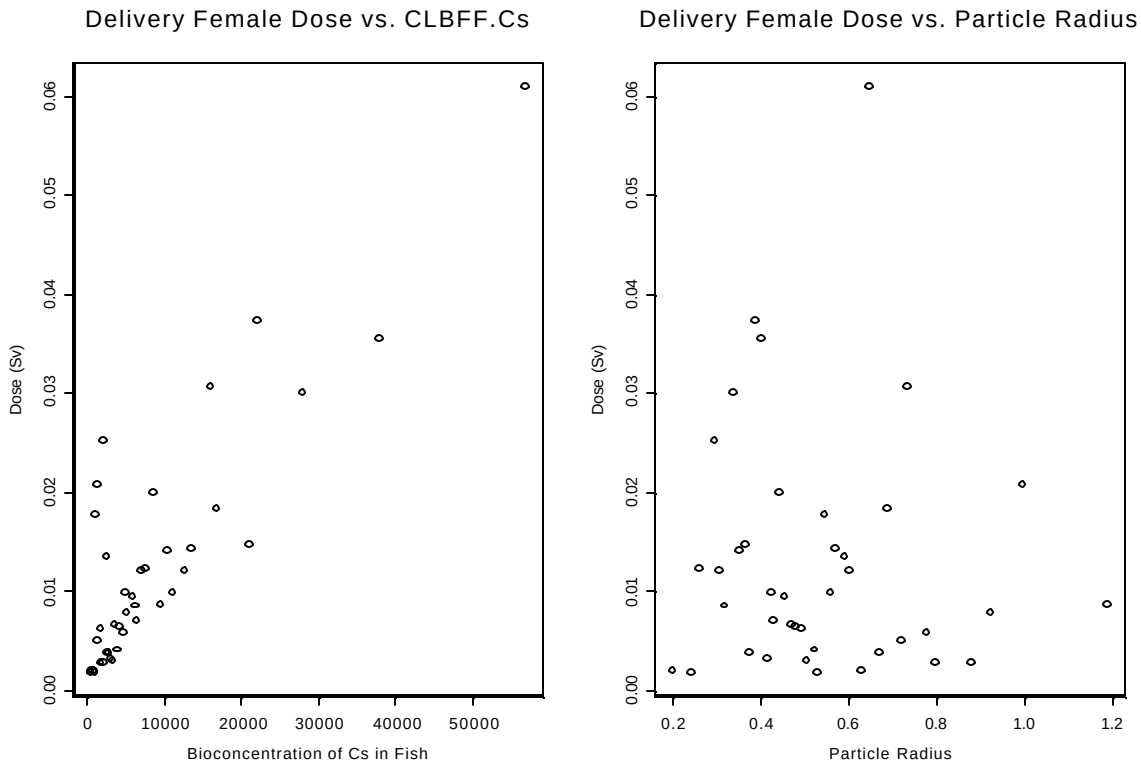


Figure 12-5 Examples of Scatter Plots for the Delivery Family Adult Female: Dose vs. Bioconcentration of Cesium in Fish (Left Plot) and Dose vs. Particle Radius (Right Plot)

12.6.2 Correlation Coefficients

Correlation coefficients are another way of expressing the relationship between input variables and the dose. Again, this analysis focused on linear relationships and did not consider nonlinear relationships such as dose as a function of the square of the particle radius. The correlation coefficient is a quantitative, statistical measure that represents the strength of the linear relation between two random variables (5). In this case, the two random variables are the dose and the input variable selected for examination. Correlation coefficients range between -1.0 and +1.0. A value of +1.0 indicates a perfect direct relationship; a value of -1.0 indicates a perfect negative relationship. For example, the size of one's bank account may have a correlation of +1 with the size of one's paycheck, but a correlation of -1 with the size of one's expenditures.

Correlation coefficients for the CLBFF-Cs and radius scatter plots given above are 0.864 and -0.032, respectively. This quantitatively demonstrates that CLBFF-Cs is over 10 times more effective in changing the dose than is the radius.

12.6.3 Stepwise Regression Analysis

The dose to the 28 hypothetical individuals considered in this analysis is the summation of incremental doses through various exposure pathways and from various radionuclides. These doses depend on many environmental and behavioral variables. Thus, in determining the most important variables, it is important to consider them together for the purpose of establishing an order of most to least significant within the

group. This can be accomplished with the stepwise regression analysis technique. In this type of analysis, the relationship of the dose to all of the sampled input variables is represented as a polynomial; that is, the statistical model for the dose is a sum of linear terms where each term is a product of a coefficient and an input variable.

A main focus of the stepwise regression analysis is to determine the best value of the coefficient for each input variable. This statistical model is built in a stepwise fashion by sequentially adding (or subtracting) one independent variable at a time. The result of this analysis is a statistical model that describes the dose as a function of a small set of independent variables (e.g., Dose ~ f(CLBFF-Cs +CLBFF-Sr)) which are the most important in affecting dose; input variables with coefficients that are relatively small are generally deleted from the model. Because this kind of analysis can be very computationally intensive, statistical software (S-Plus; Insightful, 2002) was used. As the software performed the stepwise regression, it automatically checked the coefficient of determination (R^2) and the statistical level of significance. Variables that do not have significant correlation with the dose or result in an increase in the R^2 are generally left out.

The statistic R^2, the coefficient of determination, is a "measure of the proportion of the total variability in the dependent variable that is accounted for by the regression equation" (6). A value of 1 for R^2 suggests that all the variability in the dependent variable (dose) is accounted for by the variability in the selected independent variables. A low value for R^2 is often interpreted to mean that the variability in the dependent variable is not linked to the variation in the independent variables. This is true to some extent. A low R^2 is many times a reflection of a small range of variation of the independent variable. Or, it might indicate that some of the variables should be considered in a nonlinear fashion (e.g., X^2 or 1/x).

The stepwise regression analysis was conducted for the hypothetical families that consume fish (Delivery, Near Water, and Outdoor Family) by considering all 14 of the sampled input variables. For those hypothetical families that did not consume fish (Migrant, Rural Families 1 and 2, Urban/Suburban), the stepwise regression analysis was conducted without any of the bioconcentration factors in fish (i.e., CLBFF for cesium, strontium, and phosphorus).

