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Critical Radionuclide and Pathway Analysis for the Savannah River Site, 2016 Update

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EXECUTIVE SUMMARY

During the operational history of Savannah River Site, many different radionuclides have been released from site facilities. However, as shown in this analysis, only a relatively small number of the released radionuclides have been significant contributors to doses to the offsite public. This report is an update to the 2011 analysis, *Critical Radionuclide and Pathway Analysis for the Savannah River Site*.

SRS-based Performance Assessments for E-Area, Saltstone, F-Tank Farm, H-Tank Farm, and a Comprehensive SRS Composite Analysis have been completed. The critical radionuclides and pathways identified in those extensive reports are also detailed and included in this analysis.

The following recommendations/considerations were identified during this assessment:

- In the SRS PA's and CA, the following long-lived radionuclides were identified as being important in long-term dose projections (>100 y): iodine-129, chlorine-36, technetium-99, niobium-94, niobium-93m, neptunium-237, radium-226, nickel-59, cesium-135, carbon-14, and protactinium-231. Because of recommendations in Jannik (1997), several of these long-lived radionuclides (iodine-129, technetium-99, carbon-14 and neptunium-237) were previously added to the SRS environmental monitoring program radionuclide analytical suite. But the remainder of these radionuclides has not been routinely analyzed for in SRS effluent or environmental samples. Consideration should be given to periodically analyzing for these radionuclides in aqueous surveillance samples.
- Because of the reduced releases of atmospheric tritium at SRS (Figure 3-2), the frequency of detection of tritium-in-air at site boundary air-surveillance sampling stations has also been reduced (Abbott and Jannik 2016). It is recommended that the data-quality objectives for the site's air-surveillance stations be reconsidered, to determine if they are still located at the proper distances and directions from the major onsite sources.
- A regional cesium-137 background level for hogs has yet to be determined. It is recommended that a cesium-137 background concentration, based on hogs harvested from the nearby military bases, be established.
- Like hogs, a cesium-137 background level for turkeys has yet to be determined. It is recommended that one be established for SRS.
- Tritium, which does not bioaccumulate in fish, remains at an equilibrium concentration between the water in which fish live and the fish flesh. The dose from tritium in fish has been, and will continue to be, less than 1% of the estimated total fisherman dose. Therefore, it is recommended that tritium in fish flesh be discontinued as an analyte.

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1.0 INTRODUCTION

This report is an update to the analysis, *Critical Radionuclide and Pathway Analysis for the Savannah River Site,* that was performed in 2011 (Jannik and Scheffler, 2011),which is included on the CD that is attached to this report.

During the operational history (1954 to present) of the Savannah River Site (SRS), many different radionuclides have been released to the environment from various production facilities. However, as will be shown by this updated radiological critical contaminant/critical pathway analysis, only a small number of the released radionuclides have been significant contributors to potential doses and risks to offsite people. The term "critical pathway analysis" is used in the Department of Energy's (DOE) effluent monitoring and environmental surveillance Handbook DOE-HDBK-1216-2015 (DOE, 2015). It means that an evaluation should be conducted at each DOE site to determine the most important ("critical") radionuclides and exposure pathways, which will then be used as a basis for establishing the site's environmental surveillance program.

The analysis covers radiological releases to the atmosphere and to surface waters, the principal pathways that carry contaminants off site. These releases potentially result in exposure to offsite people. The groundwater monitoring performed at the site shows that an estimated 5 to 10 percent of SRS groundwater has been contaminated by radionuclides. However, from the extensive monitoring performed, no evidence exists that groundwater contaminated with these constituents has migrated offsite (SRS, 2015). Therefore, with the notable exception of radiological source terms originating from shallow surface water migration into site streams, onsite groundwater was not considered as a potential exposure pathway to offsite people.

In addition, in response to the DOE Order 435.1 (DOE, 1999), several Performance Assessments (WSRC 2008; LWO 2009; SRR 2010; SRR 2011) and a Comprehensive SRS Composite Analysis (SRNL, 2010) have been completed at SRS. These assessments have not been updated since their original issuance. The critical radionuclides and pathways originally identified in these extensive reports are detailed and included in this analysis (where applicable).

