Assessment of Strontium in the Savannah River Site Environment^(U)

W. H. Carlton
A. G. Evans
L. A. Geary
C. E. Murphy, Jr.
R. N. Strom

SAVANNAH RIVER SITE

Westinghouse Savannah River Company
Savannah River Technology Center
Aiken, SC 29808

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W. H. Carlton
A. G. Evans
L. A. Geary
C. E. Murphy, Jr.
R. N. Strom

Approved by

A. L. Boni
Research Manager
Environmental Technology Section

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Westinghouse Savannah River Company
Savannah River Technology Center
Aiken, SC 29808

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MASTER

Executive Summary

The "Assessment of Strontium in the Savannah River Site Environment" is published as a part of the Radiological Assessment Program (RAP). It is the sixth in a series of eight documents on individual radioisotopes released to the environment as a result of SRS operations. The earlier documents describe the environmental consequences of tritium, iodine, uranium, cesium, and plutonium. Documents on carbon and technetium will be published in the future. These are living documents and current plans call for revising and updating each one on a two-year schedule.

Strontium exists in the environment as a result of above-ground nuclear weapons tests, the Chernobyl accident, the destruction of satellite Cosmos 954, small releases from reactors and reprocessing plants, and the operation of industrial, medical, and educational facilities.

Strontium has been produced at SRS during the operation of 5 production reactors. About 300 curies of radiostrontium were released into streams in the late 50s and 60s, primarily from leaking fuel elements in reactor storage basins. Smaller quantities were released from the fuel reprocessing operations. About 400 Ci were released to seepage basins. A much smaller quantity, about 2 Ci, was released to the atmosphere.

The overall radiological impact of SRS releases on the offsite maximum individual can be characterized by total doses of 6.2 mrem (atmospheric) and 1.4 mrem (liquid), compared with a dose of 12,960 mrem from non-SRS sources during the same period of time. Radiostrontium releases have resulted in a negligible risk to the environment and the population it supports.

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Chapter 1. Radiostrontium in the Environment

Strontium is an essential element in human nutrition. Man-made radioactive isotopes of strontium, if introduced into the global and regional environments, eventually will reach humans via the food chain. Thus, man-made radioactive isotopes of strontium may contribute to the radiation dose that humans receive from all sources.

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Radiostrontium in Global Environments

Radioactive isotopes of strontium exist in nature at minute levels and are collectively known as radiostrontium. A natural mechanism for radiostrontium production is fission of naturally occurring uranium and thorium. Such fission occurs either by spontaneous fission decay or by neutrons in nature inducing fission. Radiostrontium produced by this mechanism is localized primarily in ore deposits containing uranium and thorium.

Man-made sources that contribute radiostrontium to the global environment are above-ground nuclear weapons tests and nuclear reactor operations. Nuclear weapons testing has been the most significant man-made source of radiostrontium in the global environment. Above-ground testing has introduced approximately 2.2×10^7 curies of ^{90}Sr to the atmosphere, most of which has deposited on the earth as fallout on a regional scale and a global scale (Eisenbud, 1987a). Since the mid-1960s, when the USA and USSR ceased above-ground testing, radiostrontium concentrations in the atmosphere have decreased dramatically because the radiostrontium has been deposited on the earth's surface as fallout.

The other man-made source that contributes radiostrontium to the global environment is nuclear reactor operations. Ideally, all the radiostrontium produced in nuclear reactors is contained in the fuel until reprocessing occurs. However, under accident conditions, radiostrontium can be released to the global environment, as exemplified by two widely publicized accidents, the satellite Cosmos 954 in 1978 and the USSR's Chernobyl nuclear reactor in 1986. USSR's satellite Cosmos 954 was powered by a nuclear reactor. It was estimated to have contained 84 curies of ^{90}Sr at re-entry into the earth's atmosphere, where it disintegrated (Eisenbud, 1987b).

The Chernobyl accident released 34,000 curies of ^{90}Sr (Gudiksen et al., 1989). Conditions were severe enough to inject some radiostrontium to high altitudes, allowing global distribution. However, most of the radiostrontium was deposited as regional fallout in Europe.

Radiostrontium in Regional Environments

Man-made sources that contribute radiostrontium to regional environments are nuclear weapons tests, nuclear reactor operations, industrial/medical/educational facilities, and nuclear fuel reprocessing operations.

The routine operation of experimental, research, power, and production nuclear reactors has released small quantities of radiostrontium to regional environments. Radiostrontium also has been released to regional environments under accident conditions.

The least significant releases of radiostrontium to local environments are from industrial, medical, and educational facilities that produce, transport, or use specific strontium radioisotopes.

Nuclear fuel reprocessing operations have been the most significant localized source of radiostrontium. Reprocessing facilities are located in several countries worldwide. Reprocessing consists of chemical separation of materials that have been irradiated in experimental, research, power, and production reactors. As a result of the chemical separation process, the radiostrontium content of irradiated materials can be released to the environment through aqueous waste streams and stack gases.

Radiostrontium in the SRS Environment

Numerous radioactive isotopes of strontium are made in the fuel and targets of the Savannah River Site's (SRS) production reactors. Most of the isotopes are short-lived and decay to insignificant activity levels during the time interval between end of irradiation and commencement of reprocessing by chemical separations at SRS.

The radiological properties of the 10 radioactive isotopes of strontium that are in use or produced at SRS are tabulated in Appendix 1, Table A1-1.

Strontium-90, with a half-life of 28 years, is the most significant strontium isotope in terms of radiation dose in the SRS environment. During the 36-year operating history of SRS, about 3 curies of ^{90}Sr have been released to the atmosphere (Cummins et al., 1991). This is obscured by the 50 curies (60 mCi/m^2) deposited on SRS as a result of fallout (Eisenbud, 1987c). About 104 curies has been released to site streams and transported to the Atlantic Ocean (Cummins et al., 1991).

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Chapter 2. Origin and Disposition of Radiostrontium at SRS

This chapter gives a general overview of the origin, uses, and disposition of radiostrontium at SRS under normal operating conditions. The locations of SRS facilities that had the potential to release radiostrontium are shown in Figure 2.1. The greatest releases of ^{90}Sr occurred prior to 1975 and originated in the reactor facilities and the chemical separations facilities, which are located near the center of the 800-square-kilometer site. Another strontium isotope, ^{89}Sr , was released as a result of SRS operations. Most of the ^{89}Sr activity released to streams originated in the reactor facilities. The history of actual releases from specific SRS facilities is presented in Chapter 3.

Figure 2.1 SRS Facilities that had Potential to Release Strontium

Origin of Radiostrontium at SRS

Radiostrontium at SRS predominantly originated in the fuel and targets irradiated in the nuclear materials production reactors. Other site operations and offsite sources (principally fallout from nuclear weapons tests) contributed to the inventory of radiostrontium at SRS.

Irradiation in Production Reactors

Most of the radiostrontium at SRS was formed as a fission byproduct in the nuclear fuel and targets during operation of the five production reactors. The production reactors' role was to produce nuclear materials—principally tritium and plutonium—for national defense purposes. Additional radionuclides—such as ^{238}Pu , a power source for certain deep-space missions—occasionally were produced for other government purposes.

Since the reactors became operational during 1953 to 1955, they have not operated continuously. They have alternated between operating periods for production and shutdown periods for maintenance or the replacement of fuel and targets. As of 1992, one reactor was operational, one was on standby, and three reactors were inactive. The history of individual reactor operations is discussed in Chapter 3.

The principal mechanism for production of radiostrontium in the reactors is neutron-induced fission. When a reactor is operating, neutron-induced fission reactions occur in the ^{235}U fuel of the reactor core. Fission reactions form a variety of fission products, including isotopes of strontium.

In addition to fission products, each neutron-induced fission reaction in the fuel produced several neutrons, some of which induced additional fission reactions and maintained a chain reaction. Some of the remaining neutrons interacted with target materials in the reactor. (Fuel and targets were encapsulated separately and referred to as elements.) One such interaction, neutron capture in a ^{238}U target, resulted in the production of a special nuclear material, ^{239}Pu .

In target materials, such as ^{238}U , neutron-induced fission is a competing reaction. In the case of ^{238}U targets, fission also occurs in the minor constituents, such as ^{235}U and ^{239}Pu .

The abundance of radioactive fission-product isotopes of strontium produced in nuclear fuel and

targets at SRS are shown in Table 2-1. The production of each fission-product isotope was calculated with the SHIELD computer code for "representative" irradiated material. This irradiated material represents the variety of operational parameters used from 1953 to 1988, including composition of fuel and targets, irradiation time, and reactor power level.

The radiostrontium activities in Table 2-1 are shown as a function of time after the end of irradiation to demonstrate that radiostrontium activity levels are significant even after two years of decay.

Other Sources Due to SRS Operations

Small quantities of radiostrontium were produced at SRS by test reactors, spontaneous fission, and neutron activation analysis. The activity levels of radiostrontium from these sources were insignificant when compared to the activity levels in irradiated nuclear fuel and targets. However, the sources are discussed in the following subsections to provide a complete overview of potential radiostrontium releases.

SRS Test Reactors

Several small nuclear reactors were in use at two SRS locations from the 1950s through the 1970s. The Heavy Water Components Test Reactor (HWCTR), located in B Area, was used in the early 1960s to test prototype fuels for a proposed heavy-water-moderated power reactor. The other test reactors, located in M Area, were used from the mid-1950s to the late 1970s. The Process Development Pile and the Lattice Test Reactor were used as zero-power mock-up facilities to test components for the production reactors. The Subcritical Experimental Pile also was used to test component designs. The Standard Pile provided neutrons for experiments such as neutron radiography and neutron activation.

Spontaneous Fission

Spontaneous fission is a radioactive decay mode that occurs in heavy elements, such as uranium, and produces neutrons and fission-product radiostrontium. Spontaneous fission is one of the mechanisms for the production of radiostrontium in nature. ^{238}U is an example of a radionuclide in which spontaneous fission rarely occurs.

Uranium of various isotopic compositions was chemically purified at other DOE facilities in preparation for use at SRS. Because of its relatively long half-life, ^{90}Sr does not reach equilibrium concentration with the ^{238}U in SRS uranium after chemical purification. Approximately 10 half-lives are required to reach 99.9 percent equilibrium. For ^{90}Sr (28-year half-life), this would require nearly 300 years of ingrowth. As a result, ^{90}Sr is present in inconsequential quantities in unirradiated SRS uranium. However, because of the age of the earth, ^{90}Sr does exist in minute quantities in uranium in nature.

^{252}Cf , produced in SRS reactors by the irradiation of ^{244}Cm targets, is a valuable neutron source because it frequently undergoes spontaneous fission. From the mid-1960s until 1987, the Savannah River Technology Center (SRTC, formerly Savannah River Laboratory) fabricated industrial and medical ^{252}Cf sources for offsite use. Some of the sources have been retained at SRS for neutron calibrations in the ^{252}Cf fabrication facility and for two neutron activation facilities. One ^{252}Cf neutron activation facility was operated in M Area in the 1970s. The other has been operational at SRTC since the mid 1970s. Radiostrontium is produced during the spontaneous fission of ^{252}Cf .

Other isotopes of uranium and isotopes of thorium, plutonium, and curium also spontaneously fission. One or more of the materials discussed in this subsection were used in M Area, the reactor areas, the chemical separations areas, the Naval Fuels Facility, TNX Semi-works, or SRTC.

Neutron Activation Analysis

Neutron activation analysis is a technique for measurement of elemental compositions in materials. The ^{252}Cf neutron activation facilities and the C and K production reactors were used for analysis of low levels of ^{129}I and uranium. For example, from the late 1970s to mid-1980s, environmental samples were activated in C Reactor to determine uranium content. Traces of fission-product radiostrontium were produced in the irradiated samples.

Materials Originating Offsite

Certain fuel irradiated at offsite non-commercial facilities were shipped to SRS for reprocessing. While awaiting reprocessing, the fuel was stored in the Receiving Basin for Offsite Fuel (RBOF), located in H Area.

Additional small quantities of ^{89}Sr and ^{90}Sr have been purchased from commercial vendors. The isotopes are used at SRS for experimental purposes, such as chemical yield determination, and instrument calibration. While curie quantities of radiostrontium are present at SRS because of commercial purchases, the amount is insignificant when compared to that produced in fuel and targets in SRS production reactors or in offsite fuel stored in RBOF.

SRS and its vicinity have been subjected to global fallout of man-made radiostrontium since the 1940s. During the era of extensive atmospheric nuclear weapons testing in the 1950s and early 1960s, fallout often was found to be the predominant source of radiostrontium in the SRS vicinity. Additional radiostrontium was deposited in the SRS environment as a result of the 1986 Chernobyl reactor accident in Russia. Environmental radiostrontium is discussed in Chapter 4.

Table 2-1. Inventory of Radiostrontium Produced in "Representative" Material Irradiated in SRS Production Reactors.

Isotope*	Half-Life	Curies remaining at various times after end of irradiation				
		0 sec	24 hrs	100 days	200 days	2 years
^{87m} Sr	2.81 h	6.020x10 ¹	1.616x10 ⁻¹	—	—	—
⁸⁹ Sr	53.21 d	9.080x10 ⁷	8.962x10 ⁷	2.468x10 ⁷	6.707x10 ⁶	6.685x10 ³
⁹⁰ Sr ⁹⁰ Y	28.28 y	2.219x10 ⁶	2.219x10 ⁶	2.204x10 ⁶	2.189x10 ⁶	2.113x10 ⁶
⁹¹ Sr	9.49 h	1.431x10 ⁸	2.479x10 ⁷	—	—	—
⁹² Sr	2.71 h	1.459x10 ⁸	3.149x10 ⁵	—	—	—
⁹³ Sr	7.5 m	1.537x10 ⁸	—	—	—	—
⁹⁴ Sr	75 s	1.456x10 ⁸	—	—	—	—
⁹⁵ Sr	25 s	1.350x10 ⁸	—	—	—	—
⁹⁶ Sr	1.06 s	9.343x10 ⁷	—	—	—	—
⁹⁷ Sr	0.44 s	4.825x10 ⁷	—	—	—	—
⁹⁸ Sr	0.7 s	1.822x10 ⁷	—	—	—	—
⁹⁹ Sr	0.29 s	4.498x10 ⁶	—	—	—	—
¹⁰⁰ Sr	0.2 s	7.823x10 ⁵	—	—	—	—
Totals		9.815x10 ⁸	1.169x10 ⁸	2.688x10 ⁷	8.896x10 ⁶	2.120x10 ⁶

*"m" designates a metastable energy state greater than the ground state of a particular isotope.

Disposition of Radiostrontium at SRS

The principal method for disposing of radiostrontium is containment while radioactive decay occurs. Table 2-1 shows that very short-lived isotopes of strontium produced in SRS reactors decayed to insignificant activity levels shortly after end of irradiation. To describe the disposition of the longer-lived isotopes, the sources of radiostrontium are categorized as follows:

Major sources

- fuel and targets irradiated in production reactors
- certain fuels irradiated offsite

Minor sources

- fuel and targets irradiated in SRS test reactors
- spontaneous fission
- neutron activation samples
- commercially purchased radiostrontium
- global fallout

Radiostrontium In Fuel and Targets Irradiated in Production Reactors

Under normal operating conditions, radiostrontium is contained within the cladding of fuel and target elements during irradiation and cooling. Cooling is the interval between the end of irradiation and the beginning of chemical separations. Irradiated materials are stored underwater in reactor basins for most of this time. Beginning in the 1970s, the cooling time was at least 200 days for most irradiated materials for control of radioiodine emissions. This cooling time reduced the inventory of ^{89}Sr by a factor of about 16 but had relatively little effect on the ^{90}Sr inventory.

Under normal operating conditions, it was possible for very small amounts of radiostrontium to escape from irradiated fuel and target elements to the reactor moderator or to the water in the cooling basins through small defects in the cladding. Air and water were monitored for such releases of radiostrontium. Actual releases are described in greater detail in Chapter 3.

Occasionally, the small defects developed into holes or splits in the cladding. This was called failure of the element. When a failure occurred, the reactor was shut down and the failed element was transferred into a container called a "harp." The harp was stored underwater in the reactor basin and vented to the filtered reactor stack. Failures occurred more frequently in the early years of operation than in later years.

A failed element had the potential to contaminate the moderator with radiostrontium; SRS reactors used heavy water as a moderator. When the moderator and miscellaneous waters were purified using the treatment systems at reactors or the Heavy Water Rework Facility in D Area (Figure 2.1), there was potential for very small quantities of ^{89}Sr and ^{90}Sr to be released. These quantities were not measurable by routine methods.

Water in the reactor cooling basins also had potential to become contaminated with radiostrontium. Beginning in the 1960s, basin water was routinely decontaminated by passing the water through ion exchange resins to remove most of the radionuclides. Spent resins were reworked in the Resin Regeneration Facility in H Area or buried at the Burial Grounds. In 1990 the Burial Grounds were renamed the Solid Waste Disposal Facility (SWDF).

During the cooling period, short-lived radionuclides decayed to insignificant levels; Table 2-1 shows this

for isotopes of strontium. After 200 days of cooling, the ^{89}Sr and ^{90}Sr constituted the only radiostrontium remaining in measurable quantities.

After the cooling period, fuel and targets were processed in the chemical separations areas. The Purex process in F Area recovered ^{239}Pu , ^{237}Np , and ^{238}U from irradiated ^{238}U targets. The Purex process extracts plutonium and uranium into an organic solvent for separation and purification from waste products (Bebbington, 1990). The HM process (H modified Purex process) in H Area recovered ^{235}U and ^{237}Np from irradiated ^{235}U fuel; until 1959, the Purex process was used in H Area. The principal difference is that the HM process uses mercuric nitrate as a catalyst to enhance dissolution of the irradiated fuel. Also in H Area, ^{238}Pu was recovered occasionally from ^{237}Np targets by the Frames process.

During chemical separation, small quantities of strontium are entrained in condensate during the evaporation of aqueous wastes and subsequently discharged to seepage basins. Small quantities of strontium have gotten into the process cooling water streams in both F and H areas as a result of heating- and cooling-coil leaks. While the bulk of this activity was collected in retention basins and subsequently transferred to the seepage basins, some leakage into Fourmile Branch did occur. Radiostrontium was not identified in the activity which seeped through small cracks that developed in some of the high-activity waste tanks and subsequently spilled into the soil underneath the tanks.

Aqueous wastes from the chemical separation processes were evaporated and sent to underground storage tanks for radioactive waste. The evaporator condensate was sent to the separation area seepage basins until November 1988, when use of the seepage basins was terminated. Miscellaneous aqueous wastes were treated periodically by the evaporation process.

Beginning in November 1988, evaporator condensate formerly sent to the F and H area seepage basins was routed to the Effluent Treatment Facility, where it was treated to remove radionuclides and chemicals before being discharged to Upper Three Runs Creek.

High-level liquid wastes generated in SRTC operations were stored in temporary waste tanks, where short-lived radionuclides decayed to insignificant levels. Periodically, the waste tanks' contents were shipped to F Area and processed through the waste system. Solid wastes generated in the SRTC handling operations were allowed to decay to low levels and were buried in the SWDF.

Most of the atmospheric and aqueous effluents in the chemical separation areas and SRTC have been monitored for possible radiostrontium releases. Monitoring techniques and measured releases from the chemical separation areas are described in Chapter 3.

