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Radionuclides in the Savannah River Site Environment

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Abstract

The Savannah River Site has produced plutonium, tritium, and other special nuclear materials for national defense, other government programs, and some civilian purposes. Radionuclides have been released to the environment during the operation of five reactors, two radiochemical processing facilities, and other supporting facilities. During the period 1954-1996, releases to the atmosphere and site streams contributed dose to the local population. The maximum individual effective dose equivalent at the site boundary was estimated to be 770 µSv from atmospheric releases and 1400 µSv from liquid releases. The 80-km population dose was 48 person-Sv.

Key words: Contamination, environmental; dose; water

Introduction

Radioactive releases of certain radionuclides from the Savannah River Site and associated dose to the population have been published (Carlton, 1994, 1996, 1999). This publication summarizes all releases that contributed at least 0.1% to the total population dose from 1954 through 1996.

This study is not intended to be a rigorous dose reconstruction from original historic measurements but is a dose assessment that uses summary information and average meteorological and population data (Cummins et al. 1991a; Cummins et al. 1991b; Arnett et al. 1992; Arnett et al. 1993; Arnett et al. 1994; Arnett et al. 1995; Arnett et al. 1996; Arnett et al. 1997). The results are reasonably accurate and extremely cost effective.

SRS Operations and Releases

The five heavy-water-moderated 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. One example is ^{238}Pu, which is a power source for deep-space missions (Carlton et al. 1996). A description of reactor facilities, locations, and operations has been published (Carlton et al. 1994).

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 to Fourmile Branch.

K Reactor was operational from 1954 until 1988 and restarted for a few months in 1992. Reactor basin purges were discharged to Pen Branch.

L Reactor was operational from 1954 to 1968, when it was placed in standby. It was refurbished in the early 1980s, restarted in 1985, and operated until 1988. During L-Reactor's second operational period, secondary cooling water from the reactor heat exchanger and reactor basin purges were discharged to L Lake, which drains into Steel Creek.

P Reactor was operational from 1954 until 1988. Reactor basin purges were discharged to Steel Creek and Par Pond. Reactor cooling water and miscellaneous effluents were discharged to Steel Creek until 1963. Most of the cooling water was later diverted to Par Pond.

R Reactor was the first operational production reactor at SRS. It operated from late 1953 until 1964. Discharges went to Lower Three Runs and Par Pond.

Two chemical separation facilities are located near the center of the site. The two separation areas are identified by letter designations F and H and were used to reprocess irradiated fuel and targets in canyon buildings. Irradiated materials were dissolved and the products of interest were chemically separated and purified from waste fission and activation products. A description of separation facilities, locations, and operations has been published (Carlton et al. 1994).

The Savannah River Technology Center (SRTC) in A Area provided research and development support for SRS production. The moderator rework facility in D Area purified heavy-water moderator from the reactors. The fuel fabrication facility in M Area produced reactor fuel elements, targets and control rods.

Atmospheric and liquid releases for the Savannah River Site are shown in Table 1. Details for individual radionuclides follow.

Tritium

Tritium was one of the principal products at SRS. It was produced in reactors in lithium-aluminum targets subjected to intense neutron irradiation. The targets were processed and the tritium packaged for shipment to other DOE facilities. A second (and undesirable) method of tritium production occurred when neutrons interacted with the heavy water moderator in the reactors. This tritium was the principal source of liquid releases and a significant contributor to atmospheric releases. A third method of tritium production, discovered at SRS, was ternary fission (Albenesius 1959). The uranium atom occasionally split into three pieces, one of which was tritium.