2.0 DESCRIPTION

The major steps in performing public radiation dose and risk assessments are:

1. Characterization and quantification of source terms
2. Calculation of atmospheric and surface water transport (dispersion/dilution)
3. Characterization and quantification of environmental pathway transport to humans (exposure pathways)
4. Calculation of radiation dose and subsequent potential risk

2.1 Source Terms

For the years 1954 through 2015, environmental release data, obtained from monitored airborne and liquid effluent release points, were used in conjunction with calculated release estimates of unmonitored radionuclides (such as noble gases, carbon-14, and fission product tritium) to quantify the annual and total amounts of radioactive materials released to the environment from SRS. In addition, since 1991, an estimate of airborne radionuclide releases from unmonitored diffuse and fugitive sources is included in the atmospheric release totals. The radiological source terms used in this analysis were compiled from Hetrick et al., 1991, and from the subsequent annual SRS environmental reports (SRS, 1990-2015). They are documented by radionuclide and are included on the attachment CD.

2.2 Exposure Pathways

At SRS, the principal pathways by which offsite people may be exposed to effluent releases of radionuclides are:

- Inhalation of radionuclides in air at the site boundary
- Ingestion of foodstuffs (i.e., leafy vegetables, grains, beef, and cow milk) raised at the site boundary and contaminated by airborne deposition or absorption of radionuclides
- Immersion in radioactive noble gas plumes at the site boundary
- External exposure from airborne radionuclides deposited on the ground at the site boundary
- Ingestion of Savannah River water contaminated by site liquid releases
- Ingestion of foodstuffs (i.e., leafy vegetables, grains, beef, and cow milk) raised downriver of the site that are irrigated with Savannah River water
- Ingestion of Savannah River fish
- Recreational submersion in Savannah River water
- External exposure from radionuclides deposited on the shoreline/sediments of the Savannah River

2.3 Transport and Exposure Models

Since 2012, to demonstrate compliance with DOE public dose standards (DOE, 2011a), SRS uses the concept of a Representative Person (RP) instead of the Maximally Exposed Individual (MEI). The RP dose is based on an age and gender-averaged reference person for an individual and typical person for a population. These terms are further defined in subsequent sections.

The radiological transport and dosimetry models used in this analysis are:

- MAXDOSE-SR - used for determining dose to the individual from routine atmospheric releases (Jannik and Stone 2013a)
- POPDOSE-SR - used for determining dose to the surrounding 80-km population from routine atmospheric releases (Jannik and Stone 2013a)
- LADTAP XL - used for determining dose to the individual and population from routine liquid releases to surface waters (Jannik and Stone 2013b)

MAXDOSE-SR and POPDOSE-SR are Savannah River National Laboratory (SRNL)-modified versions of the U.S. Nuclear Regulatory Commission (NRC) computer programs called XOQDOQ (Sagendorf et al., 1982) and GASPAR (Eckerman et al., 1980). XOQDOQ calculates downwind radionuclide concentrations, and GASPAR (using the XOQDOQ concentrations) calculates doses to individuals at specified locations. Modifications to the NRC codes have been made to accommodate input of specific SRS physical and biological data and to expand the amount of printed output data. The basic calculation methods used in the XOQDOQ and GASPAR programs have not been modified.

LADTAP XL is a Microsoft Excel™ spreadsheet version of LADTAP II, an unmodified version of the NRC program of the same name (Simpson and McGill, 1980). LADTAP XL incorporates dilution models described in NRC Regulatory Guide 1.113 (NRC, 1977a).

Concerning calculations, many parameters (such as source terms, meteorological conditions, radionuclide dose factors, dose-to-risk factors, human consumption rates, and environmental dispersion) are considered in the models used to calculate SRS offsite doses and risks. Most of the usage and transport parameters used at SRS have changed in varying degrees over the years. Therefore, in this analysis (to maintain consistency in year-to-year comparisons), the potential offsite individual and population doses and risks from each year (1954-2015) have been calculated using the most recent meteorological, demographic, consumption, transport, and dispersion parameters, as documented in Jannik and Stone (2013a and 2013b). These parameters are reviewed every five years. Some biological and physical parameters contained in Regulatory Guide 1.109 (NRC, 1977b) are included as default assumptions in the codes, but many have been replaced with SRS-specific parameters (Jannik et al., 2016).