The distributions to the atmosphere, seepage basins, and plant streams had a direct impact on the environment. Stack releases of radiostrontium were of small enough quantities that strontium transported offsite through the atmosphere could not be distinguished from fallout strontium. Waterborne strontium was measurable in Savannah River water (and silt in the tidal estuary at Savannah, GA) in the early- and mid-1960s. Radiostrontium bound in river sediments has been deposited both onsite and in the offsite swamp below the mouth of Steel Creek. Additional amounts of radiostrontium-contaminated sediments are known to exist along the Lower Three Runs Creek stream bed.

Water from the separations area seepage basins migrated downward to shallow groundwater aquifers that outcrop near Fourmile Branch, which flows into the Savannah River. Groundwater transport of strontium from the separation areas seepage basins and the SWDF has been observed and will be discussed in greater detail in Chapter 4. Groundwater migration of ^{90}Sr from the F and H area seepage basins into Fourmile Branch has been quantified since 1968, as shown in Chapter 3.

Radiostrontium in Certain Fuels Irradiated Offsite

Irradiated fuel received from certain offsite facilities is stored underwater in RBOF until it is ready for chemical separation. The fuel then enters the regular process stream in H Area. The disposition of radiostrontium becomes the same as described for fuel irradiated in SRS production reactors.

Radiostrontium in Fuel and Targets Irradiated in Test Reactors

Fuel and targets from the various test reactors were sent primarily to the RBOF for cooling before chemical separation. Some were sent to SRTC for research or to reactor materials fabrication facilities. Reactor

materials fabrication facilities only received fuel or targets that were not irradiated; these materials were blended in during the standard fabrication process for targets and fuel to be used in the production reactors. Because only minute quantities of naturally produced radiostrontium occurred in the fabricated materials, no monitoring for radiostrontium was conducted at fabrication facilities.

Radiostrontium from Spontaneous Fission

Radiostrontium produced by spontaneous fission in thorium, uranium, plutonium, and curium is retained by these elements as long as they remain in solid form. Radiostrontium produced by spontaneous fission in ^{252}Cf is retained as long as the californium remains encapsulated.

Neutron Activation Analysis Samples

Environmental samples were analyzed by high-sensitivity neutron activation for the detection of trace levels of uranium and ^{129}I . Typically, the uranium analysis was nondestructive; therefore, any radiostrontium produced from fission of uranium was not released. The radiostrontium content was minute and the samples were disposed of in the SWDF.

Traces of radiostrontium were retained in various liquids used in the purification steps and stored in the SRTC temporary waste tanks. This waste subsequently was concentrated by evaporation and added to the high-level waste awaiting processing in the DWPF.

Commercially Purchased Radiostrontium

The isotopes ^{89}Sr and ^{90}Sr were purchased from commercial vendors primarily for use as instrument calibration sources. Small quantities were purchased for standardization of counting room instruments in several SRS laboratory facilities. After measurements, the radiostrontium, in solid form, was disposed of as solid radioactive waste. In cases where chemical separation and purification of strontium occurred, the disposition of radiostrontium was similar to that described for neutron activation analysis samples.

Global Fallout Radiostrontium

Most global fallout occurred because of atmospheric nuclear weapon tests and the Chernobyl accident. Global fallout ^{90}Sr was detectable in the SRS vicinity during the 1950s, the 1960s, and the 1970s. A fairly heavy band of fallout ^{90}Sr (60-80 mCi/km²) occurred

in the midlatitudes of the northern hemisphere (including the SRS vicinity) following atmospheric tests in the early 1960s (Eisenbud, 1987). Fallout was not uniformly distributed throughout the terrestrial environment in the SRS vicinity. Such unpredictability in the terrestrial distribution was well-known in the early 1960s (Bruner, 1963).

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Figure 3.1 SRS Facilities that had Potential to Release Strontium

Chapter 3. Releases and Stored Inventories of Radiostrontium at SRS

Routine operations at SRS facilities have released radiostrontium to the regional environment surrounding SRS. The most significant releases occurred during the early years of site operations, when radiostrontium was released to seepage basins and site streams. The greatest releases of radiostrontium originated in the reactor facilities, located near the center of the 800-square-kilometer site. The proximity of these facilities to major streams within the SRS boundary is shown in Figure 3.1, which also shows the location of other facilities having the potential to release radiostrontium.

This chapter presents a discussion on radiostrontium at SRS facilities in terms of possible release pathways, emission control features, and annual releases to the aqueous and atmospheric environments.

The releases that have occurred usually were the result of abnormal operating events, such as fuel failures, cooling-coil leaks, or faulty storage containers. One such event in 1957 was the failure of a fuel tube in the R Area isolation basin. As a result of the failure, the R Area releases for 1957 were approximately 10 curies of ^{90}Sr to Par Pond (vs 0.51 curies released by all other operating areas to site streams) and another 175 curies to the R Area seepage basins (out of a site total of 185 curies released to all seepage basins that year). The combined effects of leaking "harps" (failed fuel element storage containers) and disassembly basin purges directly to streams resulted in chronic releases to streams from 1959 through 1970. The maximum releases occurred in 1960, when 18.4 curies of ^{90}Sr were released to plant streams from the reactor areas. (Area-by-area contributions were L, 8.7 Ci; C, 3.1 Ci; R, 2.8 Ci; K, 2.7 Ci; and P, 1.1 Ci). The R Area release was to

Par Pond, but for purposes of dose assessment, the releases are assumed to be directly to the stream.

Initially, water clarity in the reactor areas' vertical tube storage (VTS) basins was maintained by continuously purging the basins with fresh, filtered river water. In an effort to minimize the release of radioactivity to plant streams, recirculating filters were added. Then, in the early 1970s, sand filters were installed in all the operating reactor areas, and the VTS water was totally recirculated. Because of the buildup of tritium in the VTS basin water, however, periodic purges of the basins were still necessary. These purges were passed through ion exchange beds to remove most of the radioactivity before discharge to the environment. Purges occurred to seepage basins and plant streams. Since 1978, purges have been directed to seepage basins. Radiostrontium releases to site streams since 1973 have resulted primarily from activity migrating in groundwater from seepage basins.

Reactor Facilities

The five production reactors at SRS are identified by the letter designations C, K, L, P, and R. The reactors were designed to irradiate various targets to produce special nuclear materials (principally tritium and plutonium) for national defense purposes. Specific radionuclides for other government purposes also were produced, including ^{238}Pu , which is a power source for certain deep-space missions.

Facility Operations

The reactors became operational in 1953–1955 but have not operated continuously. They have been shut down periodically for maintenance, safety upgrades, or replacement of fuel and targets. In 1992, three reactors are inactive, one is on standby and one is operational.

When a nuclear reactor is operating, nuclear fission reactions occur in the reactor core. The principal components of the core are the fuel, targets, control rods, and moderator. Control rods are neutron-absorbing materials positioned in the core to control the power level of a reactor.

The moderator in SRS reactors is heavy water, which is circulated around the fuel and target elements in the reactor core. The moderator decreases the kinetic energy (slows the speed) of neutrons emitted in the fission process. Slow neutrons have a greater probability than fast neutrons for interaction with fuel and target materials.

The moderator also functions as the primary coolant to remove heat from fuel and target elements. Heat then is transferred from the moderator to the secondary coolant by heat exchangers. SRS reactors

used either river or pond water as the secondary coolant in the heat exchangers.

In reactors that used water from the Savannah River as the secondary coolant, the river water was passed through the shell side of the heat exchanger and discharged to a site stream that flowed back to the Savannah River. When the L Reactor was upgraded and restarted in the 1980s, a cooling lake (L Lake) was constructed to mitigate the thermal impact on Steel Creek. River water was pumped through the L-Area heat exchangers and discharged into L Lake without recirculation. L Lake overflowed into Steel Creek. Reactors that used pond water as the secondary coolant discharged the water from the heat exchanger to a canal that flowed to a series of cooling ponds. Cooled pond water was recirculated through the heat exchanger.

Under normal operating conditions, fuel and target elements were irradiated for a specified time, removed from the reactor core, and stored underwater in the Vertical Tube Storage (VTS) basin of the reactor building. Storage in VTS for the cooling period, which, as of 1988, was at least 200 days, allowed short-lived radionuclides to decay to low levels before reprocessing of the fuel and targets began. After cooling, the elements were moved to the disassembly basin and prepared for transfer to the chemical separation areas.

The abnormal condition of a fuel or target failure is detected by sensors in the reactor core. When a failure occurred, the reactor was shut down and the failed element transferred into a "harp." The harp was stored underwater in the reactor basin and vented to the reactor stack.

Pathways for Release

During normal reactor operations, traces of radiostrontium escaped from irradiated fuel or target elements if a defect developed in the cladding. The defect typically was a micro-scale crack. If a defect developed while the element was in the reactor core, radiostrontium escaped from the irradiated material to the moderator by leaching from the exposed irradiated material.

Some of the exposed uranium and plutonium on failed elements became dispersed in the moderator. After the failed elements were removed and the

reactor restarted, the dispersed uranium and plutonium continued to circulate with the moderator. Neutrons generated during subsequent reactor operation caused fission in any circulating uranium and plutonium, thereby producing small quantities of radiostrontium directly in the moderator. Most of these impurities were removed from the moderator by an on-line ion exchange purification process, which removed most of the uranium, plutonium, and fission products.

Once radiostrontium was in the moderator, it could circulate with the moderator and adsorb onto fuel and target surfaces. Should a leak develop in a heat exchanger tube, some radiostrontium could be released along with primary coolant into the secondary coolant and subsequently be released to the environment. Any radiostrontium released by this pathway was not quantified; however the secondary coolant was monitored for beta-gamma activity. Leakage to the secondary coolant was a minor pathway compared to that released from the tube storage basins. Low operating temperatures of the reactors (below the boiling temperature of heavy water), coupled with very high boiling points for radiostrontium compounds, minimized volatilization of strontium into the blanket gas so that airborne releases of radiostrontium were minimal.

Similar pathways occurred during cooling of irradiated materials in the VTS basin and during subsequent handling of those materials in the disassembly basin. Radiostrontium escaped to basin water from cladding microdefects or by water leaching radiostrontium from the exposed irradiated material in failed elements. Water also leached adsorbed radiostrontium from the exterior surfaces of fuel and targets. Once radiostrontium was in the basin water, it circulated with the water, became trapped in the deionizer, and adsorbed onto fuel and target surfaces. Again, low temperatures and radiostrontium solubility minimized the airborne release of radiostrontium from the VTS.

Continuous purges of the VTS basin water were the primary pathways by which aqueous radiostrontium was released to the environment. As indicated in earlier discussions, VTS basin waters initially were purged directly to site streams to remove the heat generated by the stored irradiated fuel and targets and to maintain clarity in the storage basins. After installation of basin heat exchangers, deionizers, and filters in the 1960s, the volume of purge water decreased significantly, as did the releases of radioactivity.

Periodic purges were performed to eliminate tritium, the accumulation of which resulted in exposure to operating personnel. Purges have been discharged to earthen seepage basins as well as streams. When discharged to streams, the purge water became diluted with much larger volumes of secondary cooling water. Reactor basin discharges to site streams ceased in 1978.

A source of wastewater that had low potential for containing radiostrontium was the reactor process sewer system. This system received cooling water principally from the shell side of heat exchangers for

reactor basins and other miscellaneous process waters. Process sewer water periodically was sampled and analyzed for radionuclides.

Other wastewater was collected in process sumps at the reactor facilities. Occasionally, it contained moderator from leaks that developed during reactor operations or spills that occurred when line breaks were made during maintenance periods. The wastewater was collected and analyzed for radionuclides and moderator content. Possible disposition methods, depending on analysis results, were processing through the Heavy Water Rework Facility or through the waste evaporators in the separation areas or discharging to seepage basins or streams.

The only known mechanism for atmospheric releases of radiostrontium is from resuspension of particulates generated as a result of evaporation of moderator following leaks or spills. Air in the process ventilation system first passed through a HEPA filter designed to remove particulates, such as radiostrontium, then was exhausted to the atmospheric environment from a 60-meter stack. However, during periods when the reactor was shut down for repairs, maintenance, or replacement of fuel and targets, air from reactor building levels that were six and 12 meters below grade elevation was allowed to bypass the filter beds enroute to the stack. This bypass occurred because a large air flow was required to remove tritium from process areas where work was performed. The capacity of the HEPA filters was insufficient to handle an air flow that was two to three times greater than normal for an extended period of time. All the air exiting the building via the stacks, however, is monitored for gross beta-gamma activity, whether or not it passes through the filter compartments. The potential for atmospheric releases of strontium is so small that specific radiochemical analyses for radiostrontium are not performed on the stack air filters.

Direct atmospheric releases of radiostrontium from the VTS basin water are minimal. Occasional minute traces of strontium may be present in air samples as a result of decay of volatile noble gases that escape from failed fuel tubes. The levels are so low that extremely sensitive instruments are required for detection. Radiostrontium is not detectable in routine air sampling.

Because strontium compounds are not readily volatilized, the only source of airborne strontium near the seepage basins is resuspension of strontium-containing dusts that could form in dry basins that earlier had received liquid discharges. The atmospheric concentrations of radiostrontium at these

basins are expected to be less than minimum detectable concentrations because no radiostrontium was typically detected in VTS air, and the water was passed through a deionizer before being purged.

Emission Control

Various measures were implemented to minimize releases of radioactivity. One of these was extensive improvement in the quality of materials fabricated for irradiation. Such improvements minimized the formation of defects in the cladding of fuel and targets.

In the reactor areas, procedural changes were implemented to reduce releases. Provisions were made in 1963 for the recirculation of basin water through heat exchangers to be cooled and deionized for the removal of radionuclides (except tritium), which considerably reduced discharge volumes. Prior to 1963, basin water was purged continuously to site streams. Although the deionizers were effective in removing particulates, permanent sand filters were installed in the late 1960s to maintain water clarity. The residues collected on the sand filters were transported to F Area to be processed and stored in waste tanks. Spent deionizer resin was transported to H Area for regeneration.

Most of the radiostrontium released in the early years of reactor operations originated in failed fuel elements. Failures or suspected failures of elements were detected by reactor core sensors. In 1957, the practice of placing failed elements in "harp" storage containers was implemented.

Under normal operating conditions, moderator and some residual radionuclides adhered to fuel and target surfaces when they were removed from the reactor core. To reduce the adhered radioactivity, flushing of these elements during the discharge process was implemented in the late 1960s. This removed most of the adhered moderator and some residual radionuclides (such as radiostrontium). After flushing, the elements were stored in the VTS. The flush water was collected in drums for treatment in the D-Area Heavy Water Rework facility.

Atmospheric releases were minimized by the use of a confinement system intended not only for routine

operations but for a reactor incident. The system consists of a demister filter bank, a particulate HEPA filter bank, and a carbon filter bank to remove radioiodine.

Release Monitoring

Reactor stack air has been continuously sampled for particulate radioactivity. Because of the very low level of airborne radiostrontium in the reactor exhaust air, specific analyses for these radionuclides were not performed.

Several techniques were used to monitor aqueous releases. Cooling water was monitored for beta-gamma activity, and specific radiochemical analyses for radiostrontium have been performed. Basin purge water has been analyzed routinely in the laboratory for total radiostrontium since the mid-1950s. Recounting the samples after ingrowth of ^{90}Y permits determination of both ^{89}Sr and ^{90}Sr from the same analysis.

History of Measured Releases

Aqueous releases from each reactor have decreased significantly over the years of operation. Typically, less than one percent of the total aqueous releases of ^{90}Sr from a given reactor occurred after recirculation of VTS basin water through sand filters began in the 1970s.

In terms of annual releases to streams, the stream transport of ^{90}Sr decreased slowly from about 1.7 curies in 1973 to 0.2 curies in 1989. The rapid decline in releases from VTS basins was offset somewhat by increases in the migration rate of ^{90}Sr from seepage basins, as shown in Figure 3.2. Most of the migrating ^{90}Sr originated in the separations areas. Atmospheric releases, small to begin with, did not experience the multiple order-of-magnitude decreases that characterized the aqueous releases.

The greatest measured aqueous releases of ^{90}Sr from reactors occurred during the period 1957 through 1970. These releases typically were associated with failures of irradiated fuel elements in the reactor core.

Figure 3.2 Seepage Basin Migration Contribution to Total ^{90}Sr Stream Releases

C Reactor

C Reactor was operational from 1955 until it was shut down for extensive maintenance in 1985; it was placed in standby mode in 1987. Reactor basin purges were discharged into Fourmile Branch and three seepage basins, designated 904-66G, -67G, and -68G. The seepage basins were used from 1959 to 1970 and again from 1978 through 1984. Gross beta releases to

Figure 3.3 Gross Beta Releases to Atmosphere, C Area

atmosphere from C area are shown in Figure 3.3 and Table 3-1. Releases to streams and seepage basins from C area are summarized in Figures 3.4 and 3.5 and Table 3-2.

The total measured aqueous release of radiostrontium from C Reactor to Fourmile Branch during the reactor's operational lifetime was 13.04 curies of ^{89}Sr and 11.40 curies of ^{90}Sr . Cumulative releases to seepage basins totaled 0.031 curies of ^{89}Sr and 0.45 curies of ^{90}Sr . The greatest annual release of ^{90}Sr to Fourmile Branch, 3.12 curies, occurred in 1960. The greatest annual release of ^{89}Sr to Fourmile Branch, 2.59 curies, occurred in 1970. Annual releases of ^{90}Sr in excess of 1 curie occurred only twice during the period 1959 through 1971 (1960 and 1970). Annual releases of ^{89}Sr in excess of 1 curie occurred on five different occasions during the same period of time (1961, 1967, 1968, 1970, and 1971). Discharges of treated liquid purges of the VTS basins have been directed to the seepage basins since 1982.

K Reactor

K Reactor was operational from 1954 until the 1988 shutdown. Reactor cooling basin purges were discharged to Pen Branch and to two earthen basins outside the building — one designated 904-65G and the other designated 904-88G. Because basin 904-65G had poor seepage characteristics, it received disassembly basin purges only in 1959 and 1965. Basin 904-88G was used to receive disassembly basin

Figure 3.4 Strontium Releases to Streams, C Area

Figure 3.5 Strontium Releases to Seepage Basins, C Area

purges and occasional miscellaneous wastewater discharges from 1965 through 1989.

The total measured aqueous release of radiostrontium to Pen Branch from K Reactor through 1989 was 45.6 curies of ^{89}Sr and 11.30 curies of ^{90}Sr . Releases from K Area to seepage basins were 84.9 curies of ^{89}Sr and 6.8 curies of ^{90}Sr . Measured atmospheric release of gross beta activity from K Area is shown in Figure 3.6 and Table 3-1. Measured annual aqueous releases of radiostrontium to streams and seepage

Figure 3.6 Gross Beta Releases to Atmosphere, K Area

basins are shown in Figure 3.7, Figure 3.8, and Table 3-3. The maximum annual ^{90}Sr release to Pen Branch, 2.65 curies, occurred in 1960; the maximum annual ^{89}Sr release to streams was 23.9 curies in 1968. Maximum annual release to seepage basins amounted to 45.6 curies of ^{89}Sr in 1969 and 3.6 curies of ^{90}Sr in the same year. Releases of ^{90}Sr in excess of 1 Ci/yr to Pen Branch occurred five times during the period 1954 through 1989 (1960, 1962, 1963, 1967, and 1968). Migration of ^{90}Sr from the K Area seepage basins was small but detectable (1.1×10^{-5} curies) in 1989.