Table 12-10 and Table 12-11 present the results of the stepwise regression analysis, respectively, for the Delivery Family (which ate fish) and Rural Family 2 (which did not). Table 12-12 presents the stepwise regression analysis results for each of the Adult Females representing all scenarios. The five most important variables are listed in order of importance. The rank ordering is based upon the correlation coefficient and the contribution to the R^2. In general, for those variables that contribute more than 0.1 to the multiple R^2, there is little uncertainty concerning their rank. In this analysis, this generally applies to the top three variables. Variables ranked fourth and fifth made a very small contribution to the multiple R^2 and thus might change with a different sampling using the Latin Hypercube Sampling program.

Table 12-10 Delivery Family Stepwise Regression Results Listing Input Variables in Order of Influence and the Sum of R^2 for the Variables Listed

Adult Female	Adult Male	Child Born 1955	Child Born 1964
CLBFF-Cs	CLBFF-Cs	CLBFF-Sr	CLBFF-Sr
CLBFF-Sr	CLBFF-Sr	CLBFF-Cs	CLBFF-Cs
F	F	CLFMK I-131	CLBFF-P
CLBFF-P	BIOMA2	CLFMT I-131	BIOMA2
BIOMA2	CLBFF-P	LEAFRS	F
R^2 = 0.98	R^2 = 0.98	R^2 = 0.96	R^2 = 0.97

Note: Refer back to Table 12-2 for descriptions of the variables.

Table 12-11 Rural Family 2 Regression Results Listing Input Variables in Order of Influence and the Sum of R^2 for the Variables Listed

Adult Female	Adult Male	Child Born 1955	Child Born 1964
DEPRF1,2	LEAFRS	LEAFRS	LEAFRS
LEAFRS	DEPRF1,2	F	F
F	F	DEPFR 1,2	DEPFR 1,2
DPVRES	DPVRES	DPVRES	DPVRES
CONSUM	CONSUM	CONSUM	CONSUM
R^2 = 0.597	R^2 = 0.576	R^2 = 0.793	R^2 = 0.5793

Note: Refer back to Table 12-2 for full descriptions of the variables.

Table 12-12 Stepwise Regression Results for the Adult Female of Each Scenario

Delivery Female[1]	Migrant Female	Near Water Female[1]	Outdoor Female[1]	Rural Family 1 Female	Rural Family 2 Female	Urban Female
CLBFF-Cs	LEAFRS	LEAFRS	CLBFF-Cs	DEPRF1,2	DEPRF1,2	DEPRF 1,2
CLBFF-Sr	DEPFR 1,2	DEPRF 1,2	CLBFF-Sr	LEAFRS	LEAFRS	WTIM
F	F	F	CLBFF-P	F	F	CLFMK I-131
BIOMA2	DPVRES	DPVRES	DEPRF1,2	DPVRES	DPVRES	CLMFT I-131
CLBFF-P	CONSUM	CONSUM	CLFMT I-131	CONSUM	CONSUM	CONSUM
R^2 = 0.98	R^2 =0.692	R^2 =0.692	R^2 =0.939	R^2 =0.593	R^2 =0.597	R^2 =0.731

[1] Ate Fish
Note: Refer back to Table 12-2 for full descriptions of the variables.

In the case of the Delivery Family (Table 12-11), the most important variables to the dose are the bioconcentration factors for cesium, strontium, and phosphorus in fish, suggesting that much of the variability in dose to the Delivery Family is from the variability of the uptake factors for cesium, strontium, and phosphorus by fish. As described in Chapter 3.0, the Delivery Family gets 50 percent of its fish from Lower Three Runs Creek, which drains from the area with P and R reactors. This list of variables may be shortened even more by dropping CLBFF-P, because CLBFF-Cs and CLBFF-Sr yield an R^2 of 0.91, which is most of the variation.

After strontium and cesium in fish, the important variables for the Delivery Family Child Born in 1955 are those variables associated with uptake of iodine-131by beef cattle and milk cows (CLFMT I-131 and CLFMK I-131), reflecting the relatively large releases of iodine-131 in the early years of site operation.

The most important variables for the Rural Family 2 (Table 12-12) are related, as expected, to ingestion. However, the variable LEAFRS (resuspension factor) could also impact inhalation dose. The variable CONSUM (forage consumption rate) is associated with the uptake of radionuclides (especially I-131) by beef cattle and milk cows. The R^2 values for this set of stepwise regression analyses (approximately 0.6

for each receptor) indicate that the relationship between the independent variables and the dose may not be linear or that there is a small range for one of the variables (CONSUM has a range of 9 to 62; less than 1 order of magnitude).

Table 12-13 compares the stepwise regression results for the Adult Female in each of the seven scenarios; this is intended to show how results are scenario dependent, but comparisons based on other family members may identify different variables. In general, the results of the stepwise regression analysis are consistent with the scenarios as they are defined. Specifically, of the hypothetical families that eat fish, the Delivery Family got its fish from Lower Three Runs Creek and the Savannah River, which exposed them to cesium, strontium, and phosphorus releases from the SRS at relatively higher concentrations than those families obtaining fish from only the Savannah River. The members of the Outdoor Family fished along the Savannah River shoreline adjacent to the SRS and were thus exposed to radionuclides transported through the wetlands area. Thus, it is reasonable that the most significant variables in determining the variation in dose to these families are the variations in bioconcentration factors for cesium and strontium.

In contrast, although the Near Water Family got its fish from the Savannah River, the consumption of fish was smaller than for the Outdoor Family. The bioconcentration factors cesium, strontium, and phosphorus in fish were not among the most important variables for this scenario. Instead, the Near Water and Migrant families exhibit a similar ranking of important variables. The most important variables for these families are related to exposure by air and consumption of locally grown fruits, vegetables, milk and beef. Although these families lived on opposite sides of the SRS, the similarity in the sensitivity rankings suggest that exposure through pathways related to air transport did not vary substantially around the circumference of the SRS.

The two Rural families showed the same sensitivities to input variables. Like the Migrant and Near Water families, the most important variables affecting variation in dose are those related to airborne transport and uptake through farm products.

The first-ranked variable for the Migrant and Near Water families is LEAFRS. This variable contributed 0.41 to the total R^2. The second-ranked variable DEPRF1,2 contributed 0.15. By contrast, the contribution to the total R^2 for the two Rural families was 0.23 for DEPFR1,2 and 0.21 for LEAFRS. The reasons for these differences in variable ranking and their relative contribution are not clear.

The ranking of variables for the Urban/Suburban Family is different from those families living in more rural settings closer to the SRS. This family's primary exposure to radionuclides from the site was through the milk produced in the New Ellenton area. DEPRF1,2 is the most significant variable with a contribution of 0.4 to the total R^2. Other variables are for removal of deposited radionuclides from plant surfaces (WTIM) and the uptake of I-131 into milk and beef (CLFMT I-131 and CLFMK I-131).