The external dose conversion factors, used in the codes, are taken from the U.S. Environmental Protection Agency's (EPA) Federal Guidance Report #12 (EPA, 1993). The internal dose conversion factors are taken from the DOE Derived Concentration Technical Standard (DOE, 2011b).

2.3.1 *Atmospheric Dose Calculations*

Individual and population airborne pathway doses were calculated, using the MAXDOSE-SR and POPDOSE-SR codes, for the following pathways:

- Plume shine
- Inhalation
- Cow milk consumption
- Ground shine
- Vegetation consumption
- Meat (beef) consumption

2.3.1.1 Reference Person Parameters for RP Individual Air Pathway Doses

The RP dose is based on a reference person intake (at the 95th percentile of national and regional data) developed specifically for SRS (Stone and Jannik, 2013). The major parameters used in calculating doses to the RP are summarized in Table 2-1 (Jannik et al., 2016).

Table 2-1. Major Parameters in MAXDOSE-SR for Individual Dose Calculations

Parameter	Value
Inhalation (m^3/y)	6,400
Ingestion	
Cow's milk (L/y)	260
Meat (kg/y)	81
Leafy vegetables (kg/y)	31
Other produce (kg/y)	289
Release Location and Height	58000E, 62000N; height = 61m
Meteorological Data	H-Area Met Tower (2007-2011)

2.3.1.2 Typical Person Parameters for Population Air Pathway Doses

The population dose is based on typical person intake (at the 50^{th} percentile of national and regional data) developed specifically for SRS (Stone and Jannik, 2013).

The POPDOSE-SR code calculates the annual air and ground deposition concentrations per unit release for each of 160 segments (16 wind direction sectors at 10 distances) within an 80-km radius from the center of SRS. The 2010 U.S. Census Data were used in the analysis (Jannik and Dixon, 2011). The major parameters used in calculating doses to the surrounding population are summarized in Table 2-2 (Jannik et al., 2016).

Table 2-2. Major Parameters Used in POPDOSE-SR for Population Dose Calculations

Parameter	Value
Inhalation (m^3/y)	5000
Ingestion	
Cow's milk (L/y)	69
Meat (kg/y)	32
Leafy vegetables (kg/y)	11
Other produce (kg/y)	89
Release Location and Height	58000E, 62000N; Height = 61m
Meteorological Data	H-Area Met Tower (2007-2011)
Population	781,058 (2010 U.S. Census)

2.3.2 *Liquid Dose Calculations*

Using the LADTAP XL code, individual and population liquid pathway doses were calculated for the following pathways:

- Water consumption
- Fish consumption
- Recreational external exposure (swimming, boating, and shoreline use)
- Vegetable, meat, and milk consumption (crops irrigated with river water)

2.3.2.1 Agricultural Irrigation Pathway

Based on discussions with personnel in the Georgia Department of Natural Resources (GDNR), the South Carolina Department of Health and Environmental Control (SCDHEC), and the U.S. Geological Survey (USGS), no known agricultural and/or irrigation uses of Savannah River water exist downstream of SRS. However, the potential for agricultural irrigation does exist, especially on a small scale for the individual exposure scenario. In 2011, the irrigation pathway was added to compliance dose for both individual and population doses. Including agricultural irrigation as a pathway is consistent with the SRS Composite Analysis (SRNL, 2010).

Population doses from agricultural irrigation were calculated assuming that 1,000 acres of land were devoted to each of the major food types grown in the SRS area (vegetables, milk, and meat). It is assumed that all the food produced on the 1,000-acre parcels is consumed by the population residing within 50 miles of SRS (Jannik and Stone, 2013b).

2.3.2.2 Reference Person Parameters for Individual Liquid Pathway Dose

The offsite RP who receives the maximum dose from SRS routine liquid releases is a hypothetical person who lives on the shore of the Savannah River just beyond the SRS boundary, at U.S. Hwy 301 near River Mile 118. Complete mixing of all SRS liquid effluents into the river water is assumed to have occurred and the dose from the consumption of aquatic food is calculated, assuming the concentrations of radionuclides in edible tissues are under equilibrium or steady-state conditions with those in the surrounding water.