Figure 3.7 Strontium Releases to Streams, K Area

Figure 3.8 Strontium Releases to Seepage Basins, K Area

L Reactor

L Reactor was operational from 1954 to 1968, when it was placed in standby. It was refurbished beginning in the early 1980s, restarted in 1985, and operated until the 1988 shutdown. L Lake was constructed by damming Steel Creek in the early 1980s to provide thermal mitigation of secondary cooling water from the restarted reactor's heat exchanger. Therefore, during L Reactor's second operational period, secondary cooling water from the reactor heat exchanger was discharged to L Lake, which drains into Steel Creek.

Reactor basin purges were discharged to Steel Creek, L Lake, and a seepage basin designated 904-64G. The seepage basin was used intermittently in 1958, 1959, 1961 to 1965, 1967 to 1969, and 1985 through 1989. The L Area Oil and Chemical Basin (904-83G) was used from 1961 to 1979 to receive wastewater containing various oils and chemicals from all the reactor areas. It is adjacent to the 904-64G seepage basin.

The total measured aqueous release of radiostrontium from L Reactor through 1989 was 100 curies of ^{89}Sr and 22 curies of ^{90}Sr to Steel Creek. An additional 4 mCi of ^{89}Sr and 2.2 curies of ^{90}Sr was released to the L Area seepage basins. Measured annual release of gross beta activity from L Area to the atmosphere is shown in Figure 3.9 and Table 3-1. Measured annual aqueous release of radiostrontium

Figure 3.9 Gross Beta Releases to Atmosphere, L Area

from L Area are shown in Figures 3.10, Figure 3.11, and Table 3-4. The greatest annual release to Steel Creek was 57.9 curies of ^{89}Sr in 1964 and 8.74 curies of ^{90}Sr in 1960. Releases of ^{90}Sr in excess of 1 Ci/yr occurred six times during the period 1954 through 1970 (1960, 1963, 1964, 1965, 1966, and 1967). In its second operational period, aqueous radiostrontium was not discharged directly to Steel Creek.

P Reactor

P Reactor was operational from 1954 until the 1988 shutdown. Reactor basin purges were discharged to Steel Creek and Par Pond during 1954 to 1956, 1969, and 1971 to 1977 and to three seepage basins during 1957 to 1968, 1970, and 1978 through 1989. The seepage basins have designations 904-61G, -62G, and -63G. Reactor cooling water and miscellaneous effluents were discharged to Steel Creek until 1963; most of the cooling water was later diverted to Par Pond. When L Lake was constructed in the mid-1980s, all aqueous effluents were diverted to Par Pond.

The total measured stream release of radiostrontium from P Reactor through 1989 was 31.85 curies of ^{89}Sr and 18.88 curies of ^{90}Sr to the Steel Creek/Par Pond system. An Additional 9.1 millicuries of ^{89}Sr and 4.74 curies of ^{90}Sr were released to seepage basins. Measured annual release of gross beta activity to the atmosphere from P Area is shown in Figure 3.12 and Table 3-1. Measured annual aqueous release of radiostrontium is shown in Figures 3.13, Figure 3.14, and Table 3-5. The greatest annual releases to Steel Creek were 10.1 curies of ^{89}Sr in 1962 and

Figure 3.10 Strontium Releases to Streams, L Area

Table 3-1. Gross Beta Releases From Reactor Areas and SRTC to Atmosphere by Year (Curies)

Year	C Area Fig 3.3	K Area Fig 3.6	L Area Fig 3.9	P Area Fig 3.12	R area Fig 3.15	SRTC Fig 3.24
1954	—	—	—	—	—	—
1955	—	—	—	—	—	—
1956	—	—	—	—	—	—
1957	—	—	—	—	—	—
1958	—	—	—	—	—	1.00×10^{-2}
1959	—	—	—	—	—	4.90×10^{-1}
1960	1.00×10^{-3}	1.83×10^{-3}	3.70×10^{-4}	2.10×10^{-4}	3.00×10^{-4}	8.00×10^{-2}
1961	1.25×10^{-3}	1.70×10^{-3}	2.27×10^{-3}	1.75×10^{-3}	1.20×10^{-3}	9.00×10^{-2}
1962	5.00×10^{-3}	4.00×10^{-3}	1.00×10^{-2}	6.90×10^{-2}	5.00×10^{-3}	2.20×10^{-1}
1963	9.30×10^{-3}	9.69×10^{-2}	6.60×10^{-3}	1.30×10^{-3}	4.50×10^{-3}	1.84×10^{-1}
1964	1.90×10^{-3}	1.40×10^{-3}	4.40×10^{-3}	1.00×10^{-3}	7.00×10^{-4}	5.21×10^{-2}
1965	4.00×10^{-4}	8.00×10^{-4}	2.80×10^{-3}	2.50×10^{-3}	—	8.69×10^{-2}
1966	1.30×10^{-3}	5.00×10^{-4}	5.10×10^{-3}	9.00×10^{-4}	—	5.10×10^{-3}
1967	3.00×10^{-5}	2.10×10^{-4}	9.60×10^{-4}	1.30×10^{-5}	—	1.24×10^{-2}
1968	5.10×10^{-4}	7.64×10^{-4}	1.14×10^{-4}	1.12×10^{-3}	—	1.60×10^{-3}
1969	3.35×10^{-4}	4.56×10^{-4}	—	3.75×10^{-4}	—	1.03×10^{-2}
1970	2.00×10^{-4}	1.45×10^{-4}	—	3.18×10^{-4}	—	5.86×10^{-3}
1971	3.00×10^{-5}	5.00×10^{-5}	—	6.00×10^{-5}	—	1.41×10^{-3}
1972	6.00×10^{-5}	1.94×10^{-4}	—	9.10×10^{-5}	—	6.70×10^{-4}
1973	1.41×10^{-4}	2.86×10^{-4}	—	1.32×10^{-4}	—	7.00×10^{-6}
1974	8.80×10^{-5}	9.90×10^{-5}	—	5.80×10^{-5}	—	3.50×10^{-5}
1975	1.00×10^{-4}	1.21×10^{-4}	—	1.23×10^{-4}	—	3.10×10^{-5}
1976	4.21×10^{-4}	1.28×10^{-4}	—	1.39×10^{-4}	—	2.30×10^{-5}
1977	1.81×10^{-4}	1.78×10^{-4}	—	1.09×10^{-4}	—	7.00×10^{-6}
1978	5.50×10^{-5}	6.60×10^{-5}	—	2.70×10^{-5}	—	—
1979	5.60×10^{-5}	6.50×10^{-5}	—	3.90×10^{-5}	—	—
1980	9.46×10^{-4}	3.03×10^{-4}	—	1.70×10^{-4}	—	3.60×10^{-5}
1981	3.33×10^{-4}	4.19×10^{-4}	—	1.53×10^{-4}	—	1.00×10^{-5}
1982	5.50×10^{-5}	1.86×10^{-4}	3.64×10^{-4}	2.60×10^{-5}	—	1.90×10^{-5}
1983	4.90×10^{-5}	1.51×10^{-3}	2.40×10^{-5}	2.70×10^{-5}	—	1.85×10^{-4}
1984	1.66×10^{-4}	1.38×10^{-4}	1.00×10^{-6}	7.40×10^{-5}	—	5.10×10^{-5}
1985	1.20×10^{-4}	1.70×10^{-4}	9.00×10^{-6}	1.11×10^{-5}	—	1.60×10^{-5}
1986	6.90×10^{-5}	4.55×10^{-4}	3.30×10^{-5}	3.82×10^{-4}	—	2.60×10^{-5}
1987	1.68×10^{-4}	1.93×10^{-4}	4.50×10^{-5}	4.50×10^{-5}	—	3.20×10^{-5}
1988	1.62×10^{-4}	1.11×10^{-3}	3.66×10^{-4}	3.66×10^{-4}	—	3.40×10^{-5}
1989	3.00×10^{-6}	1.00×10^{-4}	1.02×10^{-4}	1.02×10^{-4}	—	1.00×10^{-6}

— Denotes No Data Available

2.34 curies of ^{90}Sr in 1968. Releases of ^{90}Sr in excess of 1 Ci/yr occurred in 1960 and every year from 1962 through 1970. Migration of ^{90}Sr in groundwater from the seepage basins to streams has been observed via groundwater outcropping since 1987. The maximum measured annual release via migration was 0.64 mCi in 1989.

Figure 3.11 ^{90}Sr Releases to Seepage Basins, L Area

Figure 3.12 Gross Beta Releases to Atmosphere, P Area

Figure 3.13 Strontium Releases to Streams, P Area

R Reactor

R Reactor was the first operational production reactor at SRS. It operated from late 1953 until 1964, when it was placed on inactive status. Reactor basin water was discharged into Lower Three Runs Creek from 1954 to 1958, into Par Pond from 1958 to 1964, and into a seepage basin system from 1957 to 1964. R Reactor had six seepage basins, designated 904-103G, -104G, -57G, -58G, -59G, and -60G.

Figure 3.14 Strontium Releases to Seepage Basins, P Area.

The original seepage basin, 904-103G, was used only from June to December 1957. Use of this basin was terminated because of surface outcropping and from leakage into an abandoned sewer. The basin was backfilled in 1958. Basins 904-104G, -57G, -58G, and -59G—in use from 1957 to 1960—were deactivated, backfilled, and covered with asphalt in 1960. Basin 904-60G—in use from 1958 to 1964—was backfilled in 1977.

Reactor heat-exchanger cooling water and miscellaneous effluents were discharged to Lower Three Runs Creek from 1954 to 1958. After 1958, these effluents were discharged to Par Pond, which was constructed by the damming of Lower Three Runs Creek. Initially, R-Reactor effluents were discharged directly to Par Pond. Beginning in 1961, a canal and pond system that eventually drained into Par Pond (Figure 3.1) replaced direct discharges into Par Pond.

The total measured release of radiostrontium from R Reactor to the Par Pond-Lower Three Runs system during its operational lifetime was 25.8 curies of ^{89}Sr and 26.6 curies of ^{90}Sr . An additional 200 curies of ^{90}Sr was discharged to seepage basins. Most of the strontium releases to streams went into Par Pond. Measured annual releases of gross beta activity from R Area to atmosphere is shown in Figure 3.15 and Table 3-1. Measured aqueous release of radiostrontium from R Reactor is shown in Figures 3.16, 3.17, and Table 3-6. The maximum annual release of 175 curies of ^{90}Sr to the

seepage basins occurred in 1957 following the failure of an experimental fuel tube in the VTS Isolation Basin. A total of 10.4 curies of ^{90}Sr was released to Par Pond in 1957 as a result of the same incident.

Summary of Reactor Releases

The total measured aqueous release of radiostrontium from reactor areas through 1989 was 301 curies of ^{89}Sr and 327 curies of ^{90}Sr . This consisted of 216 curies of ^{89}Sr and 90 curies of ^{90}Sr to site streams and ponds and 85 curies of ^{89}Sr and 237 curies of ^{90}Sr to seepage basins.

Figure 3.16 Strontium Releases to Streams, R Area

Figure 3.15 Gross Beta Releases to Atmosphere, R Area

Figure 3.17 ^{90}Sr Releases to Seepage Basins, R Area

Table 3-2. Radiostrontium Releases from C Area and SRTC by Year (Curies)

<u>Year</u>	⁸⁹ Sr <u>C Stream</u> Fig 3.4	⁹⁰ Sr <u>C Stream</u> Fig 3.4	⁸⁹ Sr <u>C Basin</u> Fig 3.5	⁹⁰ Sr <u>C Basin</u> Fig 3.5	^{89, 90} Sr <u>SRTC Basin</u> Fig 3.25
1954	—	—	—	—	—
1955	—	1.690x10 ⁻²	—	—	—
1956	—	1.560x10 ⁻²	—	—	—
1957	—	2.860x10 ⁻²	—	—	—
1958	—	5.330x10 ⁻²	—	—	—
1959	—	6.006x10 ⁻¹	—	1.911x10 ⁻¹	—
1960	—	3.120x10 ⁻¹	—	8.550x10 ⁻²	—
1961	1.310x10 ⁰	6.300x10 ⁻¹	—	2.600x10 ⁻²	—
1962	—	5.400x10 ⁻¹	—	5.070x10 ⁻³	—
1963	3.200x10 ⁻¹	8.200x10 ⁻¹	—	6.370x10 ⁻²	—
1964	6.900x10 ⁻¹	3.500x10 ⁻¹	—	2.000x10 ⁻²	—
1965	7.900x10 ⁻¹	2.800x10 ⁻¹	—	8.000x10 ⁻³	4.630x10 ⁻²
1966	9.600x10 ⁻¹	2.900x10 ⁻¹	—	2.000x10 ⁻²	7.100x10 ⁻³
1967	1.940x10 ⁰	5.600x10 ⁻¹	—	2.000x10 ⁻³	1.810x10 ⁻²
1968	2.120x10 ⁰	8.700x10 ⁻¹	—	3.000x10 ⁻²	1.070x10 ⁻²
1969	7.700x10 ⁻¹	8.000x10 ⁻¹	3.000x10 ⁻²	—	6.800x10 ⁻³
1970	2.590x10 ⁰	1.520x10 ⁰	—	—	8.430x10 ⁻³
1971	1.240x10 ⁰	7.800x10 ⁻¹	—	—	1.350x10 ⁻³
1972	8.000x10 ⁻²	4.000x10 ⁻²	—	—	4.600x10 ⁻⁴
1973	7.600x10 ⁻²	5.000x10 ⁻³	—	—	1.110x10 ⁻²
1974	1.420x10 ⁻¹	7.900x10 ⁻²	—	—	7.800x10 ⁻⁴
1975	7.000x10 ⁻³	—	—	—	6.800x10 ⁻⁴
1976	1.000x10 ⁻³	1.000x10 ⁻³	—	—	2.620x10 ⁻⁴
1977	1.099x10 ⁻³	1.231x10 ⁻³	—	—	6.600x10 ⁻⁵
1978	—	1.841x10 ⁻⁵	—	—	2.244x10 ⁻⁴
1979	—	—	1.560x10 ⁻⁴	8.700x10 ⁻⁴	8.600x10 ⁻⁵
1980	—	—	—	—	9.300x10 ⁻⁵
1981	—	1.600x10 ⁻⁵	—	—	1.260x10 ⁻⁴
1982	—	—	1.165x10 ⁻⁴	4.160x10 ⁻⁴	—
1983	—	—	5.520x10 ⁻⁴	2.458x10 ⁻³	—
1984	—	—	1.490x10 ⁻⁴	2.110x10 ⁻⁴	—
1985	—	—	3.600x10 ⁻⁵	5.300x10 ⁻⁵	—
1986	—	—	5.281x10 ⁻⁵	1.033x10 ⁻⁵	—
1987	—	—	—	—	—
1988	—	—	—	—	—
1989	—	1.300x10 ⁻⁵	—	—	—

— Denotes No Data Available

Table 3-3. Radiostrontium Releases from K Area by Year (Curies)

Year	⁸⁹ Sr To Stream Fig 3.7	⁹⁰ Sr To Stream Fig 3.7	⁹⁰ Sr Migration From Basin	⁸⁹ Sr To Basin Fig 3.8	⁹⁰ Sr To Basin Fig 3.8
1954	—	—	—	—	—
1955	—	1.430x10 ⁻²	—	—	—
1956	—	3.120x10 ⁻²	—	—	—
1957	—	8.450x10 ⁻²	—	—	—
1958	—	4.003x10 ⁻²	—	—	—
1959	—	2.496x10 ⁻¹	—	—	2.600x10 ⁻²
1960	—	2.650x10 ⁰	—	—	4.030x10 ⁻³
1961	6.360x10 ⁰	6.700x10 ⁻¹	—	—	—
1962	1.900x10 ⁰	1.220x10 ⁰	—	—	—
1963	9.700x10 ⁻¹	1.190x10 ⁰	—	—	—
1964	7.000x10 ⁻¹	7.000x10 ⁻¹	—	—	—
1965	3.470x10 ⁰	6.900x10 ⁻¹	—	—	1.200x10 ⁻³
1966	5.300x10 ⁻¹	5.400x10 ⁻¹	—	—	—
1967	4.710x10 ⁰	1.010x10 ⁰	—	—	—
1968	2.388x10 ¹	1.300x10 ⁰	—	—	1.270x10 ⁰
1969	1.310x10 ⁰	4.200x10 ⁻¹	—	4.561x10 ¹	3.610x10 ⁰
1970	9.700x10 ⁻¹	1.500x10 ⁻¹	—	3.844x10 ¹	1.630x10 ⁰
1971	2.800x10 ⁻¹	1.100x10 ⁻¹	—	4.800x10 ⁻¹	1.500x10 ⁻¹
1972	2.400x10 ⁻¹	9.000x10 ⁻²	—	2.800x10 ⁻¹	3.000x10 ⁻²
1973	3.800x10 ⁻²	3.000x10 ⁻³	—	2.000x10 ⁻²	5.000x10 ⁻³
1974	—	—	—	1.600x10 ⁻²	1.000x10 ⁻³
1975	6.000x10 ⁻³	1.060x10 ⁻³	—	1.000x10 ⁻³	—
1976	—	—	—	1.300x10 ⁻²	7.000x10 ⁻³
1977	2.250x10 ⁻¹	2.504x10 ⁻²	—	5.620x10 ⁻⁴	2.170x10 ⁻⁴
1978	—	1.062x10 ⁻⁶	—	3.202x10 ⁻⁴	1.952x10 ⁻⁴
1979	—	—	—	—	1.700x10 ⁻⁴
1980	—	1.410x10 ⁻³	—	—	—
1981	—	—	—	—	—
1982	—	—	—	—	9.360x10 ⁻⁴
1983	—	—	—	1.013x10 ⁻⁵	1.013x10 ⁻⁵
1984	—	—	—	2.140x10 ⁻⁴	8.200x10 ⁻⁵
1985	—	—	—	1.390x10 ⁻⁴	4.570x10 ⁻⁴
1986	—	5.460x10 ⁻³	—	4.180x10 ⁻⁴	—
1987	—	—	—	7.691x10 ⁻⁴	1.434x10 ⁻³
1988	—	—	—	1.559x10 ⁻³	1.871x10 ⁻³
1989	—	8.810x10 ⁻⁴	1.100x10 ⁻⁵	—	1.100x10 ⁻⁴

— Denotes No Data Available

Table 3-4. Radiostrontium Releases from L Area by Year (Curies)