Carbon-14

SRS produced ^{14}C by various reactions in the fuel, moderator, and core construction materials in SRS production reactors. The mechanisms included neutron-induced reactions [(n,p); (n,[alpha]); and (n,[gamma])] and ternary fission (Hayes and MacMurdo, 1977). The (n,p) reaction produced ^{14}C by reaction of neutrons with ^{14}N. Nitrogen occurred as an impurity in the fuel, as dissolved gas, as nitric acid, as ammonium hydroxide (used for pH control purposes in the moderator), and as an impurity in the core material. Small quantities of ^{14}C also were produced by the (n,p) reaction with nitrogen in the air in the annular cavity outside the reactor tank. The (n,[alpha]) reaction occurred primarily with ^{17}O in the moderator. The (n,[gamma]) reaction with ^{13}C produced a negligible amount of ^{14}C in SRS reactors, which released ^{14}C to the atmosphere as ^{14}CO and $^{14}CO_2$ through their ventilation systems.

Radiocarbon releases from the separations facilities were to the atmosphere. Dissolution of fuel and targets in strong nitric acid solutions assured the oxidation and volatilization of any carbon compounds in the fuel and target elements during processing. Atmospheric releases of ^{14}C were calculated from known operating power levels and fuel types using the assumptions given in Hayes and MacMurdo (1977). In more recent years, stack releases of ^{14}C have been measured to confirm the calculated data.

Phosphorus-32

During normal reactor operations at SRS, small amounts of ^{32}P were in the moderator; these originated from (n,p) activation of sulfur leached from moderator deionizers (Longtin, 1966). In the mid-1960s, phosphoric acid, H_3PO_4, was used to clean heat exchangers, and the residual ^{31}P was converted to radioactive ^{32}P by neutron absorption (Ashley, 1966). When reactor elements were discharged to the disassembly basin, ^{32}P on the outside surfaces leached into disassembly basin water. Continuous purging of the basin water was the primary pathway by which aqueous activation products were released to the environment. The basin water initially was 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 purged water decreased significantly, as did the release of radioactivity.

Argon-41

Argon-41 originated at SRS as an activation product when neutrons produced in SRS's reactor vessels irradiated air surrounding the vessel. Stable ^{40}Ar captured a neutron and became ^{41}Ar, which was swept from the vicinity of the reactor vessel and exhausted through a 61-m stack.

Chromium-51

Chromium-51 activity in the moderator originated from activation of stable ^{50}Cr in stainless steel reactor components in the reactor tank. Additional ^{51}Cr was produced from ^{50}Cr contained in erosion and corrosion products of stainless steel used in the reactor cooling system piping (Longtin, 1972). The ^{51}Cr was formed when the erosion and corrosion products were transported into the reactor vessel and exposed to neutrons. Chromium-51 was released to site streams in a manner identical to that of ^{32}P.

Cobalt-60

Most atmospheric ^{60}Co releases came from SRTC during the period 1968-1984. The releases were the result of research on a thermoelectric generator program that used many thousands of curies of ^{60}Co as the heat source (Angerman 1973; Zecha 1987).

Cobalt-60 activity in the moderator originated through the activation of ^{59}Co contained in erosion and corrosion products. Cobalt-60 was released to site streams in a manner identical to that of ^{32}P.

Zinc-65

64Zn, which was found as a trace element in aluminum reactor fuel and target components (Fox, 1975). Zinc-65 was released to site streams in a manner identical to that of ^{32}P.

Strontium

The principal mechanism for production of strontium was neutron-induced fission in the reactors. When a reactor was operating, neutron-induced fission reactions occurred in the ^{235}U fuel of the reactor core. Fission reactions formed a variety of fission products, of which strontium was one of the most important.(br>

Strontium was not observed in atmospheric releases from the reactors. Most strontium released to the atmosphere came from the separation process in F Area and H Area. In contrast, most of the strontium released to streams came from basin purges in the reactor areas. Releases of unidentified beta-gamma occurred primarily from A Area and were assumed to be ^{90}Sr for dose calculations.

Zirconium-Niobium-95, ^{106}Ru, ^{144}Ce

The principal mechanism for production of ^{95}Zr, ^{95}Nb, ^{106}Ru, and ^{144}Ce was neutron-induced fission in the reactors. When a reactor was operating, neutron-induced fission reactions occurred in the ^{235}U fuel of the reactor core. Fission reactions formed a variety of fission products, which included those listed above.