It is conservatively assumed that the RP 1) uses untreated river water for drinking and foodstuff irrigation, 2) consumes river (RM 118) fish, and 3) receives external exposure from the shoreline, swimming, and boating. The major consumption and usage parameters used as inputs to LADTAP XL for calculating the RP dose are summarized in Table 2-3 (Jannik et al., 2016).

Table 2-3. Major Parameters Used for LADTAP XL Individual Dose Calculations

Parameter	Value
RPUsage Rates	
Fish	24 kg/y
Drinking water	800 L/y
Shoreline	20 hr/y
Swimming	14 hr/y
Boating	44 hr/y
Cow's milk	260 L/y
Meat	81 kg/y
Leafy vegetables	31 kg/y
Other vegetables	289 kg/y
River Flow Rate at River Mile 118.8 (Annual Average)	9,700 cfs

2.3.2.3 Typical Person Parameters for Population Liquid Pathway Dose

A majority of the population doses resulting from SRS liquid releases are calculated for the people served by the City of Savannah Industrial and Domestic Water Supply Plant (Savannah I&D), near Port Wentworth, Georgia, and by the Beaufort-Jasper Water and Sewer Authority's (BJWSA) Chelsea and Purrysburg Water Treatment Plants, near Beaufort, South Carolina. According to the treatment plant operators, the population served by the Savannah I&D facility during 2015 was 35,000 persons. The population served by the BJWSA Chelsea facility was 82,900 persons. The BJWSA Purrysburg facility served 64,200 persons. The total population dose resulting from routine SRS liquid releases is the sum of five contributing categories: (1) BJSWA water consumers, (2) Savannah I&D water consumers, (3) consumption of fish and invertebrates of Savannah River origin, (4) recreational activities on the Savannah River, and (5) consumption of irrigated foodstuffs (Jannik and Stone, 2013b).

The major consumption and usage parameters, used as inputs to LADTAP XL for calculating the population liquid pathway doses, are summarized in Table 2-4 (Jannik et al., 2016).

Table 2-4. Major Parameters Used for LADTAP XL Population Dose Calculations

Parameter	Value
Population Usage Rates	
Fish	3.7 kg/y
Invertebrate	1.5 kg/y
Drinking Water	300 L/y
Shoreline Time	822,000 person-hr/y
Swimming	295,000 person-hr/y
Boating	3,110,000 person-hr/y
Cow's milk	69 L/y
Meat	32 kg/y
Leafy vegetables	11 kg/y
Other produce	89 kg/y
River Flow Rate at Drinking Water Plants (Annual Average)	10,000 cfs

2.3.3 *Atmospheric and Liquid Pathway RP Risk Calculations*

For the RP, the total, lifetime stochastic risks from SRS radiological atmospheric and liquid releases were estimated using the total morbidity (fatal and non-fatal cancer-incidence) risk coefficient for 30-year-old adults (at time of exposure), documented by the National Research Council in BEIR VII (2006). The BEIR VII (sex-averaged) total morbidity risk coefficient, 8.7E-07 per mrem, includes factors for solid cancers and leukemia.

According to risk assessment guidance provided by EPA, the upper-bound value of 30 y was used to determine and compare projected lifetime risks (EPA, 1993). For the projected 30-y lifetime risk comparisons, the average dose for the last 10-y (2006-2015) was multiplied by 30 y and then multiplied by the BEIR VII risk factor. It is assumed that future SRS radiological operations and conditions will not vary significantly from this 10-y baseline.