<u>Year</u>	⁸⁹ Sr <u>To Stream</u> Fig 3.10	⁹⁰ Sr <u>To Stream</u> Fig 3.10	⁸⁹ Sr <u>To Basin</u> Fig 3.11	⁹⁰ Sr <u>To Basin</u> Fig 3.11
1954	—	—	—	—
1955	—	3.640x10 ⁻²	—	—
1956	—	6.500x10 ⁻²	—	—
1957	—	1.547x10 ⁻¹	—	—
1958	—	1.378x10 ⁻¹	—	4.030x10 ⁻²
1959	—	3.458x10 ⁻¹	—	5.200x10 ⁻³
1960	—	8.740x10 ⁰	—	7.150x10 ⁻³
1961	2.800x10 ⁰	9.000x10 ⁻¹	—	3.422x10 ⁻²
1962	2.110x10 ¹	8.800x10 ⁻¹	—	2.747x10 ⁻²
1963	6.290x10 ⁰	1.290x10 ⁰	—	3.861x10 ⁻¹
1964	5.794x10 ¹	3.030x10 ⁰	—	1.280x10 ⁰
1965	2.620x10 ⁰	1.730x10 ⁰	—	4.100x10 ⁻²
1966	4.030x10 ⁰	1.820x10 ⁰	—	2.000x10 ⁻²
1967	4.370x10 ⁰	1.520x10 ⁰	—	2.260x10 ⁻¹
1968	6.600x10 ⁻¹	6.900x10 ⁻¹	—	9.100x10 ⁻²
1969	2.300x10 ⁻¹	5.900x10 ⁻¹	1.000x10 ⁻³	—
1970	6.000x10 ⁻²	7.000x10 ⁻²	1.000x10 ⁻³	—
1971	—	—	—	3.000x10 ⁻⁴
1972	—	—	—	—
1973	—	—	—	—
1974	—	—	—	—
1975	—	—	2.000x10 ⁻³	1.000x10 ⁻³
1976	—	—	—	—
1977	—	—	—	2.400x10 ⁻⁴
1978	—	—	—	1.521x10 ⁻⁵
1979	—	—	—	1.300x10 ⁻⁵
1980	—	—	—	—
1981	—	1.236x10 ⁻²	—	—
1982	—	2.130x10 ⁻⁴	—	—
1983	—	4.200x10 ⁻⁵	—	—
1984	—	1.000x10 ⁻⁶	—	—
1985	—	1.800x10 ⁻⁵	3.000x10 ⁻⁶	—
1986	—	—	—	—
1987	—	—	—	—
1988	—	—	—	—
1989	—	4.000x10 ⁻⁶	—	—

— Denotes No Data Available

Table 3-5. Radiostrontium Releases from P Area by Year (Curies)

Year	⁸⁹ Sr To Stream Fig 3.13	⁹⁰ Sr To Stream Fig 3.13	⁹⁰ Sr Migration From Basin Fig 3.13	⁸⁹ Sr To Basin Fig 3.14	⁹⁰ Sr To Basin Fig 3.14
1954	—	—	—	—	—
1955	—	3.640x10 ⁻²	—	—	—
1956	—	8.450x10 ⁻²	—	—	—
1957	—	2.444x10 ⁻¹	—	—	4.160x10 ⁻²
1958	—	1.157x10 ⁻¹	—	—	1.300x10 ⁻³
1959	—	1.560x10 ⁻¹	—	—	4.200x10 ⁰
1960	—	1.120x10 ⁰	—	—	2.004x10 ⁻¹
1961	5.000x10 ⁻²	9.100x10 ⁻¹	—	—	4.303x10 ⁻²
1962	1.008x10 ¹	2.070x10 ⁰	—	—	1.937x10 ⁻²
1963	4.190x10 ⁰	1.220x10 ⁰	—	—	3.900x10 ⁻²
1964	8.200x10 ⁻¹	2.090x10 ⁰	—	—	3.000x10 ⁻²
1965	—	2.270x10 ⁰	—	—	3.000x10 ⁻³
1966	5.700x10 ⁻¹	1.670x10 ⁰	—	—	—
1967	1.980x10 ⁰	1.490x10 ⁰	—	—	—
1968	2.380x10 ⁰	2.340x10 ⁰	—	—	1.600x10 ⁻³
1969	6.514x10 ⁰	1.520x10 ⁰	—	—	—
1970	4.700x10 ⁰	1.160x10 ⁰	—	—	—
1971	3.805x10 ⁻¹	2.600x10 ⁻¹	—	—	—
1972	1.300x10 ⁻¹	9.000x10 ⁻²	—	—	—
1973	4.300x10 ⁻²	7.000x10 ⁻³	—	—	—
1974	4.000x10 ⁻³	2.400x10 ⁻²	—	—	—
1975	1.000x10 ⁻³	—	—	—	—
1976	3.000x10 ⁻³	—	—	—	—
1977	1.637x10 ⁻³	1.500x10 ⁻⁵	—	—	—
1978	—	—	—	—	—
1979	—	—	—	—	—
1980	—	—	—	—	—
1981	—	—	—	—	6.300x10 ⁻⁵
1982	—	—	—	3.323x10 ⁻³	—
1983	—	—	—	7.119x10 ⁻⁴	1.150x10 ⁻⁴
1984	—	—	—	1.081x10 ⁻³	1.442x10 ⁻³
1985	—	—	—	2.576x10 ⁻³	1.060x10 ⁻⁴
1986	—	—	—	2.133x10 ⁻⁴	6.918x10 ⁻⁴
1987	—	—	1.510x10 ⁻⁴	1.193x10 ⁻³	5.896x10 ⁻⁴
1988	—	—	1.100x10 ⁻⁴	9.960x10 ⁻⁶	9.111x10 ⁻⁶
1989	—	—	6.444x10 ⁻⁴	—	3.800x10 ⁻⁵

— Denotes No Data Available

Table 3-6 Radiostrontium Releases from R Area, D Area and CS by Year (Curies)

Year	⁸⁹Sr R Area To Stream Fig 3.16	⁹⁰Sr R Area To Stream Fig 3.16	⁹⁰Sr R Area To Basin Fig 3.17	^{89,90}Sr DArea To Stream Fig 3.26	^{89,90}Sr CS Basin Fig 3.27	⁹⁰Sr CS Basin Fig 3.27
1954	—	3.900x10 ⁻²	—	—	—	—
1955	—	4.160x10 ⁻²	—	—	—	—
1956	—	1.976x10 ⁻¹	—	—	—	—
1957	—	1.041x10 ¹	1.750x10 ²	—	—	—
1958	—	3.510x10 ⁻¹	1.200x10 ¹	—	—	—
1959	—	3.679x10 ⁻¹	1.300x10 ¹	—	—	—
1960	—	2.790x10 ⁰	—	—	—	—
1961	8.500x10 ⁻¹	1.130x10 ⁰	—	—	—	—
1962	1.200x10 ⁰	1.850x10 ⁰	1.040x10 ⁻³	—	—	—
1963	2.194x10 ¹	5.990x10 ⁰	1.300x10 ⁻³	—	—	—
1964	1.840x10 ⁰	3.400x10 ⁰	5.400x10 ⁻³	—	—	—
1965	—	—	—	—	—	—
1966	—	—	—	—	—	—
1967	—	—	—	—	—	—
1968	—	—	—	2.000x10 ⁻²	—	—
1969	—	—	—	1.000x10 ⁻²	—	—
1970	—	—	—	8.000x10 ⁻³	—	—
1971	—	—	—	1.600x10 ⁻²	—	—
1972	—	—	—	—	—	—
1973	—	—	—	6.200x10 ⁻⁴	—	—
1974	—	—	—	3.800x10 ⁻⁴	—	—
1975	—	—	—	4.930x10 ⁻⁴	—	—
1976	—	—	—	2.765x10 ⁻³	—	—
1977	—	—	—	1.490x10 ⁻⁴	4.000x10 ⁻⁶	—
1978	—	—	—	1.800x10 ⁻⁴	—	—
1979	—	—	—	8.900x10 ⁻⁵	—	—
1980	—	—	—	9.900x10 ⁻⁵	—	—
1981	—	—	—	—	—	—
1982	—	—	—	—	—	4.000x10 ⁻⁵
1983	—	—	—	—	—	3.400x10 ⁻⁵
1984	—	—	—	—	—	—
1985	—	—	—	—	—	—
1986	—	—	—	—	—	—
1987	—	—	—	—	—	—
1988	—	—	—	—	—	—
1989	—	—	—	8.450x10 ⁻⁴	—	—

— Denotes No Data Available

Separation and Liquid Waste Facilities

Two chemical separation facilities and their associated liquid-waste storage facilities are located near the center of the site (Figure 3.1). The two separation areas are identified by letter designations F and H. In these areas the products of interest from reactor irradiation are chemically separated and purified from waste products.

Facility Operations

The two chemical separation facilities were used to reprocess irradiated fuel and targets in canyon buildings (221-F and 221-H). Irradiated materials were dissolved and the products of interest chemically separated and purified from waste fission and activation products. Occasional special campaigns for production of radionuclides such as ^{238}Pu and ^{252}Cf have occurred.

Beginning in late 1954, ^{239}Pu , ^{237}Np , and ^{238}U generally were recovered from irradiated ^{238}U targets in F Area, which used the Purex chemical extraction process. In H Area, ^{239}Pu and ^{238}U also were recovered from ^{238}U targets by the Purex process during 1955 to 1959. The H-Area facility then was modified to recover ^{235}U from irradiated enriched uranium fuel. A further modification in 1963 allowed the recovery of ^{237}Np from the fuel; the HM process (H Modified Purex) was used for chemical extraction of the uranium. Also in H Area, the Frames process was used occasionally to recover ^{238}Pu and ^{237}Np from special target elements. This process used ion exchange for separation and purification.

Waste facilities in or adjacent to the separation facilities were designed for liquid-waste handling. Depending on activity level, liquid waste was stored in waste tanks or sent to seepage basins or the Effluent Treatment Facility (ETF). In November 1988, the ETF became operational to treat waste that previously was sent to seepage basins which were closed in 1988 and have been decommissioned.

Pathways for Release

Unlike the reactor facilities, which has released ^{89}Sr and ^{90}Sr to the environment almost exclusively through aqueous effluents, the separations facilities

have released radiostrontium through atmospheric and aqueous effluents. While the aqueous releases from separation facilities has been primarily to seepage basins, some radiostrontium was released to Fourmile Branch from leaks in cooling water lines and spills in the waste storage areas. Atmospheric releases of strontium have occurred from both canyon building stacks.

Aqueous release occurred when residual radiostrontium was present in high- and low-level aqueous waste streams. Before this waste was stored in tanks, an evaporation process was used to reduce the volume. During evaporation, part of the radiostrontium distilled with the condensate in the evaporators. This condensate was sent to the seepage basins prior to 1988. After 1988, the condensate was sent to ETF. Occasional leaks in cooling-water coils in separations process vessels released small quantities of radioactivity to Fourmile Branch. Strontium, poorly retained in SRS soils, is subject to migration in groundwater. Soil retention and distance to flowing streams have delayed the movement of ^{89}Sr long enough to permit decay to background levels, but groundwater migration of ^{90}Sr has been measured from the separations areas seepage basins since 1968. While the rate of migration into streams has been declining (Figure 3.2, Table 3-7, and Table 3-8), the groundwater pathway was the greatest source of ^{90}Sr releases to streams during the period 1973 through 1989.

The disposition of various process waters from the separation facilities depended on the results of the analysis of the water for radioactivity. Water concentrated in evaporators prior to storage, was sent to seepage basins, to the ETF, temporarily retained in basins, or released to site streams.

The major source of wastewater previously discharged to the seepage basins was the overheads from the nitric acid recovery unit and the process evaporators in F and H areas. In H Area, water from the Resin Regeneration Facility and RBOF also were discharged to the seepage basin system. A flow sheet for liquid waste handling can be found in the reference Jacobsen et al., 1973. Because of this reference's date, replacement of the seepage basins with ETF is not shown.

Table 3-7. Radiostrontium Releases from F Area by Year (Curies)

<u>Year</u>	^{89, 90} Sr <u>Atmosphere</u>	⁹⁰ Sr <u>To Stream</u>	⁹⁰ Sr <u>Migration From Basin</u>	⁸⁹ Sr <u>To Basin</u>	⁹⁰ Sr <u>To Basin</u>
	Fig 3.19	Fig 3.18	Fig 3.18	Fig 3.20	Fig 3.20
1954	—	—	—	—	—
1955	1.330x10 ⁻¹	—	—	—	2.100x10 ⁻³
1956	3.180x10 ⁻²	—	—	—	6.840x10 ⁰
1957	8.120x10 ⁻³	—	—	—	5.890x10 ⁰
1958	6.800x10 ⁻³	—	—	—	2.600x10 ⁰
1959	2.610x10 ⁻³	—	—	—	2.300x10 ⁰
1960	4.700x10 ⁻²	—	—	—	4.400x10 ⁰
1961	2.700x10 ⁻²	—	—	—	1.930x10 ⁰
1962	1.200x10 ⁻²	—	—	—	2.580x10 ⁰
1963	1.900x10 ⁻²	—	—	1.520x10 ⁰	3.060x10 ⁰
1964	2.600x10 ⁻²	—	—	7.100x10 ⁻¹	1.690x10 ⁰
1965	1.170x10 ⁻²	—	—	5.100x10 ⁻¹	1.860x10 ⁰
1966	6.600x10 ⁻³	—	—	4.500x10 ⁻¹	9.600x10 ⁻¹
1967	5.500x10 ⁻³	—	—	4.000x10 ⁻¹	7.300x10 ⁻¹
1968	6.300x10 ⁻³	—	3.930x10 ⁻¹	2.700x10 ⁻¹	1.030x10 ⁰
1969	7.000x10 ⁻³	—	4.400x10 ⁻¹	1.900x10 ⁻¹	9.900x10 ⁻¹
1970	1.360x10 ⁻²	1.800x10 ⁻²	4.450x10 ⁻¹	1.600x10 ⁻¹	1.990x10 ⁰
1971	9.860x10 ⁻³	7.600x10 ⁻²	1.590x10 ⁰	3.330x10 ⁻¹	8.100x10 ⁻¹
1972	4.070x10 ⁻³	1.000x10 ⁻²	1.125x10 ⁰	2.000x10 ⁻²	4.400x10 ⁻¹
1973	3.280x10 ⁻³	1.787x10 ⁻²	1.606x10 ⁰	9.000x10 ²	9.000x10 ⁻²
1974	8.180x10 ⁻³	8.840x10 ⁻³	1.198x10 ⁰	3.000x10 ⁻²	6.000x10 ⁻²
1975	2.694x10 ⁻³	5.150x10 ⁻³	1.060x10 ⁰	4.700x10 ⁻²	1.150x10 ⁻¹
1976	2.479x10 ⁻³	5.520x10 ⁻³	8.900x10 ⁻¹	1.800x10 ⁻²	2.200x10 ⁻²
1977	1.979x10 ⁻³	3.950x10 ⁻³	6.500x10 ⁻¹	3.000x10 ⁻³	6.500x10 ⁻²
1978	2.988x10 ⁻³	4.960x10 ⁻³	4.500x10 ⁻¹	5.000x10 ⁻³	5.200x10 ⁻²
1979	2.302x10 ⁻³	2.940x10 ⁻³	4.400x10 ⁻¹	9.000x10 ⁻³	6.000x10 ⁻²
1980	2.377x10 ⁻³	6.170x10 ⁻³	3.800x10 ⁻¹	3.000x10 ⁻³	3.200x10 ⁻²
1981	1.573x10 ⁻³	3.921x10 ⁻²	2.479x10 ⁻¹	8.000x10 ⁻³	2.580x10 ⁻¹
1982	1.927x10 ⁻³	2.161x10 ⁻²	2.100x10 ⁻¹	1.900x10 ⁻²	8.100x10 ⁻²
1983	2.410x10 ⁻³	5.760x10 ⁻³	2.430x10 ⁻¹	6.000x10 ⁻³	2.300x10 ⁻²
1984	3.321x10 ³	1.176x10 ⁻²	2.000x10 ⁻¹	1.500x10 ⁻²	5.800x10 ⁻²
1985	1.605x10 ⁻³	1.389x10 ⁻²	1.100x10 ⁻¹	1.100x10 ⁻²	1.050x10 ⁻¹
1986	1.830x10 ⁻⁴	1.130x10 ⁻²	1.600x10 ⁻¹	5.000x10 ⁻³	7.000x10 ⁻²
1987	2.010x10 ⁻⁴	8.066x10 ⁻³	1.910x10 ⁻¹	3.000x10 ⁻³	2.600x10 ⁻²
1988	8.900x10 ⁻⁴	1.308x10 ⁻²	1.190x10 ⁻¹	4.000x10 ⁻³	8.000x10 ⁻³
1989	2.770x10 ⁻⁴	2.892x10 ⁻³	9.952x10 ⁻²	—	—

— Denotes No Data Available

Table 3-8. Radiostrontium Releases from H Area and ETF by Year (Curies)

Year	H Area ^{89,90} Sr Atmosphere	H Area ⁹⁰ Sr To Stream	H Area ⁹⁰ Sr Migration From Basin	H Area ⁸⁹ Sr To Basin	H Area ⁹⁰ Sr To Basin	ETF Area ⁹⁰ Sr To Stream
	Fig 3.22	Fig 3.21	Fig 3.22	Fig 3.23	Fig 3.23	No Fig
1954	—	—	—	—	—	—
1955	2.928x10 ⁻³	—	—	—	4.600x10 ⁻¹	—
1956	2.500x10 ⁻²	—	—	—	3.200x10 ⁰	—
1957	1.308x10 ⁻²	—	—	—	3.910x10 ⁰	—
1958	1.680x10 ⁻²	—	—	—	4.200x10 ⁻¹	—
1959	5.300x10 ⁻²	—	—	—	4.000x10 ⁻¹	—
1960	6.000x10 ⁻³	—	—	—	5.000x10 ⁻¹	—
1961	1.400x10 ⁻²	—	—	—	3.580x10 ⁰	—
1962	2.100x10 ⁻²	—	—	—	1.240x10 ⁰	—
1963	1.640x10 ⁻²	—	—	4.170x10 ⁰	6.930x10 ⁰	—
1964	1.350x10 ⁻²	—	—	6.000x10 ⁻¹	9.800x10 ⁻¹	—
1965	7.800x10 ⁻³	—	—	7.300x10 ⁻¹	4.700x10 ⁰	—
1966	1.460x10 ⁻²	—	—	2.100x10 ⁻¹	7.900x10 ⁻¹	—
1967	8.600x10 ⁻³	—	—	3.300x10 ⁻¹	1.160x10 ⁰	—
1968	2.770x10 ⁻²	—	4.700x10 ⁻²	1.900x10 ⁻¹	1.380x10 ⁰	—
1969	1.084x10 ⁻¹	—	2.700x10 ⁻²	2.900x10 ⁻¹	2.290x10 ⁰	—
1970	4.240x10 ⁻²	3.800x10 ⁻²	3.700x10 ⁻²	2.300x10 ⁻¹	6.700x10 ⁻¹	—
1971	2.634x10 ⁻²	2.600x10 ⁻²	9.200x10 ⁻²	2.660x10 ⁰	9.100x10 ⁻¹	—
1972	1.297x10 ⁻¹	3.400x10 ⁻²	3.900x10 ⁻²	2.030x10 ⁰	5.200x10 ⁻¹	—
1973	1.076x10 ⁻²	3.111x10 ⁻²	—	1.750x10 ⁰	7.300x10 ⁻¹	—
1974	2.930x10 ⁻³	1.341x10 ⁻²	1.000x10 ⁻²	2.600x10 ⁻¹	2.400x10 ⁻¹	—
1975	2.332x10 ⁻³	7.540x10 ⁻³	1.000x10 ⁻²	3.500x10 ⁻¹	6.760x10 ⁻¹	—
1976	2.124x10 ⁻³	8.170x10 ⁻³	2.000x10 ⁻²	1.620x10 ⁻¹	4.290x10 ⁻¹	—
1977	2.156x10 ⁻³	7.390x10 ⁻³	1.000x10 ⁻²	5.800x10 ⁻²	4.520x10 ⁻¹	—
1978	8.440x10 ⁻⁴	1.077x10 ⁻²	2.100x10 ⁻²	3.460x10 ⁻¹	1.994x10 ⁰	—
1979	1.590x10 ⁻⁴	7.940x10 ⁻³	3.000x10 ⁻²	7.400x10 ⁻²	2.612x10 ⁰	—
1980	2.020x10 ⁻⁴	2.300x10 ⁻³	1.000x10 ⁻²	4.200x10 ⁻²	1.130x10 ⁻¹	—
1981	1.385x10 ⁻³	1.150x10 ⁻³	4.720x10 ⁻²	1.130x10 ⁻¹	7.330x10 ⁻¹	—
1982	3.290x10 ⁻⁴	3.750x10 ⁻³	7.400x10 ⁻²	4.500x10 ⁻²	5.900x10 ⁻¹	—
1983	3.170x10 ⁻⁴	4.150x10 ⁻³	5.181x10 ⁻²	8.000x10 ⁻²	1.990x10 ⁻¹	—
1984	1.990x10 ⁻⁴	9.020x10 ⁻⁴	1.200x10 ⁻¹	—	2.200x10 ⁻²	—
1985	1.670x10 ⁻⁴	2.310x10 ⁻³	5.010x10 ⁻²	—	4.800x10 ⁻²	—
1986	7.370x10 ⁻⁴	2.600x10 ⁻³	8.000x10 ⁻²	5.000x10 ⁻³	3.800x10 ⁻²	—
1987	4.120x10 ⁻⁴	1.801x10 ⁻³	8.350x10 ⁻²	4.000x10 ⁻³	1.900x10 ⁻²	—
1988	1.520x10 ⁻⁴	1.038x10 ⁻³	7.300x10 ⁻²	2.200x10 ⁻²	2.000x10 ⁻²	—
1989	2.630x10 ⁻⁴	3.720x10 ⁻³	9.425x10 ⁻²	—	—	4.200x10 ⁻³

— Denotes No Data Available

Emission Control

Administrative and physical controls implemented in reactor areas in the 1960s minimized the possibility that short-cooled fuel or targets would be sent inadvertently to the chemical separation areas. Beginning in the early 1970s, fuel and targets were controlled so their nominal cooling time was 200 days before reprocessing by the Purex or HM process.

