1 INTRODUCTION

The purpose of the Dose Reconstruction Project is to determine the total cumulative effective radiation dose to the populations surrounding the Savannah River Site[1] (SRS) for a 39 year (1954 – 1992) period. 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 is the product of Phase III of the Savannah River Site[1] (SRS) Dose Reconstruction Project. It estimates the cumulative effective radiation doses and associated cancer risks for each of 28 hypothetical persons living near SRS and performing representative activities.

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 EI 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 had all ceased operation. The separation and some processing and support facilities, 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 (1). 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;
- Air and water transported some of the released material offsite within a geographically large and complex physical and ecological system.

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

- 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).

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).

[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).

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.

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

1.3.1 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.

1.3.2 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.

1.3.3 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).

1.3.4 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 Savannah 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.

1.3.5 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).

1.3.6 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).

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).

1.3.7 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).

1.3.8 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]

[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).

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).

1.3.9 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). 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 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).

[4] VAMP stands for Validation of Model Predictions, an acronym for the Coordinated Research Program on Validation 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 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).

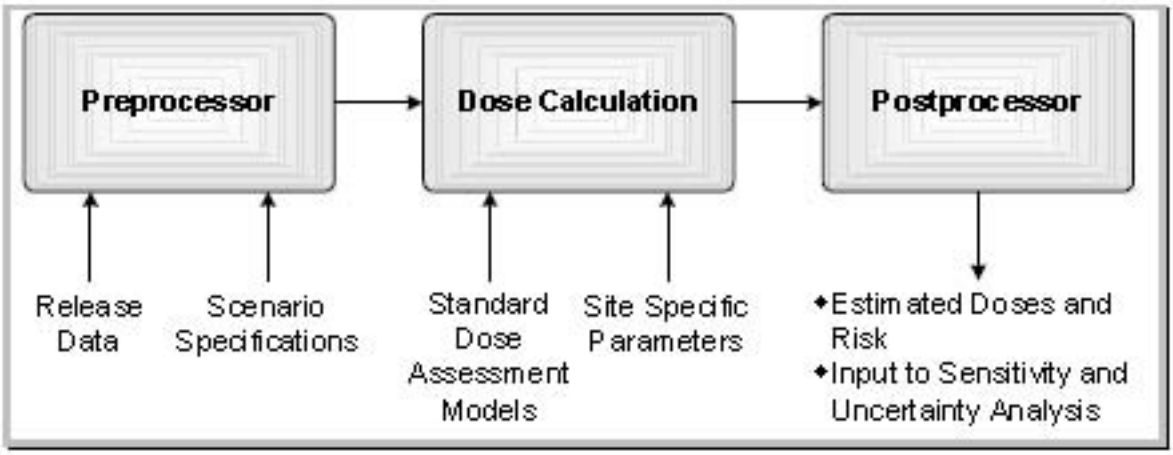

Figure 1-1 Conceptual Configuration of SRS Dose Assessment

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 decision documents (Appendix T) 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.

- **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

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

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.

1.4 References

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