Fission products rarely were seen in atmospheric releases from the reactors. Most fission products released to the atmosphere resulted from the separation process in F Area and H Area. In contrast, most of the fission products released to streams came from basin purges in the reactor areas.

Technetium

There were virtually no measurements of ^{99}Tc releases. Release quantities have been conservatively estimated.

Iodine-129 and Iodine-131

The principal mechanism for production of ^{129}I and ^{131}I was neutron-induced fission in the reactors. When a reactor was operating, neutron-induced fission reactions occurred in the ^{235}U fuel of the reactor core. Fission reactions formed a variety of fission products, which included several isotopes of iodine. The two largest contributors to environmental dose were ^{129}I and ^{131}I.

Iodine was released to the atmosphere when the fuel and target elements were chemically dissolved in F Area and H Area. The quantity of ^{131}I released depended on the cooling time between reactor shutdown and dissolution of the elements. Cooling times were much shorter during the 1950s, when there was a greater sense of production urgency.

Cesium-137

The principal mechanism for production of ^{137}Cs was neutron-induced fission in the reactors. When a reactor was operating, neutron-induced fission reactions occurred in the ^{235}U fuel of the reactor core. Fission reactions formed a variety of fission products, which included isotopes of cesium. Additional ^{137}Cs was formed in the reactor as a result of neutron activation of stable cesium generated by neutron fission.

There were no recorded atmospheric ^{137}Cs releases from the reactors. Most of the atmospheric ^{137}Cs released from the separation areas was the result of two incidents. The first occurred in 1955 during startup, primarily as a result of leakage around the sand filter bypass plug. The second occurred in 1987, when an evaporator steam flange failed in the waste management facility.

Most of the liquid ^{137}Cs releases were from the reactors as a result of leaking fuel elements in the 1950s and 1960s. The fuel elements were stored in disassembly basins, and ^{137}Cs was released to site streams when basin water was purged to maintain clarity and remove heat. Approximately two-thirds remain in the stream beds, flood plains, ponds, and swamps on or near SRS.

Uranium

Uranium releases generally have been associated with the fabrication of reactor fuel and target elements (M Area) and with the chemical processing of spent target and fuel material (F Area and H Area).

Plutonium

Plutonium at SRS was formed during the irradiation of nuclear fuel and targets during operation of the site's five production reactors.

Atmospheric plutonium releases occurred primarily in F Area and H Area and were largest during startup of the canyon facilities in 1955. Unidentified alpha releases from the reactors and other facilities were assumed to be plutonium. Approximately 70 % of atmospheric plutonium releases occurred in 1955.

Curium-244

Beginning in 1963, transplutonium isotopes were prepared by placing ^{239}Pu targets in high-flux charges in SRS reactors. After the targets were dissolved and processed in a separation facility, they were delivered to SRTC for further processing. The work involved gram quantities of curium and americium, microgram quantities of californium and berkelium, and nanogram quantities of einsteinium. By 1968, approximately 5 kg of ^{244}Cm had been recovered (Moyer 1968). The ^{244}Cm was used in an experimental program as a heat source for isotopic electrical power generators (Stoddard 1964).

Atmospheric ^{244}Cm releases were reported for F Area and H Area, but the majority of released material came from A Area during the years when research was conducted on the use of ^{244}Cm as a heat source for electricity generation.

Surface Water Transport

SRS is drained by five streams that flow into the Savannah River. Except for ^{137}Cs, it was conservatively assumed that the radionuclides released to site streams were not adsorbed or deposited in the streambeds or in the Savannah River. Site specific studies have shown that only 35% of ^{137}Cs released to streams was transported to the Savannah River (Carlton 1994). A description of the site streams has been published previously (Carlton 1994).