Canyon building exhaust air passes through sand filters to remove particulate radioactivity prior to discharge from a 61-meter stack. Air and fumes from process vessels are exhausted through a variety of scrubbers, filters, or silver nitrate reactors to remove specific gaseous contaminants before final filtration and discharge from the stack. The 61-meter stack in each facility provides sufficient loft to the off-gases to ensure that radiostrontium (and other radionuclides) are dissipated into very low concentrations over a large area. This minimizes exposure to people in and around the facility.

For liquid releases, the result of radioactivity measurements determines whether liquids are discharged to ETF (previously seepage basins) or to waste tanks.

Release Monitoring

Atmospheric releases of $^{89,90}\text{Sr}$ from separations facilities were quantified since start-up in 1954. Reprocessing of irradiated material began in F Canyon in November 1954 and in H Canyon in July 1955. Aqueous release of radiostrontium to seepage basins has been quantified since start-up. Specific radiochemical analyses for strontium in aqueous releases to streams were not begun until 1970; however liquid release to streams has been monitored for gross beta (also called nonvolatile beta) since start-up. Several techniques were used to monitor aqueous releases. Process cooling water in F Area was monitored in-line for beta-gamma activity. In H Area, batches of process cooling water were monitored prior to release. When liquid effluents were released to seepage basins, they were sampled continuously. Samples were collected weekly and analyzed by gamma spectrometry. Specific radiochemical techniques were used to analyze for radiostrontium. ETF discharges are sampled prior to release to Upper Three Runs Creek (Taylor, 1989).

History of Measured Releases

Atmospheric releases of $^{89,90}\text{Sr}$ as well as releases to seepage basins have been quantified since the start-up of the chemical separations facilities (Cummins et al, 1991). Release to streams via process cooling water discharges has been measured as nonvolatile beta since startup. Identification and quantification of the radiostrontium contribution to these releases was not initiated until 1970.

The history of releases of radiostrontium shows that H Area released about one and a half times more activity to the seepage basins than F Area. (Combined ^{89}Sr and ^{90}Sr release was 64 curies from H Area and 46 curies from F Area from 1954 until 1988, when the basins were closed.) Atmospheric releases also were higher from H Area (0.86 Ci from H Area vs 0.675 Ci from F Area), due partially to reduced filter efficiency when support tiles collapsed in the H Area sand filter in 1967.

F Area Separations

Aqueous waste from F Canyon initially was sent to waste tanks and a seepage basin designated 904-49G, also known as Old F-Area Seepage Basin. The capacity of this basin proved to be inadequate. It was abandoned in 1955 after three additional seepage basins were constructed. The new basins, designated 904-41G, -42G, and -43G, were in use from 1955 until 1988, when wastewaters were diverted to the ETF. The latter basins also were known as F Seepage Basins 1, 2, and 3.

Additionally, an earthen retention basin (281-3F) was used from 1955 to 1973 for the temporary containment of water potentially contaminated by process upsets. Use of a lined retention basin was implemented in 1973.

Releases to Streams

Cooling water for portions of the F-Area separation process is pumped from deep wells and discharged to Fourmile Branch after use. This water has been used in the "once through" or "segregated" cooling-water systems that control temperatures in the separation process or waste evaporators. Because of the possibility of cooling-coil leakage, these cooling-water streams have the potential to contain measurable amounts of radioactivity. Cooling coils

are used in the head-end dissolvers; hence, a mixture of many fission and activation products is available as a potential cooling system contaminant.

In order to minimize release of radioactivity into the cooling system when a leak does occur, positive pressure is maintained in the cooling coils in all process vessels. After the water has been used, it is monitored and released into Fourmile Branch. Should activity levels in the water preclude the discharge of the water to the creek, the contaminated water is held in a plastic lined "diversion" basin and transferred to either the H Area waste tank farm or the ETF for processing. In the past, diversion basin water that was too radioactive for release to the stream was pumped to the seepage basins.

Water from the cooling system is monitored prior to release to Fourmile Branch. From F Area start-up through 1969, this water was analyzed for gross nonvolatile beta only; no specific analyses were made for radiostrontium. Specific analysis for ^{90}Sr was

initiated in 1970. A total of 0.287 curies of strontium was released during the period 1970 through 1989; the maximum release, 0.076 curies, occurred in 1971. As indicated earlier in this chapter, ^{90}Sr migration in groundwater has been a significant source of stream releases. Releases via groundwater exceeded 1 Ci/yr during the period 1971 through 1975. The maximum year was 1973, when measured migratory releases amounted to 1.61 curies of ^{90}Sr . Annual releases are shown graphically in Figure 3.18 and presented in tabular form in Table 3-7.

Releases to Atmosphere

The total measured atmospheric release of $^{89,90}\text{Sr}$ from F Area through 1989 was approximately 0.68 curies. Measured annual releases of radiostrontium are shown graphically in Figure 3.19 and in tabular form in Table 3-7. The maximum annual release, 0.26 curies, occurred in 1959.

Figure 3.18 ^{90}Sr Releases to Streams, F Area

Figure 3.19 Strontium Releases to Atmosphere, F Area

Releases to F-Area Seepage Basins

The total measured aqueous release of radiostrontium to the F-Area seepage basin system through 1988, when discharges to the seepage basins were terminated, was 46.28 curies (4.84 curies of ^{89}Sr and 41.44 curies of ^{90}Sr). Measured annual releases of both ^{89}Sr and ^{90}Sr are shown graphically in Figure 3.20 and in tabular form in Table 3-7. The maximum annual release, 6.8 curies, occurred in 1956.

H-Area Separations

H Canyon has been operational since July 1955. In addition to the general chemical separation operation, H Area also includes the ETF and RBOF with an adjacent regeneration facility for resins from other areas. Certain offsite noncommercial irradiated fuels are stored underwater in the RBOF, as are some SRS fuel elements that have failed. This facility is equipped to disassemble and cut fuel for inspection.

Aqueous waste from H Canyon was sent to waste tanks and four seepage basins, designated 904-44G, -45G, -46G, and -56G. The basins, also known as H Seepage Basins 1, 2, 3, and 4, were used from 1955 until 1988, when wastewater was diverted to the ETF. Basin 904-46G has been inactive since 1962.

In addition, an earthen retention basin, designated 281-3H, was used from 1955 to 1973 to temporarily contain water potentially contaminated by process upsets. Use of a lined retention basin was implemented in 1973.

Figure 3.20 ^{90}Sr Releases to Basins, F Area

Releases to Streams

As in F Area, clean well water is pumped through pressurized coils in evaporators and process tanks to control temperatures, then discharged into a process sewer that empties into Fourmile Branch. Water from the cooling system is monitored prior to release to Fourmile Branch. From H Area start-up through 1969, this water was analyzed for gross nonvolatile beta only; no specific analyses were made for radiostrontium. Specific analysis for ^{90}Sr was initiated in 1970. A total of 0.21 curies of strontium was released directly to the stream during the period 1970 through 1989; the maximum release of 0.038 curies occurred in 1970. The maximum measured ^{90}Sr migration into the stream from H-Area seepage basin migration was 0.12 curies in 1984. Annual releases are shown graphically in Figure 3.21 and in tabular form in Table 3-8.

Releases to Atmosphere

The total measured atmospheric release of $^{89,90}\text{Sr}$ from H Area through 1989 was 0.863 curies. The highest release, 0.29 curies, occurred in 1955 during start-up (primarily as a result of leakage around the sand filter bypass plug). Additional elevated releases occurred during the period 1969 through 1972 following collapse of support tiles in the sand filter. Measured annual releases are shown graphically in Figure 3.22 and in tabular form in Table 3-8.

Figure 3.21 ^{90}Sr Releases to Streams, H Area

Figure 3.22 Strontium Releases to Atmosphere, H Area

Releases to Seepage Basins

The total measured aqueous release of $^{89,90}\text{Sr}$ to the H-Area seepage basin system through 1988 when discharge to the seepage basins was terminated, was 64 curies (14.75 curies of ^{89}Sr and 49.28 curies of ^{90}Sr). Measured annual releases are shown in Figure 3.23. The maximum annual release, 6.93 curies, occurred in 1963.

The ETF became operational in November 1988 to receive aqueous waste previously discharged to the separations area seepage basins.

Effluent Treatment Facility

All the low-level liquid wastes formerly discharged to the F- and H-Area seepage basins are processed in the ETF. Treated aqueous wastes from the ETF are discharged to Upper Three Runs Creek. The measured stream release of ^{90}Sr for 1989, the first year of operation, was 0.0042 curies, as shown in Table 3-8.

Waste Tank Farms

High-level, radioactive, liquid-waste storage tanks, located in F and H areas, are known to contain large inventories of the strontium isotopes ^{89}Sr and ^{90}Sr . Waste older than about 3 years contains very little ^{89}Sr . Strontium salts are relatively insoluble in the high-level waste, thus the sludge in the waste storage tanks contains most of the inventory of strontium. The total inventory of ^{90}Sr - ^{90}Y in the waste tanks has

Figure 3.23 Strontium Releases to Seepage Basins, H Area

been estimated to be 2.6×10^8 Ci. ^{90}Sr and its daughter ^{90}Y are the most abundant radionuclides (in activity) in 5-year-old waste, accounting for 46% of the total inventory of 5.6×10^8 Ci (DOE, 1991).

Radioactivity is known to have leaked into the ground from waste tanks on at least two occasions. In 1960, H-Area Tank 16 developed a leak that overflowed the saucer under the tank, and some of the high-level waste seeped into the surrounding soil (Poe, 1974). In 1961, F-Area Tank 8 inadvertently was overfilled, resulting in the release of ^{137}Cs to the soil surrounding the buried transfer line (Odum, 1976). In both these cases it was the supernate liquid, which contained little radiostrontium, that reached the environment.

Summary of Separations and Liquid Waste Facilities

Measured aqueous release of radiostrontium from the separation areas from 1954 to 1989 totaled 124 curies, 110 of which went to seepage basins and 14 which went into Fourmile Branch. Of the 14 curies released to the stream, 13.3 resulted from seepage basin migration. The combined total of radiostrontium atmospheric releases was about 1.54 Ci.

Solid Waste Disposal Facility

Radioactive solid waste generated during SRS operations has been burned in the low-level waste incinerators or buried in the SWDF. Because of the

nature of much of the waste, precise analysis of the radioactive inventory of materials committed to the SWDF is not available. Estimates of the radioactive content of packaged waste is made from radiation surveys of the packages, and conversion factors are applied based on known or assumed fission product content. The data on each package are recorded at the burial facility, and a computerized inventory is maintained. Based on these data, the estimated decay-corrected strontium content of the SWDF was 1,389 curies as of January 1987 (Hurrell et al., 1988).

Savannah River Technology Center

SRTC provided research and development support for the production facilities of SRS. Laboratory facilities handled radioactivity that ranged from environmental levels to highly radioactive materials—the latter manipulated in shielded cells. Specific radiochemical analyses for radiostrontium in atmospheric releases from SRTC were not performed. Unidentified beta-gamma activity (gross beta) releases from SRTC stacks for the period 1958 through 1989 totaled 1.25 curies. Annual gross beta releases from SRTC are shown in Figure 3.24 and Table 3-1.

Liquid radioactive wastes were accumulated in holding tanks pending shipment to F Area for treatment and disposition.

From 1954 to 1982, a seepage basin system was used for low-activity waste. The first two seepage basins, both designated 904-53G, were placed into service in 1954. The last two, 904-54G and -55G, were added in 1958 and 1960, respectively. Analyses of activity

released to the basins was limited to nonvolatile beta (gross beta) activity until 1965. Radiostrontium releases to the SRTC basins totalled 113 mCi from 1965 until 1982, when basin use was discontinued. Strontium releases to SRTC basins are shown in Figure 3.25 and Table 3-2.

Other Facilities

A number of other facilities handled materials containing radiostrontium. These were the test reactors, the Heavy Water Rework Facility, and any facility handling spontaneously fissioning elements.

No releases of radiostrontium were documented for any of the test reactors described in Chapter 2. Had there been releases from these facilities, the releases would have been small compared to those from production reactors. Operation of these test reactors was discontinued in the 1970s.

The Heavy Water Rework Facility, located in D Area, consisted of four distillation towers and associated equipment for removal of ordinary water that accumulated in the heavy water moderator used in the reactors. Leaks in the system were vented through a 21-meter stack. The aqueous waste stream was sent to Beaver Dam Creek after verification that activity levels did not exceed specific limits. The predominant radioactivity associated with this facility was tritium.

Potential existed for traces of radiostrontium to be present in the moderator, as was described in the

Figure 3.24 Gross Beta Releases to Atmosphere, SRTC

Figure 3.25 Strontium Releases to Seepage Basins, SRTC

Figure 3.26 Strontium Releases to Streams, D Area

section on reactor facilities. Releases of $^{89,90}\text{Sr}$ to streams from D Area totaled about 0.060 curies during the period 1968 through 1989, as shown in Figure 3.26 and Table 3-6.

Central Shops at SRS is responsible for fabrication and repair of equipment used in the separations and reactor areas of the site. Though equipment is decontaminated before it is sent to Central Shops, some radioactive material occasionally is present and normally is removed during cleaning operations prior to repair of the equipment. The contamination is transferred with other liquid waste streams to a seepage basin. The yearly release of radiostrontium activity released to the Central Shops Seepage Basin (Ford Basin) is shown in Figure 3.27 and Table 3-6. The total radiostrontium release for this location is 7.8×10^{-5} curies.

Figure 3.27 Strontium Releases to Seepage Basins, Central Shops

Facilities other than those already described in this chapter that handle spontaneously fissioning elements were the reactor material facilities for uranium fuel and target fabrication in M Area; the TNX Semi Works, where various processes were tested on a pilot scale with uranium; and the Naval Fuels facility, where uranium fuel for the U.S. Navy was fabricated from the late 1980s until shutdown in 1989. The presence of low-level radiostrontium due to spontaneous fission had no impact on operations because the radiostrontium was contained within the uranium metal; radiostrontium in this case is only of academic interest.

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Chapter 4. Radiostrontium Concentration and Transport Mechanisms

This chapter examines the movement of radiostrontium through the atmosphere, surface waters, and groundwater. Understanding these transport phenomena is critical to the calculation of dose in Chapter 5.

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Atmospheric Radiostrontium

Atmospheric radiostrontium is measured by air sampler, which collect atmospheric particles containing strontium and in rain gauge samplers, which collect particles falling out of the air by dry deposition and particles captured by rainfall. Deposition of atmospheric radiostrontium also contributes to the radiostrontium in soil, vegetation, and animal food products such as milk. These media also are monitored to determine the influence of SRS releases on strontium in the environment.

Two radioisotopes of strontium are found in the environment, ^{89}Sr and ^{90}Sr . Because of its short half-life of 55 days, ^{89}Sr is less of a health concern than ^{90}Sr and is not cycling in the environment long before it has decayed to very low levels. The primary source of these radioisotopes is nuclear bomb fallout.

The influence of SRS releases on atmospheric radiostrontium can be determined by looking for patterns of radiostrontium in the atmosphere that coincide with SRS releases in any of the routinely monitored environmental media. The patterns can be the temporal coincidence of releases and radiostrontium concentrations or deposition. Spatial patterns that show SRS at the center of the highest concentrations in a region also would suggest an influence from SRS releases. In addition, the radioisotopic signature of samples collected from the environment, when compared to SRS releases and nuclear weapons fallout, might also indicate the source of the radiostrontium. In the following discussions, all these techniques have been used to look for the influence of SRS operations on radiostrontium in the surrounding environment.

Figure 4.1 shows the time-series of atmospheric detonations of nuclear device testing (in megaton TNT equivalents), the average ^{90}Sr collected in rain gauges at the SRS perimeter, the ^{90}Sr deposition collected by the DOE Environmental Measurements Laboratory, and the amount of $^{89,90}\text{Sr}$ released from SRS operations. The EML measurements, made in Columbia, SC, are very similar to other measurements of deposition from nuclear bomb fallout at other locations throughout the eastern U.S. The high ^{90}Sr deposition at SRS at the beginning of measurements in the early 1960s shows the same pattern as the EML deposition measurements and is certainly from the same source, bomb fallout. This is corroborated by the high fraction of ^{89}Sr in fallout during the 1960s and early 1970s, when atmospheric testing was taking place (Figure 4.2). After 1975, the deposition of radiostrontium was greatly decreased and the fraction of ^{89}Sr approached zero.

Measurement of the concentration of ^{90}Sr in air was begun in 1967. The high values recorded for deposition in the early 1960s was missed, but concentrations from 1966 on show the same small changes around a very low atmospheric concentration.

The relationship between ^{90}Sr deposition and SRS releases after 1975 are hard to determine from inspecting the plots. Statistical regression analysis was used to test the strength of any relationships between SRS releases and rain gauge deposition. The results (Table 4-1) suggest that there is no discernible relationship for rain gauges at the SRS perimeter and at locations outside the site boundary. There does appear to be a weak relationship at sampling stations inside the SRS boundary. Even in this case, the contribution of other sources is significant. Other sources might include some small residual of atmospheric-testing ^{90}Sr , resuspension of ^{90}Sr in soil and vegetation from the atmospheric testing, and ^{90}Sr from other commercial nuclear facilities. In any case, concentrations in the deposition are quite small during the period after fallout of the majority of the weapons-test radiostrontium.

Figures 4.3 and 4.4 show the spatial pattern of ^{90}Sr with distance from the SRS center. It is obvious that no consistent spatial pattern exists, either during or after atmospheric testing. This suggests that ^{90}Sr sources other than SRS dominate the radiostrontium distribution in the environment around the site.