The projected 30-y risks were determined using equation 1:

$$Risk_{projected} = \frac{\sum_{i=2006}^{2015} Dose_i}{10\,years} * 30\,years * \frac{8.7E-07}{mrem} \qquad (1)$$

where

$Risk_{projected}$	= projected 30-y risks
$8.7E-07/mrem$	= BEIR VII total morbidity risk coefficient
$\sum_{i=2006}^{2015} Dose_i$	= dose (mrem) from radionuclide *i* for the last 10-y

The cumulative risks used in the comparisons were determined using equation 2:

$$Risk_{cumulative} = \frac{8.7E-07}{mrem} * \sum_i \sum_{y=1954}^{2015} Dose_i(y) \qquad (2)$$

where

$Risk_{cumulative}$	=	cumulative risk for the years 1954-2015
$8.7E-07/mrem$	=	BEIR VII total morbidity risk coefficient
$Dose_i$ (y)	=	dose from radionuclide *i* during year *y* (mrem)

When comparing radiological risks, if a potential risk is determined to be less than 1.0E-06 (i.e., one additional case of severe detriment in a group of 1,000,000 people), then the risk is considered minimal. If a calculated risk is greater than 1.0E-04, then some form of corrective action or remediation is usually required. However, if a calculated risk falls between 1.0E-06 and 1.0E-04, the risk is considered acceptable, if it is kept as low as reasonably achievable (ALARA).

3.0 RESULTS

In Appendix A (included on the enclosed CD), the annual and cumulative airborne and liquid source terms are documented by radionuclide for the years 1954-2015. In addition, the source terms are graphically presented for all years and separately for the most recent 10-y period (2006-2015). In Appendices B-1 and B-2 (also on the enclosed CD), the associated individual and population doses are documented for the atmospheric and liquid pathways, respectively. The relative importance of each individual radionuclide was then determined, on a cumulative and a 30-y projected basis, by percentage of total risk for the individual and percentage of total dose for the population. Also established was the relative percentage importance of individual exposure pathways for the most recent 10-y time period (2006-2015).

3.1 Critical Airborne Radionuclides and Pathways

The cumulative (1954-2015) and projected (30-y) individual and population risk comparisons are provided in Table 3-1 and Table 3-2, respectively, for each radionuclide that had a cumulative individual risk over 1.0E-10 or a cumulative population dose over 1.0E-03 person-rem. The dose and risk from unidentified alpha and beta releases are based on the dose factors for plutonium-239 and strontium-90, respectively.

3.1.1 *Individual Airborne Pathway Risk Comparison*

During the early years of operations at SRS, short-cooled (about 100 days) fuel and target rods were processed in the separations areas, because of the urgency to obtain special nuclear materials (Kantelo et al., 1993). As a result, iodine-131 was the most critical airborne pathway radionuclide on an overall cumulative risk basis (1954-2015). During the 1960's, physical and administrative controls (e.g., increasing cooling time to a minimum of 200 days) were implemented to reduce iodine-131 releases. During subsequent years, tritium, iodine-129, plutonium-239, argon-41, and carbon-14 increased in relative importance. Their percentage of importance varied depending on operational missions and accidental releases.

From 1954-2015, over 90 radionuclides were measured or estimated to have been released from SRS, but only the cumulative airborne pathway individual risks attributable to iodine-131, tritium, argon-41, iodine-129, plutonium-239, and carbon-14 releases were determined to be greater than 1.0E-06. However, on a projected 30-y risk basis, only tritium exceeds an airborne pathway potential risk or 1.0E-07 and is relatively close to potential risk of 1.0E-06 (Table 3-1).

Table 3-1. Atmospheric Pathway Individual Risk Comparisons (Unitless)