Several scenarios show sensitivity to the release factor, an expected result? the more released, the higher the dose.

12.6.4 Sensitivity Coefficients

In Section 12.6.3, the most important variables were ranked in order of their contribution to the coefficient of determination, R^2. This ranking actually is for the contribution to the variability in the dose, not the sensitivity, per se. To rank the variables in terms of their sensitivity coefficient (how a fractional change in the dose reflects a fractional change in the input variable), the uncertain variables were transformed to dimensionless quantities by dividing by the mean of each respective distribution. The transformed variables were used in the stepwise regression analysis, and while the variables found to be

dominant remained the same, the ranking changed. In this analysis, the sensitivity coefficients are based on the slope of a least-squares-fit between dose and the input variable.

Table 12-13 presents the variable rankings and their sensitivity coefficients for the Delivery Family and Rural Family 2 Adult Females. These rankings are related to how important the variables are in determining the dose; these rankings reflect only slightly the degree of uncertainty in the input variables themselves.

Table 12-13 Variable Rankings and Their Sensitivity Coefficients

Delivery Family Adult Female		Rural Family 2 Adult Female	
Variable	**Sensitivity Coefficient**	**Variable**	**Sensitivity Coefficient**
F	0.66	F	0.92
BIOMA2	-0.65	DEPFR 1,2	0.84
CLBFF-Cs	0.64	CONSUM	0.38
CLBFF-Sr	0.13	LEAFRS	0.15
CLBFF-P	0.01	DPRVES	0.09

Note: Change in sign for BIOMA2 that is more consistent with the analytical model.

12.7 Summary

The following are some of the key aspects of the uncertainty analysis:

- Forty realizations were used to investigate the uncertainty behavior of dose for each of 28 hypothetical receptors.
- In general, the distribution of dose for each receptor behaved similar to a lognormal distribution.
- Consistent with the shape of lognormal distribution, the mean of each dose distribution was higher than the median of the distribution.
- The confidence intervals were estimated for the mean and median. The sizes of these intervals were not large compared to the corresponding mean and median. This appears to reflect the sample size (40) and the underlying uncertainty quantified for the dose distributions. Also, modeling uncertainty was not estimated; only uncertainty related to the input variables was quantified.
- In general, the mean and median for the uncertainty analysis are larger than the corresponding point estimate of dose. This appears to reflect the interaction among the uncertain variables and the complexity of the dose model.
- The calculated confidence intervals do not contain the point estimates of dose.
- The sensitivity analysis generally shows the same dominance of the milk and beef ingestion pathways for those scenarios dominated by dose from air release (as did the point-estimate analysis). Similarly, for doses from water releases, the fish ingestion dominates? specifically, the fish bioconcentration factors for cesium-137, strontium-90, and phosphorus-32.

12.8 References

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13 CONCLUSIONS AND RECOMMENDATIONS

13.1 Introduction

This chapter discusses conclusions and recommendations based on the analyses described in the preceding chapters. Most of the conclusions relate to the results of the analyses, not the methods used to obtain results. The recommendations are intended to address unresolved issues that have arisen during the course of the work. The Savannah River Site Health Effects Subcommittee (SRSHES) raised some of these unresolved issues during presentations and discussions on this work. Other unresolved issues arise from the analysis but have not been resolved because they are beyond the scope of the current task. In general, while the resolution of these issues is not expected to change the major conclusions of this work, it is expected to enhance confidence in the conclusions.

13.2 Conclusions

The following bullets summarize the major conclusions of this dose reconstruction. These conclusions are then described in greater detail in the subsequent subsections.

- Doses and risks are small for all receptors and scenarios relative to doses and risks from background radiation over the 39-year period of the study.
- For people who ate fish from the Savannah River or Lower Three Runs Creek, fish ingestion was the most significant pathway, and the most important radionuclides were generally cesium-137, phosphorus-32, and strontium-90.
- For people who did not eat fish from bodies of water contaminated by releases of radionuclides to water, milk and beef were the most significant pathways and iodine-131 and tritium were the most important radionuclides.
- Immersion in argon-41 was a significant, generally small, but constant contributor to dose.
- Large doses occurred in years corresponding to large releases from the Savannah River Site (SRS), especially iodine-131; for the Adult Male, Adult Female, and Child Born in 1955, a large fraction of the total dose was received during the years 1955-1961.
- There were important differences in doses, pathway significance, and radionuclide significance between children born in 1955 and children born in 1964—those born in 1955 experienced the large iodine releases early in the site history, while those born in 1964 did not experience them.
- Doses caused by ingesting fish from Lower Three Runs Creek were significantly higher than doses caused by ingesting fish from the Savannah River.
- For air releases, the variations in air dispersion of radionuclides from the site generally produced a significant, but not dominant, variation in estimated doses.
- Consideration of uncertainty in the variables used to estimate doses could cause an estimated dose to be higher or lower than the corresponding point-estimate result. The mean of the distribution of total dose for any receptor ranged between 2.15 to 1.07 times the corresponding point-estimate dose; thus, the means of the uncertain doses were close to the corresponding point-estimate values.
- The use of hypothetical scenarios to demonstrate the interactions of a range of receptor behaviors with the site and release characteristics was an effective analytical tool.

13.2.1 Doses and Risks Are Small

Calculated doses and risks to the hypothetical receptors appear to be small. The largest point-estimate dose was 9.4 millisieverts (mSv) (0.94 rem) over the 39-year period studied for the Outdoor Family Child Born in 1955; the corresponding risk of cancer incidence is 0.10 percent, and the corresponding risk of cancer fatality is 0.024 percent. By way of comparison, the annual average radiation exposure for a member of the U.S. population is about 3.6 mSv (0.36 rem) (1), mainly from naturally occurring sources of radiation and medical sources (e.g., x rays). An annual background dose of 3.6 mSv over a period of 39 years would produce a dose of 140 mSv (14 rem).

Although estimated doses (and the risks of cancer incidence) were higher when uncertainties in variables were considered, the increases are not sufficient to change this conclusion. For example, when uncertainties were considered, the Outdoor Family Child Born in 1955 received the largest mean dose of 13 mSv (1.3 rem) and the largest median dose of 11 mSv (1.1 rem). However, the maximum dose for the same receptor was 60.3 mSv (6 rem) and the minimum dose for the same receptor was 2.53 mSv (0.25 rem).