Figure 4.5 shows the average ratio of $^{90}\text{Sr}/^{137}\text{Cs}$ at locations inside the SRS boundary. This ratio is compared to the ratio in SRS releases and the average ratio measured in bomb fallout. Before 1976, the ratios measured at SRS appear to be very similar to those in bomb fallout. After 1975, the ratios are more like those from SRS. During the latter period, however, the measured concentrations are low and the measurement error is correspondingly high.

When all evidence is taken together, it appears that most of the ^{90}Sr in the environment in the vicinity of SRS is from sources other than SRS operations.

Radiostrontium in Soil

The ^{90}Sr content of the upper 8.0 cm of soil (6.0 cm in 1973) was measured beginning in 1973. The results are reported in units of deposition (mCi/km^3). From the results (Figure 4.6) it is obvious that ^{90}Sr does not simply accumulate in the surface soil after

deposition. Strontium, which has a relatively high mobility in most soils, is being transported with water, into the deeper soil and ultimately from the site of deposition through the groundwater. The 1973 collections show the effects of deposition of radiostrontium from atmospheric testing. These effects are greatly decreased by the next measurements taken in 1976. Since this initial decrease, the amount of ^{90}Sr has remained relatively constant to the present time. The ^{90}Sr content of the soil shows no effect from proximity to SRS. The highest values in any one year are as likely to be at the outer 100-mile measuring stations as at the two station within the site boundary. This agrees with the results of air and rainfall monitoring.

Radiostrontium in Foods

Milk

Radiostrontium is routinely measured in selected foodstuffs in the SRS vicinity. The ^{90}Sr content of milk has been measured since 1959. Milk was collected from individual cows, as the mixed product of individual dairies and as the mixed product of distributors that market locally produced milk. Results are shown in Figure 4.7. The ^{90}Sr concentration in milk plainly shows the effect of deposition from atmospheric testing. The timing is similar to that demonstrated in rainfall deposition measurements. The increase in variability, shown in the one standard deviation bars around the means, during the years of greatest concentration is characteristic of the spatial variability found in bomb fallout. The ^{90}Sr concentration in milk appears to lag one or two years behind the rainfall deposition, probably reflecting the time it takes for the ^{90}Sr to move through the soil and into the cow feed. After most atmospheric testing stopped in the early 1980s, the ^{90}Sr concentration in milk decreased to a low level. A small peak in 1987 may have resulted from fallout from the Chernobyl reactor accident.

Food of Vegetable Origin

Locally grown crops have been collected for ^{90}Sr analysis since 1964. The type of material analyzed in a given year largely depended on local availability.

For the purpose of this discussion, the crops have been averaged in three groups. Fruits include peaches and plums, including some wild plums seldom used for food. Grains include wheat, oats, and rye. Corn was measured occasionally and, although it was not included, its concentrations were similar to those of other grains. Collards were the only leafy vegetable collected. Results are presented in Figure 4.8. Only the collards show a trend consistent with the influence of atmospheric testing. The relatively high ^{90}Sr content of collards may be explained by their higher calcium content and the fact that strontium is a metabolic analog for calcium. None of the vegetables show variations in ^{90}Sr content, which appears to be related to SRS ^{90}Sr releases.

Food of Animal Origins

Chicken, beef, pork, and eggs have been collected locally for ^{90}Sr analysis. The results (Figure 4.9, *pork concentrations are not shown but are practically the same as those of beef*) suggest that ^{90}Sr concentrations increased during the period of atmospheric nuclear testing. The concentrations of ^{90}Sr decreased after 1980 and cannot be detected after 1985 (not shown in figure). The relatively high concentration found in eggs in 1987 coincides with the Chernobyl reactor accident. No correlation was found between SRS releases and the concentrations of ^{90}Sr in animal foods.

Table 4-1 Regression Analysis of the Relationship Between SRS Releases and the Deposition of ^{90}Sr .

Sampling Locations	Student T Probability of Null Hypothesis	Regression Coefficient (R^2)
On Site	0.0153*	0.54
Site Perimeter	0.0667	0.30
25 Mile Arc	0.1003	0.25
100 Mile Arc	0.1588	0.26

*Slope is significantly different from zero at the 95% level.

Figure 4.1 Comparison of Nuclear Bomb Yield, Fallout ^{90}Sr Deposition, SRS ^{90}Sr Releases, and ^{90}Sr Deposition measured at the SRS.

Figure 4.2 The Fraction of ^{89}Sr in Deposition measured at SRS during the Years of Atmospheric Nuclear Bomb Testing.

Figure 4.3 The Air Concentration of ^{90}Sr averaged for Four Distances from the Center of SRS. Measurements were averaged for Two Periods, During (1967-1975) and After (1976-1986) Atmospheric Nuclear Testing.

Figure 4.4 The Rain gage Deposition of ^{90}Sr averaged by Distance from the Center of SRS. Measurements were averaged for Two Periods, During (1963-1975) and After (1976-1986) Atmospheric Nuclear Testing.

Figure 4.5 The ratio of $^{90}\text{Sr}/^{137}\text{Cs}$ measured at Sampling Location within the Boundary of the SRS. The Ratio is compared to the Ratio in SRS Releases and the Ratio in Nuclear Test Fallout.

Figure 4.6 Deposition of ^{90}Sr to Soil at and in the Vicinity of SRS.

Figure 4.7 The ^{90}Sr Concentration in Milk Collected from Dairies and Distributors in the Vicinity of SRS.

Figure 4.8 The Concentration of ^{90}Sr in Vegetable Foods collected in the Vicinity of the SRS.

Figure 4.9 The Concentration of ^{90}Sr in Foods of Animal Origin in the Vicinity of the SRS.

Aqueous Concentrations and Transport

Surface Waters on the Savannah River Site

Strontium transported by SRS surface waters originated from three sources: fallout, atmospheric releases from SRS operations, and direct releases to streams. Fallout deposited on the Savannah River watershed can be estimated from the average deposition in the Southeastern U.S., 60 mCi/km² (Eisenbud, 1987). Approximately 46 Ci of ^{90}Sr were deposited on SRS and 1,640 Ci were deposited on the 10,579 square miles of the Savannah River basin (Langley and Marter, 1973). Atmospheric strontium releases from SRS operations have totaled about three Ci (including unidentified beta), and direct releases to streams have totaled 104 Ci (Cummins et al., 1991). Several streams have received cooling water from reactors and process water from separation facilities, with more than 80% of the liquid releases occurring in the reactor areas. Most of the strontium entering the streams was transported directly to the Savannah River, while a little over 10% was deposited in stream beds, flood plains, or ponds (Gladden et al., 1985).

Lower Three Runs Creek

Lower Three Runs Creek has the second-largest drainage area of SRS streams. Both P and R reactors have discharged effluents to the Lower Three Runs system. On the main SRS site, a large (2,600 acres) impoundment, Par Pond, was constructed in 1958 to provide recirculating cooling water through P and R reactors. Several smaller ponds were built between the reactors and Par Pond to provide additional cooling for reactor cooling water before it entered Par Pond. The average natural flow rate of Lower Three Runs Creek at the Par Pond dam is 1 m³/sec. From the Par Pond dam, the creek flows 38 kilometers to the Savannah River.

Upper Three Runs Creek

Upper Three Runs Creek is the largest on site, with a watershed of 540 km², a natural flow rate of 7 m³/sec, and a length of 40 km. Effluents are received from M Area and SRTC. Since 1988, the Effluent Treatment Facility in H Area has been releasing treated water.

Steel Creek

Steel Creek is 18 km long and has a watershed of 90 km². The natural flow rate is 1 m³/sec but was as high as 22 m³/sec when both P and L reactors discharged cooling water to the creek in the early 1960s. P Reactor cooling water was diverted to Par Pond in 1964 and L Reactor was shut down in 1968, then restarted in 1985. P-Reactor disassembly basin water continued to flow to Steel Creek. L Lake was built in 1985 to provide cooling for L-Reactor discharges. Steel Creek travels about 3 km through a swamp before entering the Savannah River (Murphy et al., 1991).

Fourmile Branch

Fourmile Branch has a watershed of 57 km², is approximately 24 km long, and has a natural flow of 0.14 m³/sec. It receives effluent from F and H areas and received cooling water from C Reactor until 1985.

Pen Branch

Pen Branch has a watershed of 55 km², is approximately 24 km long and has a natural flow of 0.2 m³/sec. Once it reaches the Savannah River Swamp, the flow path becomes relatively undefined through the swamp parallel to the Savannah River for about 8 km before entering Steel Creek. Pen Branch receives cooling water from K Reactor.

Site Stream Summary

Total measured release of ⁹⁰Sr to SRS streams from 1954 through 1989 was 104 Ci. The reactors released 90.2 Ci and the separations areas released 13.7 Ci. Most of the separation areas releases resulted from

seepage basin migration. Table 4-2 lists the releases from various SRS areas (Cummins et al., 1991). Strontium is soluble in water, and almost 90% of the ⁹⁰Sr entering the streams is carried rapidly to the Savannah River. Dose calculations in this document will assume that all of the ⁹⁰Sr remained in the water and was available to downstream users of the river.

Table 4-2 Releases of ⁹⁰Sr by Area, 1954 Through 1989

Area	Curies Released
C Liquid to Streams	11.4
F Liquid to Streams	00.3
F Migration from Basin	12.2
H Liquid to Streams	00.2
H Migration from Basin	01.0
K Liquid to Streams	11.3
L Liquid to Streams	22.0
P Liquid to Streams	18.9
R Liquid to Streams	26.6
Total	103.9

Savannah River

The Savannah River forms most of the border between Georgia and South Carolina and drains approximately 25,900 km² in eastern Georgia and western South Carolina. The flow rate averages about 285 m³/sec at Augusta and increases to 340 m³/sec downriver near Clyo, GA. Water from the river is used at two water treatment plants, Beaufort-Jasper and Port Wentworth.

Groundwater Concentrations and Transport

SRS Groundwater System

The Savannah River Site lies on the Atlantic Coastal Plain about 20 miles southeast of the edge of the Piedmont Physiographic Province. The Coastal Plain is underlain by a seaward dipping wedge of sediments that thins and overlaps the crystalline rocks of the Piedmont. Early investigations of the hydrogeology at the site (Siple, 1967) established three geologic and hydrogeologic systems: 1) crystalline basement rocks composed of metamorphic

and intrusive igneous rocks; 2) well-indurated Triassic-aged sediments in the Dunbarton Basin; and 3) the overlapping, weakly consolidated Cretaceous to Recent Coastal Plain sediments.

The crystalline basement rocks have very low permeabilities. Water is stored primarily in the fractures and joints in the rocks. The permeability of the Triassic rocks is also likely to be relatively low. Two test wells drilled into the Triassic rocks showed that the water in these rocks is geopressured and that the hydraulic head of the water is above land surface.

The origin of the overpressuring is uncertain but has been ascribed to osmotic pressure across the overlying impermeable confining units (Marine, 1974).

Both the crystalline basement rocks and the Triassic rocks are overlain by varying thicknesses of weathering residue containing degraded minerals and clay. Overlying these old soils is a depositional blanket of indurated, poorly-sorted clayey sediments of the Cape Fear Formation (Bledsoe, 1988). This unit and the residual soils hydraulically separate and isolate the younger, sedimentary materials from the Triassic sediments and the crystalline basement rocks.

The third hydrogeologic system is the Cretaceous and younger sedimentary rocks of the Coastal Plain sediments. The sediments were largely deposited in shallow marine and fluvial environments (Gohn, 1988). The thickness of the sedimentary units increases toward the southeast across the site. At the

northwest boundary, the sedimentary section is about 700 feet thick and it is about 1400 feet thick at the southeastern boundary. As more detailed information has become available, the stratigraphic names applied to the various units have been modified based on the predilections of successive investigators.

The principal aquifers on the site have frequently been named after the principal formations, for example the Barnwell Formation and the Barnwell Aquifer. As stratigraphic names have changed, the names of the aquifers have also been changed as a result.

Figure 4.10 compares some of the changes that occurred in the hydrostratigraphic nomenclature since the mid-1960s. The currently recommended nomenclature (Aadland et al., 1992) takes into account the progressive thickening of the aquifers across the site and the effectiveness of the confining units that separate the aquifer units. The recent

	1967	1967	1990		1989	Revised hydrostratigraphic nomenclature Aadland et al., 1992			
Tertiary	Hawthorn Aquifer	Tertiary Sand Aquifer	Upland Unit		Upland Unit/ Hawthorn	Florian-Midville Aquifer System		Florian Aquifer System	
	Barnwell Aquifer		Barnwell Group	Tobacco Rd Formation					
	McBean Aquifer			Orangeburg Group	Dry Branch Formation				Clinchfield Sand Mbr Griffins Landing Mbr Irwinson Sand Mbr Twiggs Clay Mbr
	Congaree Aquifer		McBean Formation Green Clay		McBean				Santee
			Congaree Formation	Congaree	Warley Hill				
Cretaceous	Ellenton Aquitard	Confining Unit	Group Black Mingo	Williamsburg Formation	Black Mingo	Dublin-Midville Aquifer System			
				Ellenton Formation	Ellenton Formation				
	Upper Tuscaloosa Aquifer	Black Creek Aquifer	Lumbee Group	Peedee Formation	Peedee Formation				
	Mid Tuscaloosa Clay Aquitard	Confining Unit		Black Creek Formation	Black Creek Formation				
	Lower Tuscaloosa Aquifer	Middendorf Formation		Middendorf Formation	Middendorf Formation				
	Basal Clay Aquitard	Confining Unit		Cape Fear Formation	Cape Fear Formation				
							Appleton Confining System		

Figure 4.10 Stratigraphic and Hydrostratigraphic Nomenclature Used on the Savannah River Site

changes avoid tying the aquifer nomenclature to the lithostratigraphic names and extend five existing hydrostratigraphic nomenclature from surrounding regions into the SRS.

At the base of the Coastal Plain sediments is an aquitard, the Appleton Confining System, composed of residual soils of the basement rocks and dense clays of the Cape Fear Formation. Overlying this confining unit are two aquifers in Cretaceous sands (McQueen Branch and Crouch Branch). These sands are generally considered to be prolific water producers and are generally the source of water for water-supply wells on the site. They are separated from each other by the relatively less permeable beds that make up the Black Creek Formation.

The Tertiary aquifers are separated from the underlying Cretaceous aquifer units by confining beds of the Black Mingo Group, especially the Ellenton Formation. On the Northwestern corner of site, the separation is not as effective as in the southern portion.

In the Southeastern area, the Tertiary section can be divided into two separate aquifers, the Gordon (Formerly called the "Congaree Aquifer") and Upper Three Runs (frequently referred to as the "Barnwell Aquifer" or "Watertable Aquifer"). The aquitard or confining beds that separate these two units is a glauconitic clayey zone of the McBean Formation that is locally referred to as the "green clay." This clay pinches out and becomes more sandy toward the northwest.

In some areas of the site, it is necessary to modify the hydrostratigraphic nomenclature due to local changes in lithologies and topography. For example, in some portions of the site an aquitard unit referred to as "tan clay" subdivides the uppermost aquifer into two separate zones. In the southern portion of the site, the "tan clay" unit is thin or sporadic and does not form a consistent aquitard.

The level of the water table is controlled primarily by local topographic features. The surface of the Atlantic Coastal Plain at the site is a relatively flat plateau (the Aiken Plateau) that has been dissected by stream erosion.

The incision of the streams has left relatively isolated, flat-lying surfaces separated by 90 to 125 feet deep stream valleys. The depth to the water table below land surface varies from 0 feet, when it outcrops in the stream valleys or wetlands, to a depth of 125 feet below the remnant plateau areas. The depth of the water table is usually controlled by the elevation of

the nearest tributary stream of the Savannah River. At many localities on site the water table is situated in Tertiary sediments of low water-producing capabilities and perched water tables exist sporadically across the site

The direction of groundwater flow at any locality may change or even reverse at successively deeper aquifers. The aquifers in the Tertiary sediments receive local recharge and flow is generally toward nearby stream valleys. In general, flow at the water table is toward minor tributaries and deeper Tertiary aquifers flow toward major tributaries of the Savannah River. The deepest aquifers at SRS, the Dublin-Midville Aquifer System, receive recharge in the outcrop areas of the Cretaceous sediments to the north of the site. Groundwater flow beneath the site in this system is toward the Savannah River.

Over much of the site, the potentiometric surface, or hydraulic "head" of the deeper aquifers in the Cretaceous sediments is higher than that of the overlying Tertiary aquifers (Christensen and Gordon, 1983). This head reversal is an important characteristic of many of the waste disposal areas and has provided protection to the deeper aquifers on the site from downward transport of contaminants. Figure 4.11 outlines the areas where there is an upward hydraulic gradient across the confining units near the Cretaceous-Tertiary boundary.

Figure 4.11 Hydraulic Head Differences Across Confining Units Near the Cretaceous/Tertiary Boundary

Strontium in SRS Groundwater

General

Groundwater monitoring on the Savannah River Site is performed by the Environmental Monitoring Section of the Environmental Protection Department using a system of wells that have been installed around each of the facilities and especially around each of the waste disposal areas and seepage basins. The majority of these wells are sampled on a quarterly basis and the results reported in the Annual Savannah River Site Environmental Reports.

The environmental geochemistry of strontium is very similar to that of calcium and consequently is fairly well understood at the present time. Generalizations applied to one of these alkaline earth elements is usually applicable to the other as well. Both elements are lithophilic and occur primarily as carbonates, sulfates, or phosphates in sediments such as those found at the Savannah River Site.

In alkaline soils or ground water, strontium will form a carbonate mineral, strontianite, that is slightly less soluble than the calcium carbonate analog, calcite. The sulfate mineral of strontium, celestite, is about two orders of magnitude less soluble than gypsum, the calcium sulfate analog. In the absence of anions, such as sulfate or carbonate, strontium is transported in ground water as a divalent, uncomplexed ion. The only significant limitations to strontium mobility in the groundwater result from ion exchange processes. For kaolinite, the dominant clay mineral in SRS sediments, strontium is only moderately sorbed on the exchange sites and can be easily displaced.

The primary pathway for radiostrontium entering the groundwater on the site has been through discharges to retention and/or seepage basins at the reactor sites and in the General Separation Areas. Radiostrontium has not been identified in the liquids that have seeped from high-level waste tanks.

Table 4-3 shows the quantities of ^{90}Sr (decay corrected to 1992) discharged to the various basins on site. ^{89}Sr values, when decay corrected, represent an insignificant fraction of the radiostrontium. The vast majority of the radiostrontium discharge was to three localities, R-, F-, and H-Areas seepage basins. Other direct pathways to ground water are minor compared

to these instances and recent analyses of radiostrontium in the groundwater at the remaining seepage basins at SRS, show little evidence of elevated activities.

R-Area Basins

In R Area, the majority of radioactivity sent to the basins resulted from the failure of an experimental fuel element during a calorimeter test during the fall of 1957. The majority of the activity released to the basin was beta activity from tritium, ^{90}Sr , and ^{137}Cs . An estimated 200 Ci of ^{90}Sr and 470 Ci of ^{137}Cs was discharged to Basin #1 as a result of the incident. This basin was deactivated, backfilled, covered with asphalt, and a clay dike constructed around the perimeter to contain the lateral migration of the radionuclides from the site (Pekkala et al., 1987). The ground water in the immediate vicinity of the basins contains elevated nonvolatile beta emitters. Measured activities in some wells immediately adjacent to the basins routinely exceed 10,000 pCi/L however, the relative contributions of ^{90}Sr and ^{137}Cs to this measured activity is not known at the present time.