Dose to Humans

SRS offsite doses were calculated with the transport and dose models developed for the commercial nuclear industry (USNRC 1977a; USNRC 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 collective dose.

Liquid Releases

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

MAXIGASP and POPGASP are SRS-modified versions of the Nuclear Regulatory Commission (NRC) programs XOQDOQ (Sagendorf et al. 1982) and GASPAR (Eckerman et al. 1980). The modifications were made to meet the requirements for input of physical and biological data that are specific to SRS. The basic calculations in the XOQDOQ and GASPAR programs have not been modified. LADTAP XL is a spreadsheet version of LADTAP II (Simpson and McGill 1980).

In 1988, the U. S. Department of Energy (DOE) issued dose conversion factors to ensure that doses are calculated in a consistent manner at all DOE facilities (U.S. DOE 1988). The factors are based on ICRP recommendations (ICRP 1979) and were used in conjunction with the models described to calculate all doses.

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 nine onsite towers. A database containing the 60-min average values for the period 1987-1991 is accessed by the dispersion codes to estimate downwind concentrations of released radionuclides. Offsite doses have been calculated assuming two release points. Doses were calculated for A-Area releases (near the edge of the site) using A-Area meteorology. Doses were calculated for the remainder by assuming the releases occurred at the geographic center of the site and using meteorology measured by the H-Area tower.

The dispersion of atmospheric releases from SRS was modeled using XOQDOQ, which estimates concentrations in the plume as a function of downwind distance and compass sector. The model takes into account depletion due to dry deposition and radioactive decay.

The doses estimated by GASPAR 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 contaminated crops
- **Milk**-internal dose from consumption of milk produced in a contaminated area
- **Meat**-internal dose from consumption of meat produced in a contaminated area.

Additional information on the details of the modeling are available (Carlton et al. 1994).

Modeling doses from liquid releases

The consequences of liquid releases from SRS were modeled using LADTAP XL. Pathway-specific doses 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
- **Salt water invertebrates**-internal dose from consuming shell fish from the Savannah River estuary
- **Recreation**-external dose from recreation activities in and along the Savannah River (boating, swimming, and shoreline activities).

LADTAP XL estimates individual and population doses at specific downriver 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 or removal by the water treatment process at the downriver water treatment plants.

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 16 river km between Lower Three Runs and the Highway 301 sampling station (Cummins et al. 1991a). The nearest water treatment plant is 140 river km downstream from SRS.

LADTAP XL generates maximum individual and population doses for all of the exposure pathways identified above. SRS calculations are performed with site-specific information. Radioisotope concentration in the Savannah River is decreased by the inflow of streams downriver from SRS. Additional dilution occurs at the Beaufort-Jasper water treatment plant due to the inflow of surface water and at the Port Wentworth water treatment plant due to the close proximity of Abercorn Creek to the intake. Since SRS-released tritium is readily measured in the Savannah River, and in the processed water of each system, a derived river flow rate based on simple dilution was calculated. This allows more accurate estimates of strontium concentrations at these treatment plants.

Doses from atmospheric releases

As shown in Table 2, the effective dose equivalent theoretically received by the maximally exposed adult individual was 770 μSv. The radionuclide contributing the highest portion of this dose was ^{131}I, followed by ^{3}H, Pu (includes ^{238}Pu, ^{239}Pu, and gross alpha), and ^{41}Ar.

A person living in the SRS area would have received an effective dose of approximately 1.2 x 10^5 μSv from exposure to natural sources of radioactivity and an additional 2.6 x 10^4 μSv from medical practices and various consumer products during the 43 y period (Cummins et al. 1991b).

The population doses in Table 3 were based on 1980 census data (555,100 people within 80 km) and current meteorological and dose factor data. It was assumed that this population lived in the SRS vicinity (within 80 km) throughout the period of site operation. The total collective effective dose from atmospheric releases through 1996 was 32 person-Sv.