13.2.2 Important Exposure Pathways and Radionuclides

Chapter 11 discusses the point-estimate doses for each receptor within each of the seven scenarios, including the contributions to these doses by the various radionuclides and exposure pathways. Although each scenario and each receptor within the scenario demonstrated unique characteristics, some generalizations can be made about the radionuclides and exposure pathways contributing most to dose. For any given realization in the uncertainty analysis, the importance of the various radionuclides and scenarios could be different; however, the same general trends that occur in the point-estimate analysis appear to be present. Other conclusions from the uncertainty analysis are presented in Section 13.2.8.

For scenarios exposed to water releases through ingestion of fish taken from the Lower Three Runs Creek and the Savannah River downstream of the SRS (Delivery Family, Outdoors Family, and Near River Family), the dominant radionuclides were cesium-137, strontium-90, and phosphorus-32. Table 13-1 shows the fraction of dose resulting from fish ingestion for the 12 receptors in the 3 scenarios exposed to water releases. In many cases (8 out of 12), the percentage of dose from fish ingestion is greater than 50 percent. For 83 percent of the receptors (10/12), fish ingestion was the largest source of dose. Beef ingestion edged out fish ingestion for the two remaining receptors.

Table 13-2 shows the percent of total dose over 39 years for a selected set of radionuclides. Cesium-137, strontium-90, and phosphorus-32 were the dominant radionuclides for exposures to water releases by fish ingestion. This is shown most clearly by the large percentage of dose from these isotopes for all members of the Delivery Person Family. However, for the Child Born in 1955 for the Delivery Person Family, iodine-131 (from ingestion of terrestrial foods contaminated by air releases) was a significant source of dose; for the Children Born in 1964 in the Outdoors Family and the Near River Family, phosphorus-32 was the most important isotope. For the Adults in the Near River Family, cesium-137 was the most important radionuclide. For the Adults in the Outdoors Family, iodine-131 was the most important radionuclide.

Thus, it can be seen that the fish ingestion pathway accounted for a large fraction of the dose for most of the receptors exposed to water releases. The important radionuclides producing dose through this pathway depended, in part, on the timing of the exposure; for Children Born in 1964, important radionuclides tended to shift from cesium-137 to phosphorus-32 for water resources (see Section 13.2.5 for additional discussion). In addition, for the Children Born in 1955, iodine-131, which is not related to fish ingestion, was an important isotope (the most important isotope for two scenarios).

Table 13-1 Percent of Total Dose from Fish Ingestions for Various Receptors in the Three Scenarios Exposed to Water Releases

Scenario	Receptor	Percent of Total Dose from Fish Ingestion
Delivery Person Family	Adult Female	92.8*
	Adult Male	90.2*
	Child Born in 1955	57.9*
	Child Born in 1964	92.9*
Outdoors Family	Adult Female	48.2*
	Adult Male	34.6
	Child Born in 1955	11.8
	Child Born in 1964	79.3*
Near River Family	Adult Female	71.0*
	Adult Male	66.2*
	Child Born in 1955	35.4*
	Child Born in 1964	82.3*

*For these receptors, fish ingestion was the largest source of dose.

Table 13-2 Percent of Total Dose from Fish Ingestions for Various Receptors in the Three Scenarios Exposed to Water Releases

Scenario	Receptor	Percent of Total Dose				
		Cs-137	Sr-90	P-32	I-131	Sum
Delivery Person Family	Adult Female	77.0	9.7	4.3	4.3	95.3
	Adult Male	74.8	9.5	4.2	6.0	94.5
	Child Born in 1955	39.8	11.3	5.4	37.9	94.4
	Child Born in 1964	49.5	25.1	15.0	*	89.6
Outdoors Family	Adult Female	18.8	*	17.5	42.2	59.7
	Adult Male	14.4	*	12.6	45.3	57.9
	Child Born in 1955	2.5	1.6	6.0	82.9	93.0
	Child Born in 1964	8.5	5.0	57.5	4.7	75.7
Near River Family	Adult Female	29.7	6.5	25.4	10.8	72.4
	Adult Male	28.1	6.2	24.1	14.5	72.9
	Child Born in 1955	9.0	5.0	18.0	50.8	82.8
	Child Born in 1964	10.9	5.7	59.7	*	76.3

*5% or less.

Thus, it can be seen that the fish ingestion pathway accounted for a large fraction of the dose for most of the receptors exposed to water releases. The important radionuclides producing dose through this pathway depended, in part, on the timing of the exposure. For the Children Born in 1964, the important radionuclides tended to change from cesium-137 to phosphorus-32 for water releases (see Section 13.2.5 for additional discussion). In addition, for the Children Born in 1955, iodine-131, which is not related to fish ingestion, was an important isotope (the most important isotope for two scenarios).

13.2.3 Important Exposure Pathways and Radionuclides for Air Releases

(Note: the general comments made in the initial paragraph of Section 13.2.2 apply here as well.) For scenarios not exposed to water releases by ingesting fish (Rural Families One and Two, Urban/Suburban Family, Migrant Family), the most significant radionuclides were iodine-131 and tritium, and the most significant exposure pathways were ingestion of milk and beef.

Table 13-3 shows the percent of total dose from beef and milk ingestion, and the combination for scenarios not exposed to water releases from the SRS. Of these receptors, 75 percent (12/16) obtained more than half their dose from these two pathways. For the remaining four receptors, these two pathways together accounted for the largest fraction of dose with air immersion also an important pathway.

Table 13-3 Percent of Total Dose from Beef and Milk Ingestion, and the Combination, for Scenarios not Exposed to Water Releases from the SRS

Scenario	Receptor	Percent of Total Dose from Beef Ingestion	Percent of Total Dose from Milk Ingestion	Sum of Percent from Two Pathways
Rural Family One	Adult Female	50.7	16.1	66.8
	Adult Male	57.1	15.3	72.4
	Child Born in 1955	43.2	43.9	87.1
	Child Born in 1964	15.3	35.4	50.7
Rural Family Two	Adult Female	52.4	16.1	68.5
	Adult Male	58.8	15.3	74.1
	Child Born in 1955	43.7	44.2	87.9
	Child Born in 1964	14.6	32.4	47.0
Urban/Suburban Family	Adult Female	42.6	24.1	66.7
	Adult Male	27.4	13.1	40.5
	Child Born in 1955	30.4	55.7	86.1
	Child Born in 1964	11.6	31.7	43.3
Migrant Family	Adult Female	52.1	11.6	63.7
	Adult Male	58.7	11.0	69.7
	Child Born in 1955	48.2	36.2	84.4
	Child Born in 1964	17.8	22.4	40.2

*Since the Migrant Worker Family was only present near the SRS for six months, it may be more appropriate for comparison purposes to double these doses.