In 1975, a substantial increase in radioactivity was noted in a monitor well down gradient from basin #1. Most of the activity was attributed to ^{90}Sr . The subsequent investigation revealed that the migration had occurred primarily through an abandoned sewer line that traversed the basin #1 area (Pekkala et al., 1987). None-the-less, the information illustrates the relative mobilities of strontium and cesium in the groundwater environment. Since the half-lives of ^{90}Sr and ^{137}Cs are very similar (28 vs 30 years), the predominance of the radiostrontium in the downgradient well indicates that cesium is retained to a much greater degree than strontium in the soils beneath the basin.

General Separation Area Basins

During the period of 1954 to 1988, seepage basins were used on the Savannah River Site for the disposal of waste water that contained low concentration levels of chemicals and radionuclides. The seepage basins were intended to delay the release of radionuclides that could not otherwise be contained and to allow time for radioactive decay to decrease the activity (Reichert, 1968). Several of these basins were located in the General Separation Area near F Area and H Area (see Figure 4.12).

Table 4-3 Radiostrontium Releases to Seepage Basins through 1988, Decay Corrected to 1992

Basin	⁹⁰ Sr (Ci)
A-Area Seepage Basins ¹	6.2x10 ⁻²
C-Area Seepage Basins	2.2x10 ⁻¹
F-Area Seepage Basins	2.0x10 ⁺¹
H-Area Seepage Basins	2.3x10 ⁺¹
K-Area Seepage Basins	7.6x10 ⁻²
K-Area Containment Basins	3.8x10 ⁺⁰
L-Area Seepage Basins	9.0x10 ⁻¹
L-Area Oil and Chemical Basins	1.8x10 ⁻¹
P-Area Seepage Basins	2.1x10 ⁺⁰
R-Area Seepage Basins	8.6x10 ⁺¹
Central Shops Seepage Basins	5.8x10 ⁻⁵
1. Discharge reported as ^{89/90} Sr. Assumed to be ⁹⁰ Sr for decay correction.	

F-Area Seepage Basins

The first seepage basin on site was constructed in 1954 just north of F Area, but the seepage rate was inadequate to handle the volume of waste water coming from the F-Area facilities. Three additional basins were constructed south of F Area and received effluent during the period 1954 to 1988. Water infiltrating from the F-Area seepage basins encountered a perched water table 15 to 25 feet below the surface and then a normal water table at a depth of 60 to 65 feet below the land surface. Flow of water at the water table aquifer is toward Fourmile Branch at a rate estimated to be about 0.5 ft/d (Stone and Christensen, 1983). The water infiltrating from these basins produced a plume that could be identified in monitor wells by its high conductivity and tritium activities.

Stone and Christensen (1983) reviewed the then available groundwater data and found only tritium, ⁹⁰Sr, and uranium to be notably mobile in the

subsurface at this site. Nonvolatile beta measurements are routinely conducted on the groundwater as part of the quarterly sampling program. Analyses of ⁹⁰Sr in the samples indicates that about one-half of the nonvolatile beta is contributed by this radionuclide.

H-Area Seepage Basins

The four H-Area seepage basins covered an area of 42,700 m² and were in use from 1955 to 1988. The majority of the liquids discharged to these basins contained low-level radioactivity from the H-Area separations facility. In addition, the effluents to these basins contained metals (including mercury and cadmium), nitrate in the form of HNO₃, and NaOH (Killin et al., 1985). The basins were closed in 1988 and have since been capped.

Though in close proximity to the F-Area basins, the hydrogeology at the H-Area basins is distinct. The depth of the water table is only about 20 feet, and the basins are located closer to the groundwater discharge zone along Fourmile Branch. Much of the groundwater flow in this area of the plant appears to occur in narrow, high permeability channels in the sediments. While a small percentage of the seepage basin waters penetrate into a deeper aquifer, the majority migrate to an outcrop of the water table, or "seepine" above Fourmile Branch (Figure 4.12).

Groundwater monitoring in H Area for radioactive parameters has been conducted since the basins were placed into operation. As in F Area, about one-half of the nonvolatile beta in the ground water is ⁹⁰Sr. Other nonvolatile beta emitters that have been identified in the ground water include ¹⁴C, ⁶³Ni, ⁸⁹Sr, ⁹⁹Tc, ¹²⁹I, ¹³⁴Cs and ¹³⁷Cs. These radioisotopes are usually minor compared to ⁹⁰Sr. Reichert (1968) noted that within less than 10 years the ⁹⁰Sr was being transported to and discharged at the seepine of Fourmile Branch. Discharge of radiostrontium to the seepage basins was viewed by Reichert as being the limiting factor in the use of the seepage basins as it appeared to be reaching Fourmile Branch with minimal retardation or opportunity for radioactive decay. Follow-up studies at the groundwater discharge area near Fourmile Branch (Haselow et al., 1990) showed continuing discharges with concentrations up to 3,200 pCi/L of ⁹⁰Sr.

Figure 4.12 Location Map of Waste Disposal Sites in the General Separations Area

Summary

Radiostrontium is relatively mobile in the SRS groundwater. The principal reasons include very low alkalinity and generally low pHs in SRS ground water. Kaolinite, the principal clay component in the

tertiary aquifers has low cation exchange capacity and low specificity for strontium. As a result, retardation by cation exchange or sorption is low and ^{90}Sr is a major contributor to nonvolatile beta in the SRS groundwater environment.

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Chapter 5. Assessment of Dose/Risk from SRS Strontium Releases

This chapter describes the health impacts associated with exposure to strontium. The methodology used to produce dose estimates is presented. The results of a dose assessment for strontium releases during the 1954–1989 period are discussed.

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Relationship of Dose to Risk and Health Effects

Ionizing Radiation

Ionizing radiation strips electrons from the matter through which it passes. The interaction of ionizing radiation with biological systems can induce a series of physical and chemical reactions that can cause permanent changes in the genetic material of cells. These changes (mutations) may cause abnormal functioning within the cell or lead to cell death.

The nature of radiation-induced cellular changes depends on the magnitude of the dose and the rate at which it is received. For the low doses and dose rates encountered in the environment from SRS releases, the most significant effect is cancer induction. This is believed to be a stochastic effect; that is, an increase in dose increases the probability of the effect, but the severity of the effect is independent of the dose.

A characteristic of stochastic risks is the absence of a threshold. In other words, it is conceivable that any dose of radiation, no matter how small, might give

rise to cancer. On the other hand, there is no way to be certain that a given dose, no matter how large, has caused or ultimately will cause cancer in an individual.

Cancer Risk Estimates

The most comprehensive estimates of cancer induction by exposure to ionizing radiation come from studies of the atomic bomb survivors at Hiroshima and Nagasaki. Less-definitive studies include those of medical patients exposed to therapeutic and diagnostic radiation. Studies of laboratory animals have increased the understanding of dose-effect relationships. The International Commission on Radiological Protection (ICRP) has evaluated all these studies and concluded that the best estimate of lifetime risk of fatal cancer for members of the general population is approximately 500 cases per 1,000,000 person-rem (ICRP, 1991). This is equivalent to one case per 2,000 person-rem.

Strontium Exposure and Dose to Man

Distribution and Retention of Strontium in the Human Body

Strontium is absorbed into the body through ingestion and inhalation. Absorption from the gastrointestinal tract is moderate, with about 30 percent entering the blood stream. Inhaled strontium, which is deposited in the lungs, is rapidly absorbed into the blood stream. A large fraction of strontium in the blood is deposited in bone.

manner at all DOE facilities (DOE, 1988). The factors, based on ICRP recommendations (ICRP, 1979), are used in conjunction with the models described to calculate all the doses reported in this document.

Future changes are anticipated in the dose calculation methodology. The ICRP (ICRP, 1989), which recently issued age-specific dose factors for ingestion of some of the more common isotopes, is developing age-specific dose factors for inhalation of radioisotopes.

Strontium Dosimetry

In 1988, DOE issued internal dose conversion factors to ensure that doses are calculated in a consistent

Models of Strontium Transport and Dose

With the exception of tritium, most of the radioactive materials released from SRS have such low concentrations in the offsite environment that they are not detectable by conventional monitoring techniques. Therefore, radiation doses to offsite individuals and populations are calculated with

mathematical models. These models use known transport mechanisms for atmospheric and liquid releases and known major pathways of exposure to man. Atmospheric and aqueous dispersion models periodically are verified using environmental

measurements of tritium released during normal SRS operations.

The first models used at SRS for calculating offsite doses were developed by SRTC (Cooper, 1975). These models, MREM (atmospheric releases) and RIVDOSE (liquid releases), first were used in 1972. MREM and RIVDOSE were replaced in 1982 with the more technologically advanced models now in use.

SRS annual offsite doses are calculated with the transport and dose models developed for the commercial nuclear industry (NRC, 1977a; NRC, 1977b). The models are implemented at SRS in the following computer programs:

Atmospheric Releases

- MAXIGASP: calculates maximum and average doses to offsite individuals
- POPGASP: calculates offsite population doses

Liquid Releases

- LADTAP XL: calculates maximum and average doses to offsite individuals and collective dose to offsite populations

MAXIGASP and POPGASP are SRTC-modified versions of the Nuclear Regulatory Commission (NRC) programs XOQDOQ (Sagendorf et al., 1982) and GASPAP (Eckerman et al., 1980). The modifications were made to meet requirements for input of physical and biological data specific to SRS. The basic calculations in the XOQDOQ and GASPAP programs have not been modified. LADTAP XL (Hamby, 1991a) utilizes the same basic dispersion and dosimetric models as the NRC version, LADTAP II (Simpson and McGill, 1980), and can be run on a personal computer in a user-friendly environment.

Modeling Atmospheric Dispersion of Radioactive Releases

The routine atmospheric transport of radioactive materials from SRS is evaluated on the basis of meteorological conditions measured continuously at seven onsite meteorological towers. The towers relay wind speed, wind direction, and atmospheric stability information at 1.5-second intervals to SRTC via the WIND (Weather INFORMATION and Display) system. A database of this information containing the 60-minute average values for the period 1982-1986 is accessed by the dispersion codes to estimate downwind concentrations of released radionuclides.

The dispersion of an atmospheric release from SRS is modeled using XOQDOQ, which computes concentrations at ground level as a function of downwind distance and compass sector. At the user's option, the plume can be depleted as a result of dry deposition and/or radioactive decay. Also at the user's option, plume concentrations can be reduced by taking into account the upward displacement of the effluent resulting from thermal buoyancy and/or momentum effects. This option is not used at SRS; i.e., no credit is taken for plume rise.

The plume concentration information generated by XOQDOQ then is used by the dose modeling program GASPAP to estimate doses to offsite individuals and populations. GASPAP is used to estimate doses from a number of pathways, which are illustrated in a general sense in Figure 5.1.

The doses estimated by GASPAP are reported on a pathway-specific basis as follows:

- Plume - external dose from radioactive materials suspended in the atmosphere
- Ground - external dose from radioactive materials deposited on the ground
- Inhalation - internal dose from inhalation of radioactive materials present in the plume
- Vegetation - internal dose from consumption of crops produced in a contaminated area
- Milk - internal dose from consumption of milk produced in a contaminated area

Figure 5.1. Simplified Pathways Between Radioactive Materials Released to the Atmosphere and Man

- **Meat** - internal dose from consumption of meat produced in a contaminated area.

MAXIGASP

The calculations required by XOQDOQ and GASPARG to estimate maximum and average individual doses are performed at SRS using the computer program MAXIGASP, which calculates annual average ground-level air concentrations and 50-year committed doses at a number of points along the site boundary in each of 16 compass sectors.

The program's main output is the maximum dose equivalent to an individual along the SRS perimeter. The maximally exposed individual is assumed to reside continuously at the location of highest exposure and to have living and eating habits that maximize dose. These assumptions provide a ceiling on dose estimates from atmospheric releases, and no such "maximum individual" is believed to exist.

The parameters used to calculate doses with MAXIGASP are presented in Table 5-1.

POPGASP

Calculations required by XOQDOQ and GASPARG to estimate population dose from atmospheric releases are performed at SRS using POPGASP, which calculates annual average ground-level air concentrations and annual doses for each of 160 regions (16 wind-direction sectors at 10 distances per sector) within an 80-kilometer radius of the release location.

In addition to compass-sector-specific meteorological information, POPGASP uses sector-specific data on population distribution. Comparable data on milk, meat, and vegetable production and consumption also are used in the code (Hamby, 1991b). These databases are quite extensive and are available for review in the SRS Environmental Report, published annually. With respect to the human parameters used in POPGASP, the key values are shown in Table 5-1.

Modeling Doses from Liquid Releases

The consequences of liquid releases from SRS are modeled using LADTAP XL (Liquid Annual Doses To All Persons). The potential pathways of exposure from liquid releases to the environment are shown in Figure 5.2. The pathway-specific doses calculated by LADTAP XL are grouped into the following four categories:

- **Potable drinking water** - internal dose from consuming drinking water of Savannah River origin
- **Sport fish and commercial fish** - internal dose from consuming fish of Savannah River origin
- **Saltwater invertebrates** - internal dose from consuming shellfish from estuaries of the Savannah River
- **Recreation** - external dose from recreation (boating, swimming, and shoreline) activities in and along the Savannah River

LADTAP XL estimates individual doses at specific downstream locations. The only removal mechanism included in the transport model as it is used at SRS is radioactive decay. No credit is taken for adsorption on stream sediments.

The major assumption inherent in the application of LADTAP XL to SRS releases is that liquid discharges undergo complete mixing in the Savannah River before reaching potentially exposed populations. This assumption is supported by repeated measurements indicating that complete mixing occurs in the river between SRS and the Highway 301 sampling station (Cummins et al., 1990a).

LADTAP XL generates maximum individual and population doses for all the exposure pathways

Figure 5.2. Simplified Pathways Between Radioactive Materials Released to Ground or Surface Waters and Man

identified above. LADTAP XL calculations are performed with SRS-specific information to the extent that it is available. Summary tables of principal

input values used in LADTAP XL are shown in Tables 5-2 and 5-3.

Table 5-1. Site- and Age-Specific Parameters for Atmospheric Releases.

Demographic Data		Age Distribution, %		
Population Group	Population Size	Children	Teens	Adults
50-mile radius	555,100	18.6	11.1	70.3
Maximum Individual (MAXIGASP)				
Exposure Pathway	Infant	Child	Teen	Adult
Inhalation (m ³ /yr)	1,400	3,700	8,000	8,000
Ingestion				
Cow's milk (L/yr)	244	244	297	230
Meat (kg/yr)	0	30	48	81
Leafy vegetables (kg/yr)	0	17	28	43
Fruits, grains, and other vegetables (kg/yr)	0	276	334	276
External exposure				
Transmission factor for shielding from buildings	0.7	0.7	0.7	0.7
General Population (POPGASP)				
Exposure Pathway	Infant	Child	Teen	Adult
Inhalation (m ³ /yr)	1,400	3,700	8,000	8,000
Ingestion				
Cow's milk (L/yr)	186	186	218	120
Meat (kg/yr)	0	17	27	43
Leafy vegetables (kg/yr)	0	8.5	14	21
Fruits, grains, and other vegetables (kg/yr)	0	171	205	163
External exposure				
Transmission factor for shielding from buildings	0.5	0.5	0.5	0.5

Table 5-2. Site- and Age-specific Parameters for Liquid Releases.

Maximum Individual Dose Assessments (LADTAP II).				
Site Parameters				
Savannah River flow rate (ft ³ /sec)				6,000 or measured average
Transit time from SRS to Savannah River (hr)				24
Shore-width factor				0.2
Human Parameters				
	Infant	Child	Teen	Adult
Water Consumption (L/yr)	260 (330) ^a	260 (510) ^a	260 (510) ^a	370 (730) ^a
Fish Consumption (kg/yr)	0	6	14	19
Shellfish Consumption (kg/yr)	0	2.7	6.1	8
Shoreline Recreation (hr/yr)	0	27	128	23
Swimming (hr/yr)	0	10	50	8.9
Boating (hr/yr)	0	25	117	21

^a The values in parentheses are EPA parameters mandated for use when calculating maximum individual doses to Beaufort-Jasper and Port Wentworth water users.

Table 5-3. Additional Site- and Age-Specific Parameters for Liquid Releases.

Average Individual/Population Dose Assessments (LADTAP II)				
Site Parameters				
Savannah River flow rate (ft ³ /sec)				10,000 or measured average
Transit time from SRS to Savannah River (hr)				24
Transit time from SRS to water treatment plants (hr)				72
Retention time in water treatment system (hr)				24
Shore-width factor				0.2
River dilution in estuary				3
Aquatic food harvest, edible portions (kg/yr)				
Sport fish				35,000
Commercial fish				2,700
Saltwater invertebrates				390,000
Demographic Data				
Population Group	Size	Age Distribution, %		
		Children	Teens	Adults
50-mile radius	555,100	18.6	11.1	70.3
Beaufort-Jasper water users	50,000	21	10	69
Port Wentworth water users	15,000	0	0	100
Human Parameters				
	Infant	Child	Teen	Adult
Water Consumption (L/yr)	260	260	260	370
Fish Consumption (kg/yr)	0	2.9	6.8	9
Shellfish Consumption (kg/yr)	0	0.7	1.5	2
Usage (person-hr)				
Shoreline Recreation (hr/yr)				960,000
Swimming (hr/yr)				160,000
Boating (hr/yr)				1,100,000

Validation of Transport Models Using Monitoring Data

Atmospheric Releases

The radionuclide concentrations predicted by XOQDOQ are compared routinely with measured values of tritium concentrations in air to evaluate the code's performance. (Tritium is the only radionuclide released by SRS that can be routinely detected offsite using conventional measuring techniques.) Predicted values tend to exceed observed values, but not to a degree that would indicate an excessively conservative approach (see Figure 5.3).

Other comparisons of predicted and measured concentrations have been made (Marter, 1984) and have exhibited similar results. The available data suggest that calculated concentrations of tritium in air generally are conservative estimates of actual offsite values.

Liquid Releases

Throughout the period 1954 through 1989, drinking water doses from routine SRS releases have been dominated by tritium. Measured, rather than estimated, tritium concentrations therefore are used for the downriver locations most important in terms of dose calculations: (1) just below SRS, (2) at the Beaufort-Jasper water treatment plant, and (3) at the Port Wentworth water treatment plant. In addition to supplying measured tritium concentrations, such data allows calculation of Savannah River dilution factors

for these locations. The availability of accurate estimates of river dilution characteristics significantly enhances LADTAP's ability to predict downriver concentrations of other radionuclides, such as strontium. The results are conservative because no credit is taken for removal of strontium by adsorption in sediments.

Figure 5.3. Predicted vs Measured Tritium Oxide Concentrations in Air at the Site Perimeter

Impact of SRS Strontium Releases on the Offsite Population

The computer codes MAXIGASP, POPGASP, and LADTAP XL have been used to calculate the effective dose equivalent theoretically received by segments of the offsite population from strontium

exposure during the course of site operations. Results are shown in Tables 5-4 and 5-5 for doses attributable to atmospheric releases and in Tables 5-6 and 5-7 for liquid releases.