Doses from liquid releases

Dose equivalents were calculated for the maximally exposed individual living just downstream from SRS who subsisted on a diet of untreated Savannah River water and fish of Savannah River origin (Table 2). The total dose was 1.4 x 10^3 μSv with ^{137}Cs and ^{32}P contributing 75% the dose.

Since an individual's dose from non-SRS sources of radiation for that same time period was almost 1.5 x 10^5 μSv, it may be concluded that the contribution to downstream individual doses by SRS releases is insignificant.

The total population dose for liquid releases is the sum of the dose from the water treatment plants pathway (1.9 person-Sv, 65,000 people) plus the dose due to other liquid pathways such as fish and recreation (15 person-Sv, 555,100 people). The collective dose equivalent is 17 person-Sv distributed among 620,100 people.

The total population dose from both atmospheric and liquid releases is shown by year in Table 4 and is graphically depicted in Fig. 1. The highest years were 1955 and 1956 when atmospheric ^{131}I and Pu releases occurred. Population dose has declined over the years, decreasing by a factor of 10 by 1973 and by a factor of 100 by 1995.

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Table 1. SRS Atmospheric and Liquid Releases by Radionuclide, 1954-1996.

*

Radionuclide	Atmospheric Releases (GBq)	Liquid Releases (GBq)
^{3}H	9.6×10^{8}	5.9×10^{7}
^{14}C	1.1×10^{5}	
^{32}P		1.3×10^{3}
^{41}Ar	2.4×10^{8}	
^{51}Cr		1.7×10^{5}
^{60}Co	3.4×10^{0}	2.4×10^{3}
^{65}Zn		5.2×10^{3}
Sr	1.1×10^{2}	5.6×10^{3}
^{95}Zr,Nb		4.8×10^{3}
^{99}Tc	4.1×10^{2}	
^{106}Ru	5.2×10^{3}	2.2×10^{3}
^{129}I	2.1×10^{2}	
^{131}I	9.3×10^{4}	1.1×10^{4}
^{137}Cs	1.3×10^{2}	7.8×10^{3}
^{144}Ce		1.3×10^{4}
U*	3.2×10^{1}	9.3×10^{2}

Pu**	1.4 x 10^2	2.7 x 10^1
^{244}Cm	3.3 x 10^0	1.4 x 10^1

*Natural Uranium analyzed as ^{238}U
**Includes ^{238}Pu, ^{239}Pu, and gross alpha

Table 2. Dose to Maximally Exposed Individual by Radionuclide, 1954-1996.

Radionuclide	**Atmospheric Dose (uSv)**	**Percent of Atmospheric Dose**	**Liquid Dose (uSv)**	**Percent of Liquid Dose**
^{3}H	1.8 x 10^2	23.3	7.9 x 10^1	5.5
^{14}C	9.8 x 10^0	1.3		
^{32}P			4.6 x 10^2	32.1
^{41}Ar	7.8 x 10^1	10.1		
^{51}Cr			2.2 x 10^0	0.2
^{60}Co	7.6 x 10^0	1.0	4.4 x 10^0	0.3
^{65}Zn			7.3 x 10^1	5.1
Sr	7.2 x 10^1	9.3	2.5 x 10^1	1.7
^{95}Zr,Nb			1.5 x 10^2	10.5
^{99}Tc	1.0 x 10^0	0.1		
^{106}Ru	4.4 x 10^1	5.7	1.1 x 10^0	0.1
^{129}I	3.9 x 10^1	5.1		
^{131}I	2.1 x 10^2	27.2	1.5 x 10^1	1.0
^{137}Cs	4.7 x 10^0	0.6	6.1 x 10^2	42.6
^{144}Ce			4.7 x 10^0	0.3
U*	4.2 x 10^0	0.5	4.7 x 10^0	0.3
Pu**	1.2 x 10^2	15.5	2.8 x 10^0	0.2
^{244}Cm	1.5 x 10^0	0.2	1.1 x 10^0	0.1
Total	7.7 x 10^2		1.4 x 10^3	

*Natural Uranium analyzed as ^{238}U
**Includes ^{238}Pu, ^{239}Pu, and gross alpha

Table 3. Percent of Population Dose Contributed by Each Radionuclide, 1954-1996.