Radionuclide (Historical)	Cumulative Risk (1954-2015)	Rank	Radionuclide (Past 10-y)	Projected 30-y Risk (Based on 10-y Dose)
I-131	**3.8E-05**	1	H-3	9.4E-07
H-3	**3.6E-05**	2	I-129	6.5E-08
Ar-41	**1.0E-05**	3	Cs-137	4.3E-08
I-129	**2.9E-06**	4	Sr-90	4.1E-08
Pu-239	**2.9E-06**	5	Pu-238	2.7E-08
C-14	**1.8E-06**	6	Alpha	2.2E-08
Beta	8.9E-07	7	Beta	2.0E-08
Kr-88	6.7E-07	8	Pu-239	9.0E-09
Pu-238	6.3E-07	9	Tc-99	1.8E-09
Ru-106	2.3E-07	10	Am-241	1.3E-09
Xe-135	1.0E-07	11	Kr-85	1.1E-09
Alpha	8.9E-08	12	C-14	5.7E-10
Kr-85	8.8E-08	13	Th-232	4.3E-10
Cs-137	7.8E-08	14	Eu-154	4.2E-10
Xe-133	4.8E-08	15	Co-60	3.6E-10
Cm-244	4.6E-08	16	U-234	2.3E-10
Sr-90	4.5E-08	17	Np-237	1.5E-10
Kr-85m	3.8E-08	18	U-238	1.4E-10
Ru-103	1.7E-08	19	**Total**	**1.2E-06**
Kr-87	1.3E-08	20		
Am-241	6.2E-09	21		
Ce-144	2.4E-09	22		
Co-60	1.4E-09	23		
Cs-134	1.3E-09	24		
Nb-95	1.2E-09	25		
Zr-95	1.1E-09	26		
Tc-99	6.8E-10	27		
U-238	4.4E-10	28		
U-234	2.9E-10	29		
Xe-131m	2.6E-10	30		
U-235	2.4E-10	31		
Cm-242	2.1E-10	32		
Th232	1.5E-10	33		
Eu-154	1.4E-10	34		
Total	**9.5E-05**			

Note: *Radionuclides shown in **bold** exceed a total risk of 1.0E-06.*

In Figure 3-1, critical airborne radionuclides are presented by percent contribution to the total projected 30-y risk. As shown, tritium (80.2% of risk) is projected to be the most critical radionuclide, followed by iodine-129 (5.5%), cesium-137 (3.6%), strontium-90 (3.5%), plutonium-238+239 (3.1%), and all others combined (4.1%). As shown in Figure 3-2, atmospheric tritium oxide releases from SRS remained relatively constant, at over 30,000 Ci/y from 2006 to 2010, and then dropped to varying values above and below 20,000 Ci/y. Therefore, on a projected basis, tritium will continue to be the critical airborne radionuclide at SRS, as long as the site's Tritium Facility missions continue to remain as is.

Because of the reduced releases of atmospheric tritium at SRS (Figure 3-2), the frequency of detection of tritium-in-air at the site boundary air-surveillance sampling stations has also been reduced (Abbott et al., 2016). It is recommended that the data quality objectives for the site's air-surveillance stations be reconsidered, to determine if they are still located at the proper distances and directions from the major onsite sources.