Table 5-4. Offsite Doses from Atmospheric Releases of $^{89,90}\text{Sr}$

Year	Release (a) (Ci/yr)	Site Perimeter CEDE (b) (mrem)		EDC (c) (person-rem) 80-km Pop
		Max Ind	Average Ind	
1955	0.426	0.030	0.018	0.85
1956	0.057	0.004	0.002	0.11
1957	0.021	0.002	0.001	0.04
1958	0.024	0.002	0.001	0.05
1959	0.314	0.022	0.013	0.62
1960	0.053	0.004	0.002	0.11
1961	0.041	0.003	0.002	0.08
1962	0.033	0.002	0.001	0.07
1963	0.035	0.003	0.002	0.07
1964	0.040	0.003	0.002	0.08
1965	0.020	0.001	0.001	0.04
1966	0.021	0.002	0.001	0.04
1967	0.014	0.001	0.001	0.03
1968	0.034	0.002	0.001	0.07
1969	0.115	0.008	0.005	0.23
1970	0.056	0.004	0.002	0.11
1971	0.036	0.003	0.002	0.07
1972	0.134	0.009	0.006	0.27
1973	0.014	0.001	0.001	0.03
1974	0.011	0.001	0.000	0.02
1975	0.005	0.000	0.000	0.01
1976	0.005	0.000	0.000	0.01
1977	0.004	0.000	0.000	0.01
1978	0.004	0.000	0.000	0.01
1979	0.002	0.000	0.000	0.00
1980	0.003	0.000	0.000	0.01
1981	0.003	0.000	0.000	0.01
1982	0.002	0.000	0.000	0.00
1983	0.003	0.000	0.000	0.01
1984	0.004	0.000	0.000	0.01
1985	0.002	0.000	0.000	0.00
1986	0.001	0.000	0.000	0.00
1987	0.001	0.000	0.000	0.00
1988	0.001	0.000	0.000	0.00
1989	0.001	0.000	0.000	0.00
S	1.538	0.109	0.066	3.06

(a) Release data for $^{89,90}\text{Sr}$ from Cummins, Hetrick, and Martin, 1991.(b) CEDE = committed effective dose equivalent assuming 100% ^{90}Sr .(c) EDC = environmental dose commitment assuming 100% ^{90}Sr .

Table 5-5. Offsite Doses from Atmospheric Releases of Unidentified Beta

Year	Release (a) (Ci/yr)	Site Perimeter CEDE (b) (mrem)		EDC (c) (person-rem) 80-km Pop
		Max Ind	Average Ind	
1955	0.000	0.000	0.000	0.00
1956	0.000	0.000	0.000	0.00
1957	0.000	0.000	0.000	0.00
1958	0.010	0.043	0.026	0.03
1959	0.490	2.102	1.250	1.29
1960	0.084	0.359	0.213	0.22
1961	0.098	0.421	0.250	0.26
1962	0.313	1.343	0.798	0.83
1963	0.223	0.955	0.568	0.59
1964	0.062	0.264	0.157	0.16
1965	0.093	0.401	0.238	0.25
1966	0.013	0.055	0.033	0.03
1967	0.014	0.058	0.035	0.04
1968	0.004	0.018	0.010	0.01
1969	0.011	0.049	0.029	0.03
1970	0.007	0.028	0.017	0.02
1971	0.002	0.007	0.004	0.00
1972	0.001	0.004	0.003	0.00
1973	0.001	0.002	0.001	0.00
1974	0.000	0.001	0.001	0.00
1975	0.000	0.002	0.001	0.00
1976	0.001	0.003	0.002	0.00
1977	0.000	0.002	0.001	0.00
1978	0.000	0.001	0.000	0.00
1979	0.000	0.001	0.000	0.00
1980	0.001	0.006	0.004	0.00
1981	0.001	0.004	0.002	0.00
1982	0.001	0.003	0.002	0.00
1983	0.002	0.008	0.005	0.00
1984	0.000	0.002	0.001	0.00
1985	0.000	0.002	0.001	0.00
1986	0.001	0.004	0.002	0.00
1987	0.001	0.003	0.002	0.00
1988	0.002	0.008	0.005	0.01
1989	0.000	0.001	0.001	0.00
S	1.436	6.160	3.661	3.79

(a) Release data for unidentified beta from A, C, K, L, P, and R Areas from Cummins, Hetrick, and Martin, 1991.

(b) CEDE = committed effective dose equivalent assuming 100% ⁹⁰Sr.

(c) EDC = environmental dose commitment assuming 100% ⁹⁰Sr.

Table 5-6. Offsite Doses From Stream Releases of Strontium-89

Year	Release (Ci/yr) (a)	River Flow Rate @ (cfs) (a)	B-J Derived Flow Rate (cfs) (a)(b)	PW Derived Flow Rate (cfs) (a)	Max Ind Dose, (mrem) (c)			WTP Pop Dose, (person-rem) (f)		Total Pop Dose, (Person- rem)(df)
					Below SRS (d)	B-J WTP (e)	PW WTP (e)	B-J WTP (e)	PW WTP (e)	
1955	0.000	5974	--	7528	0.000	--	0.000	--	0.000	0.000
1956	0.000	6309	--	7949	0.000	--	0.000	--	0.000	0.000
1957	0.000	8312	--	10473	0.000	--	0.000	--	0.000	0.000
1958	0.000	11038	--	13908	0.000	--	0.000	--	0.000	0.000
1959	0.000	9748	--	12283	0.000	--	0.000	--	0.000	0.000
1960	0.000	13112	--	16521	0.000	--	0.000	--	0.000	0.000
1961	11.370	10909	--	13745	0.009	--	0.006	--	0.045	0.074
1962	24.301	10580	--	13331	0.020	--	0.013	--	0.098	0.163
1963	33.710	11138	--	14034	0.027	--	0.017	--	0.130	0.215
1964	61.990	20497	--	25826	0.027	--	0.017	--	0.130	0.215
1965	6.880	12785	28254	16109	0.005	0.002	0.003	0.044	0.023	0.082
1966	6.090	11175	18376	14080	0.005	0.002	0.003	0.060	0.023	0.098
1967	13.000	10573	22066	13322	0.011	0.004	0.007	0.106	0.053	0.193
1968	6.470	9624	16615	12126	0.006	0.003	0.004	0.070	0.029	0.118
1969	8.484	10945	22034	13790	0.007	0.003	0.004	0.069	0.033	0.124
1970	7.576	8208	27280	10342	0.008	0.002	0.005	0.050	0.040	0.116
1971	1.861	10686	43977	13464	0.002	0.000	0.001	0.008	0.007	0.020
1972	0.248	11235	27385	14156	0.000	0.000	0.000	0.002	0.001	0.003
1973	0.119	14431	23462	16544	0.000	0.000	0.000	0.001	0.000	0.002
1974	0.152	11101	22598	13182	0.000	0.000	0.000	0.001	0.001	0.002
1975	0.008	15408	30978	18987	0.000	0.000	0.000	0.000	0.000	0.000
1976	0.229	13914	35172	16660	0.000	0.000	0.000	0.001	0.001	0.002
1977	0.003	11646	19841	15306	0.000	0.000	0.000	0.000	0.000	0.000
1978	0.000	10522	24332	11450	0.000	0.000	0.000	0.000	0.000	0.000
1979	0.000	13252	34937	17469	0.000	0.000	0.000	0.000	0.000	0.000
1980	0.000	13202	30464	17219	0.000	0.000	0.000	0.000	0.000	0.000
1981	0.000	6599	11698	8579	0.000	0.000	0.000	0.000	0.000	0.000
1982	0.000	7169	19594	10135	0.000	0.000	0.000	0.000	0.000	0.000
1983	0.000	12348	12760	14723	0.000	0.000	0.000	0.000	0.000	0.000
1984	0.000	12759	26368	17196	0.000	0.000	0.000	0.000	0.000	0.000
1985	0.000	7167	9290	8959	0.000	0.000	0.000	0.000	0.000	0.000
1986	0.000	6175	8305	7526	0.000	0.000	0.000	0.000	0.000	0.000
1987	0.000	8955	13219	12619	0.000	0.000	0.000	0.000	0.000	0.000
1988	0.000	5364	7463	7152	0.000	0.000	0.000	0.000	0.000	0.000
1989	0.000	7832	8462	8650	0.000	0.000	0.000	0.000	0.000	0.000
S	182.5	10297	21797	13296	0.13	0.02	0.08	0.41	0.61	1.43

- (a) Release data from Cummins, Hetrick, and Martin, 1991. Flow rates based on USGS data at Highway 301 for the maximum individual below the site. All other doses calculated from flow rates derived from tritium data.
 (b) The Beaufort-Jasper water treatment plant began operation in 1965.
 (c) Individual doses are CEDEs (committed effective dose equivalents).
 (d) Total dose includes contribution from fish and invertebrate consumption, shoreline habitation, recreational use, and water consumption.
 (e) WTP doses calculated for water consumption only.
 (f) Population doses are CEDEs (committed effective dose equivalents).

Table 5-7. Offsite Doses From Stream Releases of Strontium-90

Year	Release (Ci/yr) (a)	River Flow Rate @ (cfs) (a)	B-J Derived Flow Rate (cfs) (a)(b)	PW Derived Flow Rate (cfs) (a)	Max Ind Dose, (mrem) (c)			WTP Pop Dose, (person-rem) (f)		Total Pop Dose, (Person- rem)(df)
					Below SRS (d)	B-J WTP (e)	PW WTP (e)	B-J WTP (e)	PW WTP (e)	
1955	0.146	5974	--	7528	0.003	--	0.002	--	0.016	0.028
1956	0.394	6309	--	7949	0.009	--	0.005	--	0.040	0.071
1957	10.922	8312	--	10473	0.184	--	0.115	--	0.845	1.490
1958	0.698	11038	--	13908	0.009	--	0.006	--	0.041	0.072
1959	1.720	9748	--	12283	0.025	--	0.015	--	0.113	0.200
1960	18.420	13112	--	16521	0.197	--	0.123	--	0.903	1.593
1961	4.240	10909	--	13745	0.054	--	0.034	--	0.250	0.441
1962	6.560	10580	--	13331	0.087	--	0.054	--	0.399	0.703
1963	10.510	11138	--	14034	0.132	--	0.082	--	0.607	1.070
1964	9.570	20497	--	25826	0.065	--	0.041	--	0.300	0.529
1965	4.970	12785	28254	16109	0.054	0.019	0.034	0.475	0.250	0.916
1966	4.320	11175	18376	14080	0.054	0.026	0.034	0.635	0.249	1.073
1967	4.580	10573	22066	13322	0.061	0.023	0.038	0.560	0.278	1.052
1968	5.660	9624	16615	12126	0.082	0.037	0.051	0.920	0.378	1.587
1969	3.807	10945	22034	13790	0.049	0.019	0.030	0.467	0.224	0.861
1970	3.446	8208	27280	10342	0.059	0.014	0.037	0.341	0.270	0.817
1971	2.950	10686	43977	13464	0.039	0.007	0.024	0.181	0.177	0.494
1972	1.428	11235	27385	14156	0.018	0.006	0.011	0.141	0.082	0.285
1973	1.671	14431	23462	16544	0.016	0.008	0.011	0.192	0.082	0.331
1974	1.334	11101	22598	13182	0.017	0.006	0.011	0.159	0.082	0.300
1975	1.189	15408	30978	18987	0.011	0.004	0.007	0.104	0.051	0.192
1976	0.928	13914	35172	16660	0.009	0.003	0.006	0.071	0.045	0.149
1977	0.698	11646	19841	15306	0.008	0.004	0.005	0.095	0.037	0.161
1978	0.487	10522	24332	11450	0.006	0.002	0.005	0.054	0.034	0.111
1979	0.481	13252	34937	17469	0.005	0.002	0.003	0.037	0.022	0.077
1980	0.400	13202	30464	17219	0.004	0.001	0.003	0.035	0.019	0.069
1981	0.348	6599	11698	8579	0.007	0.003	0.004	0.080	0.033	0.139
1982	0.310	7169	19594	10135	0.006	0.002	0.003	0.043	0.025	0.089
1983	0.305	12348	12760	14723	0.003	0.003	0.002	0.064	0.017	0.093
1984	0.333	12759	26368	17196	0.004	0.001	0.002	0.034	0.016	0.063
1985	0.176	7167	9290	8959	0.003	0.002	0.002	0.051	0.016	0.079
1986	0.259	6175	8305	7526	0.006	0.003	0.004	0.084	0.028	0.133
1987	0.285	8955	13219	12619	0.004	0.002	0.002	0.058	0.018	0.092
1988	0.206	5364	7463	7152	0.005	0.003	0.003	0.075	0.023	0.117
1989	0.203	7832	8462	8650	0.004	0.003	0.003	0.065	0.019	0.096
S	103.95	10297	21797	13296	1.30	0.20	0.81	5.02	5.99	15.57

- (a) Release data from Cummins, Helrick, and Martin, 1991. Flow rates based on USGS data at Highway 301 for the maximum individual below the site. All other doses calculated from flow rates derived from tritium data.
 (b) The Beaufort-Jasper water treatment plant began operation in 1965.
 (c) Individual doses are CEDEs (committed effective dose equivalents).
 (d) Total dose includes contribution from fish and invertebrate consumption, shoreline habitation, recreational use, and water consumption.
 (e) WTP doses calculated for water consumption only.
 (f) Population doses are CEDEs (committed effective dose equivalents).

Doses from Atmospheric Releases

Doses from atmospheric releases of $^{89,90}\text{Sr}$ are shown in Table 5-4. Since some stacks were monitored for gross beta (unidentified beta) rather than specifically for strontium, dose calculations were made assuming that all the gross beta was ^{90}Sr ; the results are shown in Table 5-5. Although the quantities of $^{89,90}\text{Sr}$ and gross beta released were similar, the gross beta calculation results in a much larger maximum individual dose because most of the gross beta releases occurred in A Area, near the edge of the site, while the $^{89,90}\text{Sr}$ releases occurred near the center of the site.

As shown in Tables 5-4 and 5-5, the largest annual effective dose equivalent from atmospheric releases theoretically received by an adult occurred in 1959. The effective dose equivalent from strontium to the "maximum" adult at the site perimeter in 1959 was 2.1 mrem. "Maximum" individuals are hypothetical persons who live at the SRS boundary and subsist on diets of locally produced milk, meat, and vegetables during the year of release. No such individuals are known to exist. Nevertheless, if one examines the case of the maximally exposed adult individual living continuously at the site perimeter throughout the period 1954-1989, the cumulative effective dose equivalent from atmospheric releases of strontium has been estimated as 6.3 mrem (Tables 5-4 and 5-5). This value is believed to present the bounding case and would make a minor contribution to the overall dose received during that time period from natural radiation.

A person living in the Central Savannah River Area would have received an effective dose of approximately 10,620 mrem from exposure to natural sources of radioactivity and an additional 2,340 mrem from medical practices and various consumer products during the 36-year period (Cummins et al., 1990b). Therefore, the cumulative dose contribution to this individual from SRS atmospheric strontium releases can be estimated at 0.05 percent.

Because the contribution of SRS strontium releases to any individual's total radiation dose is so small, it is necessary to pool the radiation exposures from a given population if an assessment of potential health risks is desired. The population dose within an 80-kilometer radius is a figure of merit frequently used to make such an assessment.

The population doses reported in Tables 5-4 and 5-5 are based on 1980 census data (555,100 people within 80 km) and current meteorological and dose factor data. If it is assumed that this population has lived in

the SRS vicinity throughout the period of site operation, the total collective effective dose received by that population through 1989 would be 6.9 person-rem.

Risks associated with this collective dose are quite small. The ICRP nominal risk estimate for the number of excess fatal cancers potentially induced by a collective dose of 6.9 person-rem is 0.003. Conversely, in that small population, at the current fatal cancer frequency of 16% (EPA, 1989b), there will be on the order of 90,000 spontaneous fatal cancers from all other causes. Therefore, it is impossible to demonstrate a relationship between any of the cancer deaths occurring in this population and the releases of strontium to the atmosphere from SRS.

Doses from Liquid Releases

Dose equivalents potentially received by downstream consumers of Savannah River water and fish are shown for ^{89}Sr in Table 5-6 and ^{90}Sr in Table 5-7. The dose calculations are based on the total number of curies released directly to onsite streams from 36 years of SRS operations. The release levels reflect contributions from all known effluents. Doses have been calculated for a "maximum" individual living just below SRS who subsists on a diet of untreated Savannah River water and fish of Savannah River origin. Such doses are believed to represent the bounding case for strontium releases to surface water. Drinking water doses also have been calculated for "maximum" individuals at both of the downstream water treatment plants and for the populations served by the plants.

The maximum doses occurred in 1960, the year of highest strontium releases. The dose was reduced somewhat by higher than average river flow rates. The effective dose equivalent to the maximum individual for that year has been estimated at 0.197 mrem. If the hypothetical "maximum" exposure conditions are used as the bounding case for the 36-year period of site operation considered here, the cumulative effective dose to such an individual would be on the order of 1.43 mrem.

Since this individual's dose from non-SRS sources of radiation for that same time period would have exceeded 12,000 mrem, it may be concluded that the contribution to downstream individuals' doses by SRS strontium releases is insignificant. An effective dose equivalent of ≤ 1 mrem/yr has been termed a Negligible Individual Risk Level by the National Council on Radiation Protection and Measurements (NCRP, 1987).

With respect to the effect of liquid strontium releases on the populations downstream of the SRS, drinking water doses for users of the Beaufort-Jasper (50,000 customers) and Port Wentworth, (15,000 effective consumers) water treatment plants also have been estimated. Different terminology is used to describe the two populations to reflect the difference in their compositions. The Beaufort-Jasper plant services residential areas and therefore provides full-scale domestic water service. The Port Wentworth facility serves a commercial complex in which contact with

treated Savannah River water is limited to industrial workers who consume tap water at work.

If the cumulative effective doses received by both of these populations are summed, the collective dose equivalent would be about 12 person-rem. Using the ICRP nominal risk factor (ICRP, 1991), the predicted impact of this collective dose is an estimated 0.006 excess fatal cancers in a population of 65,000 people—10,400 of whom, at the current fatal cancer rate, are projected to succumb to cancer from all other sources.

Comparisons of Strontium Doses with Applicable Regulations

Atmospheric Releases

The highest hypothetical effective dose received by the maximally exposed individual due to atmospheric releases of strontium from SRS was 2.1 mrem in 1959 (Table 5-5). The current annual limit on doses to members of the public recommended by the ICRP is 500 mrem. The DOE and EPA (EPA, 1989b) have established a 10 mrem/year limit on effective dose equivalent to members of the public via atmospheric releases.

Liquid Releases

The current standard for strontium in drinking water is 4 mrem/yr (EPA, 1977). As shown in Tables 5-6 and 5-7, at no time during site operations has the annual dose from SRS strontium releases to the Savannah River exceeded 0.197 mrem. It is important to note that all the dose limits described above are meant to be applied to all releases of radioactivity, not just strontium. SRS, based on strontium or total releases, is consistently a minor contributor to radiation dose in the SRS environment.

Summary of Dosimetric Impacts

The overall radiological impact of SRS strontium releases (1954-1989) on the offsite maximally exposed individual can be characterized by total doses of 6.2 mrem (atmospheric) and 1.4 mrem (liquid). During this period, however, such an individual received a dose of approximately 12,960 mrem from other sources of ionizing radiation present in the environment.

The impact of SRS strontium releases on offsite populations also has been evaluated. The total collective dose from atmospheric strontium releases (1954-1989) is estimated at 6.8 person-rem

distributed among 555,100 individuals. The total collective dose from liquid strontium releases for the same period was 12 person-rem distributed among 65,000 individuals. These collective doses are minor components of the doses received from other environmental sources.

Strontium releases from SRS have decreased dramatically over the course of site operations. Based on data published in the annual environmental reports, routine strontium releases from SRS present a negligible risk to the offsite environment and the population it supports.

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