Radionuclide	Atmospheric Dose (per-Sv)	Percent of Atmospheric Dose	Liquid Dose (per-Sv)	Percent of Liquid Dose	Total Dose (per-Sv)	Percent of Total Dose
^{3}H	1.1 X 10^{1}	34.6	1.3 X 10^{0}	7.9	1.2 X 10^{1}	25.1
^{14}C	3.0 X 10^{-1}	0.9			3.0 X 10^{-1}	0.6
^{32}P			1.1 X 10^{0}	6.7	1.1 X 10^{0}	2.3
^{41}Ar	1.9 X 10^{0}	6.0			1.9 X 10^{0}	4.0
^{51}Cr			9.6 X 10^{-2}	0.6	9.6 X 10^{-2}	0.2
^{60}Co	6.5 X 10^{-3}	0	2.8 X 10^{-1}	1.7	2.9 X 10^{-1}	0.6
^{65}Zn			1.1 X 10^{1}	66.0	1.1 X 10^{1}	23.0
Sr	6.3 X 10^{-2}	0.2	2.4 X 10^{-1}	1.5	3.0 X 10^{-1}	0.6
^{95}Zr,Nb			2.5 X 10^{-1}	1.5	2.5 X 10^{-1}	0.5
^{99}Tc	6.5 X 10^{-2}	0.2	2.4 X 10^{-3}	0	6.7 X 10^{-2}	0.1
^{106}Ru	1.2 X 10^{0}	3.7	1.4 X 10^{-1}	0.9	1.3 X 10^{0}	2.7
^{129}I	1.0 X 10^{0}	3.2			1.0 X 10^{0}	2.1
^{131}I	8.3 X 10^{0}	26.2	1.1 X 10^{-1}	0.6	8.4 X 10^{0}	17.5
^{137}Cs	3.4 X 10^{-1}	1.1	1.3 X 10^{0}	7.9	1.6 X 10^{0}	3.3
^{144}Ce			4.7 X 10^{-1}	2.8	4.7 X 10^{-1}	1.0
U*	3.2 X 10^{-1}	1.0	8.2 X 10^{-2}	0.5	4.0 X 10^{-1}	0.8
Pu**	7.1 X 10^{0}	22.4	1.2 X 10^{-1}	0.7	7.2 X 10^{0}	15.0
^{244}Cm	8.9 X 10^{-2}	0.3	1.2 X 10^{-1}	0.7	2.1 X 10^{-1}	0.4
Total	3.2 X 10^{1}		1.7 X 10^{1}		4.8 X 10^{1}	

*Natural Uranium analyzed as ^{238}U

**Includes ^{238}Pu, ^{239}Pu, and gross alpha

Table 4. Total Population Dose by Year (person-Sv)