Table 13-4 shows the percent of total dose from iodine-131, tritium, and argon-41, and their combination, for scenarios not exposed to water releases from the SRS. In these families, the Adult Male, Adult Female, and Child Born in 1955 had most of their dose from iodine-131 from a combination of ingesting milk and beef. In these same families, the Child Born in 1964 had most of its dose from tritium from a combination of ingesting milk and beef.

Table 13-4 Percent of Total Dose from Beef and Milk Ingestion, and the Combination, for Scenarios Not Exposed to Water Releases from the SRS

Scenario	Receptor	Percent of Total Dose			
		Iodine-131	Tritium	Argon-41	Total
Rural Family One	Adult Female	73.8	12.0	8.0	93.8
	Adult Male	76.9	11.3	5.7	93.9
	Child Born in 1955	93.3	3.8	1.5	98.6
	Child Born in 1964	9.3	63.9	16.6	89.8
Rural Family Two	Adult Female	76.5	9.9	7.7	94.1
	Adult Male	79.4	9.4	5.5	94.3
	Child Born in 1955	94.2	3.0	1.4	98.6
	Child Born in 1964	10.4	59.9	18.8	89.1
Urban/ Suburban Family	Adult Female	75.5	14.1	5.1	94.7
	Adult Male	50.0	10.6	34.8	95.4
	Child Born in 1955	93.5	3.5	2.1	99.1
	Child Born in 1964	9.9	63.9	18.8	92.6
Migrant Family*	Adult Female	74.7	8.9	8.6	92.2
	Adult Male	77.9	8.4	6.2	92.5
	Child Born in 1955	93.7	2.8	1.8	98.3
	Child Born in 1964	10.7	52.4	23.1	86.2

*Since the Migrant Worker Family was only present near the SRS for six months, it may be more appropriate for comparison purposes to double these doses.

Thus, it can be seen that two ingestion pathways (milk and beef ingestion) accounted for a large fraction of the dose for most of the receptors exposed only to air releases of radionuclides. The important radionuclides producing dose through these pathways depended, in part, on the timing of the exposure; for the Children Born in 1964, important radionuclides tended to shift from iodine-131 to tritium for air releases (see Section 13.2.5 for additional discussion); for the other receptors, iodine-131 was the most important radionuclide.

13.2.4 Significance of Immersion Dose from Argon-41

Releases of argon-41 produced a small but persistent dose for all receptors from immersion in the plume. Generally, doses of 0.02 to 0.09 mSv (2 to 9 millirem [mrem]) over 39 years were produced. An exception was the Adult Male for the Outdoors Family who received 0.31 mSv (31 mrem) over 39 years. In most cases, this air-immersion dose was minor, but for receptors with small doses from other sources, it could be a significant contributor. For example, for the Child Born in 1964, air-immersion dose from

argon accounted for almost 17 percent of the total dose in Rural Family One and almost 24 percent of the total dose in Rural Family Two and the Urban/Suburban Family. Immersion dose accounted for almost 39 percent of the dose to the Adult Male in the Urban/Suburban Family principally because he worked a significant amount of time onsite. For scenarios exposed to water releases, the percentage of dose from air immersion was generally small (less than 10 percent) for all receptors.

13.2.5 Major Dose Fraction for many Receptors from Large Releases in 1955-1961

Large releases of iodine-131 that occurred at the SRS in a period around 1955 to 1961 produced a major fraction of the dose in many receptors. This is shown in the tables of annual effective dose as a function of time in Chapter 11 (i.e., Tables 11-4, 11-7, 11-10, 11-13, 11-16, 11-19, and 11-22). Because the Children Born in 1964 did not experience these large iodine-131 releases, their doses tended to result from other radionuclides, principally tritium and cesium-137. The Adult Female, Adult Male, and Child Born in 1955 for those scenarios exposed only to air releases had a majority of their dose from iodine-131 releases during this time frame. For those scenarios exposed to water releases, the Adult Female, Adult Male, and Child Born in 1955 had a significant fraction of dose delivered in later years (mid-1960's), when the liquid releases were greater. In some cases, the majority of the dose came from these later water releases, but this depends on the degree to which doses from fish ingestion dominate.

13.2.6 Differences in Children Born in 1955 and 1964

Significant differences exist between doses for Children Born in 1955 and Children Born in 1964, and these differences are observed to greater or lesser degrees in all seven scenarios. These differences in doses include the magnitude of the doses, the radionuclides primarily responsible for producing the doses, and the exposure pathways through which the doses are received. Table 13-5 compares for Children Born in 1955 to the Children Born in 1964 for each scenario: 1) the total doses, 2) the radionuclide/pathway pair contributing most to this dose, and 3) the fraction of the total dose accounted for by this major radionuclide/pathway pair.

For the first four scenarios in Table 13-5, which are only exposed to air releases from the SRS, the differences between the Child Born in 1955 and the Child Born in 1964 are similar. Considering the Child Born in 1955, for three out of four scenarios the pathway was beef ingestion and the radionuclide was iodine-131; for the remaining scenario, the pathway was milk ingestion but the radionuclide remained iodine-131. The contribution to total dose was about 40 percent in three cases and 70 percent in one case. This shows that that the large iodine-131 releases early in the site history dominate the dose mechanisms for the Children Born in 1955. Considering the Child Born in 1964, for three out of four scenarios the pathway was milk ingestion and the radionuclide was tritium; for the remaining scenario, the pathway was air immersion and the radionuclide was argon-41. The contribution to total dose was about 25 percent in three cases and 37 percent in one case. This behavior illustrates that because the Children Born in 1964 did not experience the large iodine-131 releases early in the site history, radionuclides other than iodine-131 and its dominant pathways became more evident. However, the dominance of doses caused by these other radionuclides is smaller than those caused by the early releases of iodine-131. Both argon-41 and tritium were more persistently released over time than iodine-131.

For the last three scenarios in Table 13-5, the children are exposed to both air and water releases from the SRS. For the Outdoor Family and the Near River Family, the air release of iodine-131 caused the dominant dose for the Children Born in 1955; however, the dominant pathway for the Outdoor Family is beef ingestion and milk ingestion for the Near River Family. For the Children Born in 1964 for the Outdoor Family and the Near River Family, the dominant pathway is fish ingestion and the dominant radionuclide is phosphorus-32; in both scenarios, about 60 percent of the dose is produced this way. For the Delivery Person Family, unlike the other scenarios in Table 13-2, the Children Born in 1955 and 1964

have the same dominant pathway and dominant radionuclide; for both, about 40-50 percent of the dose is caused by fish ingestion and cesium-137. This is the result of the very high doses produced by ingesting fish taken from Lower Three Runs Creek.