		Dose from Liquid Releases

Year	Dose from Atmospheric Releases	Beaufort-Jasper	Port Wentworth	80-Kilometer	Total	Total
1954	1.5 X 10^{-2}		6.1 X 10^{-5}	5.6 X 10^{-4}	6.3 X 10^{-4}	1.6 X 10^{-2}
1955	5.8 X 10^{0}		5.3 X 10^{-3}	1.4 X 10^{-2}	1.9 X 10^{-2}	5.8 X 10^{0}
1956	5.7 X 10^{0}		9.4 X 10^{-3}	2.2 X 10^{-2}	3.2 X 10^{-2}	5.7 X 10^{0}
1957	1.8 X 10^{0}		3.4 X 10^{-2}	1.7 X 10^{-1}	2.0 X 10^{-1}	2.0 X 10^{0}
1958	1.4 X 10^{0}		8.1 X 10^{-3}	1.5 X 10^{-2}	2.3 X 10^{-2}	1.4 X 10^{0}
1959	1.4 X 10^{0}		1.6 X 10^{-2}	4.0 X 10^{-2}	5.7 X 10^{-2}	1.5 X 10^{0}
1960	8.6 X 10^{-1}		3.5 X 10^{-2}	4.7 X 10^{-1}	5.0 X 10^{-1}	1.4 X 10^{0}
1961	1.2 X 10^{0}		3.3 X 10^{-2}	1.9 X 10^{0}	1.9 X 10^{0}	3.1 X 10^{0}
1962	8.1 X 10^{-1}		4.4 X 10^{-2}	2.9 X 10^{0}	3.0 X 10^{0}	3.8 X 10^{0}
1963	7.9 X 10^{-1}		5.6 X 10^{-2}	3.1 X 10^{0}	3.2 X 10^{0}	3.9 X 10^{0}
1964	9.9 X 10^{-1}		2.8 X 10^{-2}	1.2 X 10^{0}	1.2 X 10^{0}	2.2 X 10^{0}
1965	7.1 X 10^{-1}	7.3 X 10^{-2}	3.8 X 10^{-2}	1.2 X 10^{0}	1.3 X 10^{0}	2.0 X 10^{0}
1966	6.5 X 10^{-1}	9.8 X 10^{-2}	3.9 X 10^{-2}	1.1 X 10^{0}	1.2 X 10^{0}	1.9 X 10^{0}
1967	5.9 X 10^{-1}	1.0 X 10^{-1}	5.0 X 10^{-2}	1.0 X 10^{0}	1.2 X 10^{0}	1.7 X 10^{0}
1968	7.4 X 10^{-1}	9.5 X 10^{-2}	4.0 X 10^{-2}	7.1 X 10^{-1}	8.5 X 10^{-1}	1.6 X 10^{0}
1969	1.7 X 10^{0}	5.4 X 10^{-2}	2.6 X 10^{-2}	2.3 X 10^{-1}	3.1 X 10^{-1}	2.0 X 10^{0}
1970	5.1 X 10^{-1}	2.8 X 10^{-2}	2.2 X 10^{-2}	1.7 X 10^{-1}	2.2 X 10^{-1}	7.3 X 10^{-1}
1971	5.6 X 10^{-1}	2.0 X 10^{-2}	1.9 X 10^{-2}	3.1 X 10^{-1}	3.5 X 10^{-1}	9.1 X 10^{-1}
1972	5.6 X 10^{-1}	2.8 X 10^{-2}	1.6 X 10^{-2}	2.9 X 10^{-2}	7.3 X 10^{-2}	6.3 X 10^{-1}
1973	4.5 X 10^{-1}	4.5 X 10^{-2}	1.9 X 10^{-2}	1.0 X 10^{-2}	7.3 X 10^{-2}	5.2 X 10^{-1}
1974	5.3 X 10^{-1}	3.7 X 10^{-2}	2.0 X 10^{-2}	1.8 X 10^{-2}	7.6 X 10^{-2}	6.1 X 10^{-1}
1975	3.0 X 10^{-1}	2.5 X 10^{-2}	1.2 X 10^{-2}	3.7 X 10^{-3}	4.2 X 10^{-2}	3.4 X 10^{-1}
1976	2.4 X 10^{-1}	2.4 X 10^{-2}	1.5 X 10^{-2}	2.5 X 10^{-3}	4.1 X 10^{-2}	2.8 X 10^{-1}
1977	2.4 X 10^{-1}	3.1 X 10^{-2}	1.2 X 10^{-2}	3.5 X 10^{-3}	4.6 X 10^{-2}	2.9 X 10^{-1}
1978	5.0 X 10^{-1}	2.1 X 10^{-2}	1.4 X 10^{-2}	1.8 X 10^{-3}	3.6 X 10^{-2}	5.4 X 10^{-1}
1979	2.0 X 10^{-1}	1.2 X 10^{-2}	7.4 X 10^{-3}	3.3 X 10^{-3}	2.3 X 10^{-2}	2.2 X 10^{-1}
1980	2.2 X 10^{-1}	1.2 X 10^{-2}	6.2 X 10^{-3}	1.3 X 10^{-3}	1.9 X 10^{-2}	2.4 X 10^{-1}
1981	2.5 X 10^{-1}	2.9 X 10^{-2}	1.2 X 10^{-2}	3.1 X 10^{-3}	4.5 X 10^{-2}	2.9 X 10^{-1}
1982	2.5 X 10^{-1}	2.3 X 10^{-2}	1.3 X 10^{-2}	2.7 X 10^{-3}	3.9 X 10^{-2}	2.9 X 10^{-1}
1983	3.3 X 10^{-1}	3.6 X 10^{-2}	9.3 X 10^{-3}	1.3 X 10^{-3}	4.7 X 10^{-2}	3.8 X 10^{-1}
1984	3.9 X 10^{-1}	1.8 X 10^{-2}	8.1 X 10^{-3}	3.6 X 10^{-3}	3.0 X 10^{-2}	4.2 X 10^{-1}
1985	2.7 X 10^{-1}	3.7 X 10^{-2}	1.2 X 10^{-2}	2.0 X 10^{-3}	5.0 X 10^{-2}	3.2 X 10^{-1}
1986	1.8 X 10^{-1}	4.6 X 10^{-2}	1.5 X 10^{-2}	2.7 X 10^{-3}	6.3 X 10^{-2}	2.4 X 10^{-1}

1987	2.8 X 10^{-1}	2.4 X 10^{-2}	7.7 X 10^{-3}	3.6 X 10^{-3}	3.6 X 10^{-2}	3.2 X 10^{-1}
1988	1.6 X 10^{-1}	3.6 X 10^{-2}	1.1 X 10^{-2}	4.1 X 10^{-3}	5.1 X 10^{-2}	2.1 X 10^{-1}
1989	1.2 X 10^{-1}	2.9 X 10^{-2}	8.5 X 10^{-3}	3.0 X 10^{-3}	4.1 X 10^{-2}	1.6 X 10^{-1}
1990	9.2 X 10^{-2}	1.5 X 10^{-2}	5.6 X 10^{-3}	2.6 X 10^{-3}	2.3 X 10^{-2}	1.2 X 10^{-1}
1991	6.8 X 10^{-2}	2.0 X 10^{-2}	7.3 X 10^{-3}	2.5 X 10^{-3}	3.0 X 10^{-2}	9.8 X 10^{-2}
1992	5.0 X 10^{-2}	1.8 X 10^{-2}	6.6 X 10^{-3}	2.2 X 10^{-3}	2.6 X 10^{-2}	7.7 X 10^{-2}
1993	6.8 X 10^{-2}	9.6 X 10^{-3}	3.9 X 10^{-3}	1.4 X 10^{-3}	1.5 X 10^{-2}	8.3 X 10^{-2}
1994	5.6 X 10^{-2}	1.1 X 10^{-2}	4.1 X 10^{-3}	2.7 X 10^{-3}	1.8 X 10^{-2}	7.4 X 10^{-2}
1995	3.1 X 10^{-2}	1.1 X 10^{-2}	3.9 X 10^{-3}	2.7 X 10^{-3}	1.8 X 10^{-2}	4.9 X 10^{-2}
1996	2.6 X 10^{-2}	1.4 X 10^{-2}	4.6 X 10^{-3}	4.0 X 10^{-3}	2.2 X 10^{-2}	4.9 X 10^{-2}
Total	3.2 X 10^{+1}	1.1 X 10^{0}	7.5 X 10^{-1}	1.5 X 10^{+1}	1.7 X 10^{+1}	4.8 X 10^{+1}

Figure 1. SRS Annual Population Dose