Table 13-5 Comparison of the Dominant Cause of Dose for Children Born in 1955 and Children Born in 1964 for all Seven Scenarios

Scenario	Child Born in	Dose (mSv/mrem)	Major Radionuclide-Pathway Pair		Percent of Total Dose
Rural Family One	1955	1.6/160	Iodine-131	Beef Ingestion	42
	1964	0.072/7.2	Tritium	Milk Ingestion	29
Rural Family Two	1955	3.8/380	Iodine-131	Beef Ingestion	43
	1964	0.14/14	Tritium	Milk Ingestion	26
Urban/Suburban Family	1955	2.7/270	Iodine-131	Milk Ingestion	70
	1964	0.11/11	Tritium	Milk Ingestion	37
Migrant Worker Family*	1955	2.2/220	Iodine-131	Beef Ingestion	37
	1964	0.083/8.3	Argon-41	Air Immersion	23
Delivery Person Family	1955	5.2/520	Cesium-137	Fish Ingestion	40
	1964	2.1/210	Cesium-137	Fish Ingestion	49
Outdoors Family	1955	9.4/940	Iodine-131	Beef Ingestion	46
	1964	1.8/180	Phosphorus-32	Fish Ingestion	57
Near River Family	1955	3.1/310	Iodine-131	Milk Ingestion	27
	1964	1.8/180	Phosphorus-32	Fish Ingestion	60

*Since the Migrant Worker Family was only present near the SRS for six months, it may be more appropriate for comparison purposes to double these doses.

In short, for all but the Delivery Person Family, the scenarios show a distinct difference in the size and dominant causes of dose between the Children Born in 1955 and 1964.

13.2.7 Importance of Lower Three Runs Creek Fish Ingestion Dose

The annual concentration of a radionuclide in the Savannah River was estimated by dividing the estimated total liquid release of the radionuclide from the SRS in a given year by the annual volume of flow in the Savannah River. For Lower Three Runs Creek, measured concentrations were used for tritium, cesium-137, and strontium-90. Generally, the concentrations in Lower Three Runs Creek were substantially higher than in the Savannah River. For example, the ratios of peak concentrations in the two bodies of water were 23, 10, and 6, respectively, for tritium, cesium-137, and strontium-90. As a consequence, eating fish taken from Lower Three Runs Creek produced higher doses for those receptors so exposed. Table 13-6 demonstrates this trend quantitatively and shows doses to the Adult Female in three scenarios: Rural Family One, the Near River Family, and the Delivery Family.

These three families received, respectively, 0, 100, and 50 percent of their fish from the Savannah River and, respectively, 0, 0, and 50 percent of their fish from Lower Three Runs Creek. When the doses from water releases for the Adult Females in the Near River Family and the Delivery Family are compared, there is a significant difference in dose (i.e., 1.8 mSv [180 mrem] for the Near River Family versus 5.7

mSv [570 mrem] for the Delivery Family). This difference in dose was produced by ingesting the same quantity of fish in both scenarios. However, for the Delivery Family Adult Female, 50 percent of the fish ingested came from Lower Three Runs Creek; for the Near River Family Adult Female, 100 percent of the fish ingested came from the Savannah River. By replacing 50 percent of the fish consumed from the Savannah River with fish from Lower Three Runs Creek, the dose from water releases was increased by more than a factor of three. By assuming the dose is linearly proportional to the quantity consumed from the two sources, an algebraic manipulation shows that if a scenario obtained 100 percent of the fish it consumes from Lower Three Runs Creek, the dose to the Adult Female would be 9.6 mSv (960 mrem). This implies that the contamination level in the water (and therefore in the fish ingested) is on average a factor of 5 greater in Lower Three Runs Creek than in the Savannah River. This is generally consistent with the concentration data presented in Chapter 7 for cesium-137 concentrations in the two bodies of water.

Table 13-6 Comparison of Fish Consumption and Dose for the Adult Female by Family Location

% of Dose From Fish Consumed from Different Sources	Rural Family #1	Near River Family	Delivery Family
Lower Three Runs Creek	0	0	50
Savannah River	0	100	50

	Dose (mSv/mrem)	Percent	Dose (mSv/mrem)	Percent	Dose (mSv/mrem)	Percent
Total Dose	0.3/30	100	2.1/211	100	6.1/610	100
Water Release Dose	0/0	0	1.8/180	85	5.7/570	93
Air Release Dose	0.3/30	100	0.3/31	15	0.4/40	7

13.2.8 Variations in Air Dispersion Significant but not Dominant

In this study, careful attention was paid to the geographical locations of the releases to air from the SRS, the geographical locations of various receptors, and the air-dispersion patterns at the SRS. One might be tempted to compare total doses from air releases to measure the impact of air dispersion; however, total dose from air releases is not a good indicator of the importance of air-dispersion variability because it does not directly reflect the concentrations experienced at the residence location for a particular receptor. The following are some of the complicating factors that prevent total dose from being a good indicator of air dispersion at the primary exposure locations:

- For several scenarios, foodstuffs (milk, deer meat, and beef) were brought to the residence location from other exposure locations (including the SRS) as mandated by the scenario specifications.
- In other cases, the receptor (especially the Adult Male) experienced exposure at a work location (including the SRS).

However, dose to the Adult Female by air immersion is a relatively good indicator of the differences due to variations in air dispersion. This is because the Adult Female was assumed to stay most of the time at the residence location (except for small amounts of time spent in recreation or at church) and because air

immersion is a good surrogate for the time integral of concentration of gamma-emitting radionuclides at the residence location.

Table 13-7 compares air-immersion doses for the Adult Female in all seven scenarios. Note that the ratio of these doses to the average dose over the seven scenarios is generally different by less than a factor of 2. The largest deviation from the average is for the Urban/Suburban Family, which has a dose smaller than the average by a factor of 2.6.

Table 13-7 Air-Immersion Doses for the Adult Female in Each Scenario as a Measure of the Effects of Air-Dispersion Differences

Scenario	Air Immersion Dose for Adult Female (mSv/mrem)	Ratio of Dose to Average Dose
Rural Family One	0.024/2.4	0.544
Rural Family Two	0.054/5.4	1.223
Urban/Suburban Family	0.017/1.7	0.385
Migrant Family*	0.039/3.9	0.883
Delivery Person Family	0.055/5.5	1.246
Outdoors Family	0.084/8.4	1.903
Near River Family	0.036/3.6	0.816
Average	0.044/4.4	

*Since the Migrant Worker Family was only present near the SRS for six months, it may be more appropriate for comparison purposes to double this dose.

Comparing the dose for each scenario to the average is parallel to quantifying “tallness” by comparing a person’s height to the average height. Although comparing the maximum dose to the minimum dose accentuates the differences in the variation across the site, the ratio in this case is 4.9—a significant but not dominant contributor to variations among receptors. The ratio of maximum total dose to minimum total dose is over 130 as shown in Table 11-2. This implies that many factors other than air dispersion have a significant effect on determining total dose to each receptor. That is, the variations that accentuate differences (e.g., time spent at different locations, quantities of foods ingested from different locations) are more significant than the air-dispersion differences related to average meteorological conditions, receptor locations, and source locations. However, this conclusion excludes consideration of onsite exposures. Due to the proximity of the onsite location to the air-release sources, significantly higher contamination and concentration levels were experienced onsite.

13.2.9 Variable Uncertainty Generally Raises Dose Estimates Slightly

Chapter 12 provides a description of the uncertainty analysis. Consideration of uncertainty in the variables used to estimate doses could cause an estimated dose to be higher or lower than the corresponding point-estimate result. Comparison of the results from the uncertainty analysis to the point-estimate analysis shows that on average the estimated doses from the uncertainty analysis are higher. Table 12-9 compares the mean and median doses from the uncertainty analysis to the point-estimate dose for each of the 28 specified receptors. The ratios of the mean doses to the corresponding point-estimate doses range from a high of 2.15 to a low of 1.07; similarly, the ratio of the median doses to the corresponding point-estimate doses range from a high of 1.54 to a low of 0.86. Thus, the means and medians of the uncertain doses were close to the corresponding point-estimate values. These results

illustrate the behavior of the central tendencies (the means and medians) of the estimated dose distributions.

As discussed in Section 12.5.1, the lognormal distribution is a reasonable fit to the uncertain distributions of dose for each receptor. It is not surprising that most of the uncertain dose distributions could be well described by a lognormal distribution because most of the variables modeled as uncertain in the uncertainty analysis were assigned lognormal distributions based on the information available. Although the receptor doses are not simple functions of the uncertain variables, the general shape of the lognormal distributions used to describe those variables is evident in the receptor dose distributions. Lognormal distributions are skewed toward higher values. For this type of distribution, the mean is always higher than the median. This behavior is evident if the extreme values of the dose distributions are examined. For example, on average, the ratio of the maximum dose from the uncertainty analysis to the point-estimate dose for the same receptor is 7.8. The maximum value of this ratio is 11.5 for the Urban/Suburban Family Child Born in 1955. In addition, on average the ratio of the minimum dose from the uncertainty analysis to the point-estimate dose for the same receptor is 0.36; the minimum value of this ratio is 0.13 for the Urban/Suburban Family Child Born in 1955. In other words, on average, the maximum value is 7.8 time higher than the point estimate while the minimum value is 2.8 times smaller than the point-estimate value.

The medians of the lognormal distributions describing the uncertain input variables were set equal to the variable value used to generate the point estimate. However, except for the Urban/Suburban Family, all the median doses were higher than their corresponding point-estimate doses. This somewhat surprising result seems to be related to several aspects of the analysis, including the properties of the models used to compute the dose and the large uncertainty for some variables. In particular, for scenarios in which exposure to liquid releases by fish ingestion was a dominant pathway, variations in the uptake factors for cesium-137, strontium-90, and phosphorus-32 seemed to combine in a manner that assured the median doses would be higher than the point-estimate doses.

Although the dose estimates derived by considering uncertainty in the input variables were larger than the point-estimate doses, the means and medians of the uncertain doses were generally no more than a factor of 2 larger than the point-estimate doses. Although this underscores the importance of performing an uncertainty analysis, the basic conclusion of low doses and risks does not change when uncertainty is considered.

13.2.10 Effectiveness of Scenarios

As described in Chapters 1, 3, and 4, the definition and use of hypothetical scenarios to span the range of realistic receptor behavior was an important aspect of implementing this intermediate phase dose reconstruction. The scenarios defined sets of hypothetical receptors whose doses and risks would reflect the interaction of the receptor behaviors with the site and release characteristics. As indicated by many of the conclusions listed previously, this strategy was successful in illustrating how the released radioactive materials interacted with different behavior patterns to yield a range of doses produced by different radionuclides and pathways. In particular, the hypothetical scenarios disclosed:

- A range of 39-year doses that spanned two orders of magnitude.
- Generally higher doses for scenarios in which receptors were exposed to liquid and air releases from the SRS than for scenarios in which receptors were exposed only to air releases. For scenarios exposed to liquid and air releases, fish ingestion was generally the most important pathway and cesium-137 the most important radionuclide; for scenarios exposed only to air releases, milk and beef ingestion were the most important pathways, and iodine-131 was generally the most important radionuclide.

- The Children Born in 1955 had substantially different doses and causes for doses than the Children Born in 1964.
- The scenario for obtaining fish from Lower Three Runs Creek experienced higher doses than scenarios for obtaining fish from the Savannah River or from waters not affected by liquid releases from the SRS.

Because use of the scenarios was able to provide this kind of information, use of hypothetical scenarios in this context is supported and the utility of the scenario definitions is confirmed.

13.3 Recommendations

Unresolved technical issues have arisen during the course of the work from two sources: 1) meetings of the SRSHES and 2) the analytical team performing the work. Some of these unresolved issues were raised at public meetings during which this work was presented and discussed. These public meetings were held in the following cities:

- Charleston, South Carolina—March 2003.
- Savannah, Georgia—September 2003.
- Columbia, South Carolina—August 2004.

Other unresolved issues arose during the development of the approach and the analysis of results. These issues have not been addressed to date because they fall generally beyond the scope of the present task. Performing this work is not likely to change the major conclusions listed in the previous section. However, performing this work can be expected to resolve a number of technical issues and thereby enhance confidence in the current conclusions. The following is a list of the recommendations which are then described briefly in the subsequent subsections:

- Look at large, acute releases to see if the pattern of doses would be changed significantly.
- Examine the buildup of long-lived radionuclides in soil to determine if terrestrial doses change significantly.
- Model contamination in reservoirs to see if it causes significant doses.
- Compare modeled concentrations in foodstuffs with empirical monitoring data for model validation.
- Perform an auxiliary analysis to determine if the breast-feeding of infants changes dose substantially.
- Perform an auxiliary analysis to determine how in-utero doses change total dose and cancer risk.
- Model consumption of venison more carefully to see if the result changes.
- Model dose from the consumption of drinking water taken from the Savannah River for municipal water supplies some distance downstream from the SRS (i.e., the municipal water intakes at Port Wentworth, Georgia, and Hardeeville, South Carolina, for Beaufort and Jasper Counties).
- Obtain technical peer review of the study by publishing papers on the methods and results in peer-reviewed journals.

The following sections discuss each recommendation briefly.

13.3.1 Acute Releases vs. Annual Average Releases

This present analysis was performed assuming that the reported SRS annual releases occurred uniformly throughout each year. In fact, the Phase II report clearly documents that these annual reported releases included some acute releases (i.e., relatively large releases over short periods of time). Because the acute

releases were subject to air-dispersion conditions during the time of their release, the doses from such acute releases may not have been accurately portrayed by using the multi-year average meteorology that is more appropriate for routine, relatively constant releases. It is recommended that the importance of modeling air releases as acute instead of chronic, annual releases be determined by computing doses for the largest acute releases in two ways: 1) modeled as acute releases with air-dispersion conditions corresponding to the time of release and 2) modeled as chronic releases using the multi-year average meteorology. Differences in dose estimates for the two computational approaches would help to determine whether the approach used in this study has sufficient precision. Only a few of the largest acute releases would need to be studied (10-25) to make the determination. One problem in performing this evaluation is that air-dispersion conditions were not measured onsite in the early years when many of the larger acute releases occurred. This may introduce additional uncertainty into the evaluation because onsite air-dispersion conditions would need to be extrapolated from nearby but offsite weather stations.

13.3.2 Evaluate Soil Buildup of Long-Lived Radionuclides

A preliminary evaluation was performed while developing the analytical approach to estimate the importance of the buildup of long-lived radionuclides in soil. Because soil buildup did not appear to be significant, the dose modeling was performed without taking into account residual contamination that might have remained in the soil from one year to later years (i.e., the dose from each year was assumed to result only from the releases during that year). A more detailed examination could confirm that this dose from residual radioactivity in the soil was indeed negligible. Because dose pathways associated with such soil buildup were not significant, it is unlikely that the residual doses will be significant. For example, uptake of radionuclides by plant roots from the soil was much smaller than uptake from radionuclides deposited on plant surfaces; also, ground plane dose, which would be increased by residual soil contamination, was a very minor pathway. It is recommended that for a few scenarios (air-release-only scenarios will likely show the largest effect) doses be computed by accounting for soil buildup of radionuclides from one year to the following years to quantify the importance of this effect.

13.3.3 Evaluate Significance of Reservoir Contamination

Air releases of radionuclides could contaminate bodies of water used for drinking in two ways: 1) direct deposition of radionuclides from the air into the body of water (lake, pond, or reservoir) and 2) deposition of radionuclides onto the surface water basin of the water body and subsequent migration to the water body by surface runoff. These transport pathways were not modeled because more direct pathways (i.e., deposition of airborne radionuclides onto crops in the food chain and ingestion of fish from water bodies contaminated directly by SRS water releases) appeared to be more likely to produce significant doses. It is recommended that airborne contamination of otherwise uncontaminated water bodies be modeled to determine the significance of the contamination produced and the potential doses from the contamination. This will indicate whether the dose estimates produced by this study have sufficient precision.

13.3.4 Compare Modeled Contamination in Foodstuffs to Monitoring Data

As a means of enhancing confidence in this intermediate-phase dose reconstruction, a partial validation of the modeling of releases and environmental transport may be desirable. A partial validation of these aspects of the modeling could be accomplished by comparing intermediate modeling results (such as contamination levels in soil and food) to field measurements. These field measurements are contained in the annual site Environmental Reports. Additional computer computations would be required to obtain these intermediate results because they were not permanently recorded during the previous calculations. It is recommended that this partial validation effort be pursued.

13.3.5 Evaluate Significance of Breast-Feeding Infants

The current study did not model the pathway of breast milk ingestion by infants; instead, ingestion of contaminated cow's milk was modeled. There are methods by which the breast-milk pathway could be modeled. The modeling of the cow's milk pathway, as currently implemented, may be more conservative (i.e., may produce a higher dose). It is recommended that the breast milk pathway be evaluated by some comparative modeling to determine its significance.

13.3.6 Evaluate Significance of In-Utero Doses

Some approaches are available to estimate the fetal doses in-utero from pregnant women experiencing environmental exposures to radiation and radioactivity. The current approach did not include this pathway. It is recommended that some of the scenarios with higher dose levels be analyzed first to determine if the fetal doses are significant.

13.3.7 Refine Modeling of Deer Meat Ingestion

The current approach models contaminated venison as "beef" taken from cattle grazing at the various exposure locations incorporated into the analysis. A more precise approximation to venison contamination may be obtainable by modeling uptake of radionuclides by deer ingestion of various plant species typically ingested by deer; such an approach would require modeling the uptake of radionuclides by these additional plant species. Because ingestion of contaminated beef produced large doses from iodine-131, a likely outcome from this more precise approach dose from venison ingestion may actually be lower calculated doses to humans. However, it is recommended that this more precise approach be pursued to remove a persistent criticism of the current approach.

13.3.8 Estimate Doses from Drinking Water from the Savannah River

None of the scenarios specified for this study considered receptors located far downstream on the Savannah River (e.g., Port Wentworth, Georgia, and Hardeeville, South Carolina, for Beaufort and Jasper Counties) where river water is used for municipal water supplies. The radionuclide content of this drinking water is carefully monitored to comply with the applicable limits on radionuclide concentrations in drinking water promulgated by the U.S. Environmental Protection Agency. Nevertheless, the residual radioactivity content will produce a dose, although it is likely to be small. A problem in estimating doses from this pathway is that the contribution of radionuclides in the drinking water from the SRS may be difficult to distinguish from the contribution of radionuclides from other sources. It is recommended that doses from this pathway be estimated to address this concern raised by the SRSHES.

13.3.9 Obtain Technical Peer Review

It is recommended that technical peer review be obtained for the methods and results of this study. An important avenue to obtain this type of peer review is by publishing papers on the methods used and the results obtained in peer-reviewed technical journal. In addition, further peer review may be acquired by presenting papers on this study at technical conferences. By vetting this study in the technical literature, confidence in the results will be enhanced.

13.4 References

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