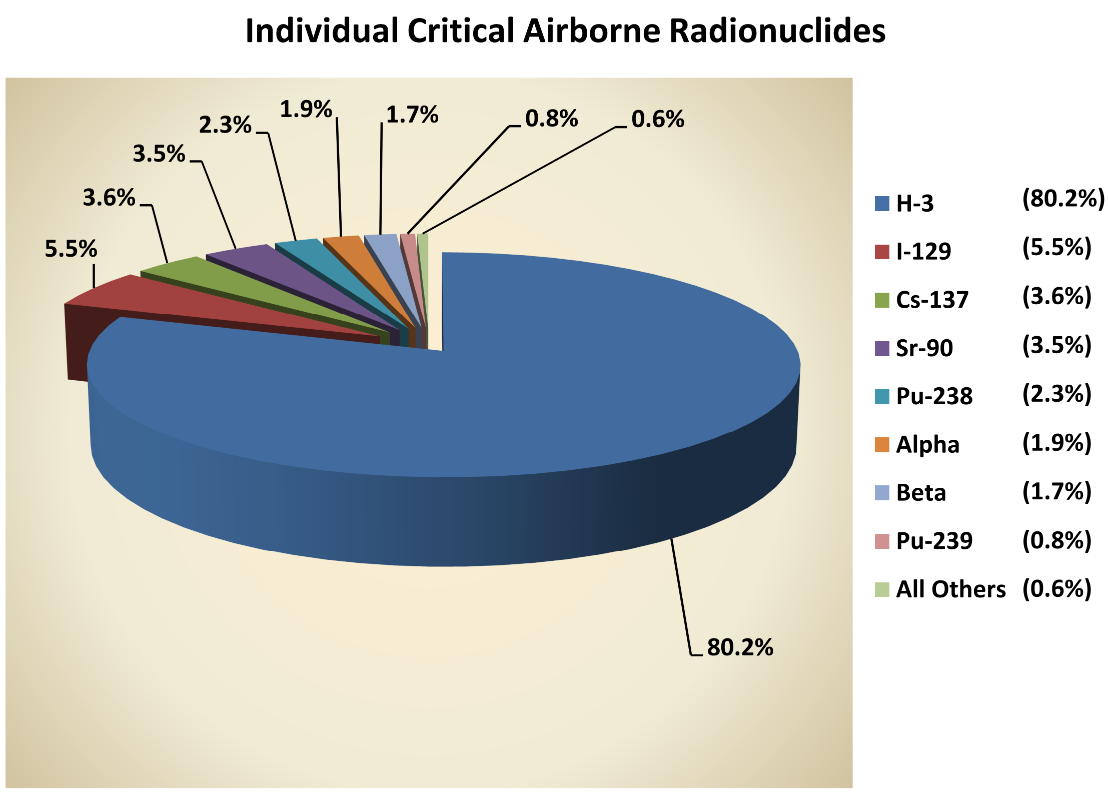

Figure 3-1. Individual Critical Airborne Radionuclides by Percent of Projected 30-y Risk

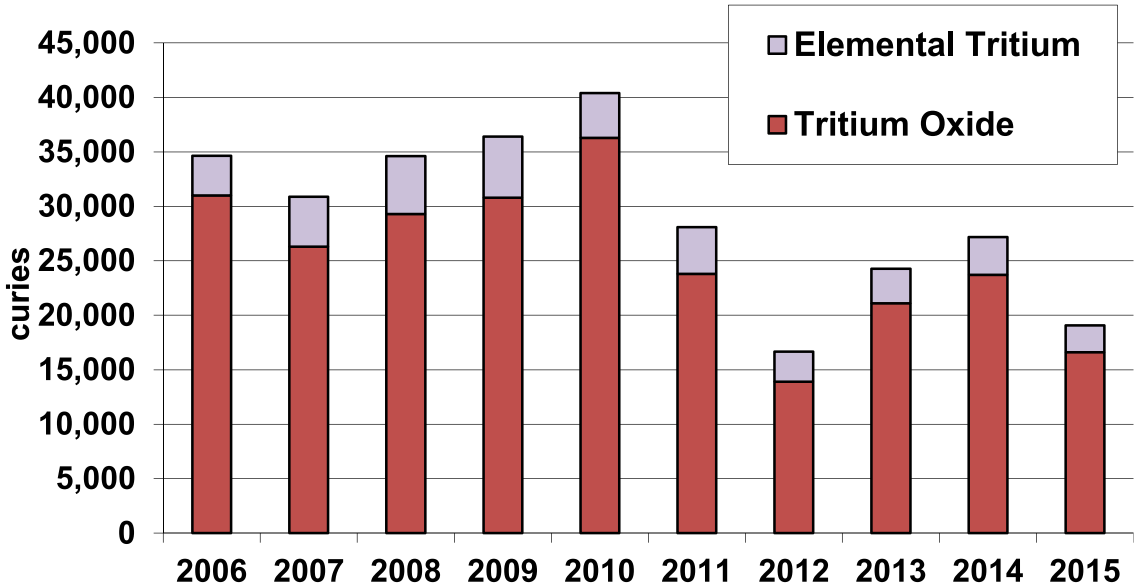

Figure 3-2. Ten-Year History of Annual Atmospheric Tritium Releases

3.1.2 *Individual Critical Airborne Exposure Pathways*

As noted, iodine-131 was the most critical contaminant during the early years of operations (1954-1960). As a result, on a cumulative basis, cow milk and vegetation consumption were the most critical pathways, accounting for about 75% of the dose from iodine-131 releases (Carlton, 1992). In subsequent years, tritium dominated the airborne pathway individual risk. Inhalation and vegetable consumption became the critical pathways, and the plume pathway was negligible.

In Figure 3-3, critical airborne pathways are presented by percent contribution to the total projected 30-y risk (based on the past 10-y). Because tritium is projected to remain the critical airborne pathway radionuclide at SRS, the inhalation (40.2%) and vegetable consumption (35.9%) pathways will remain important. Due to continuing iodine-129 releases from the site's Separations Areas, the milk consumption pathway (19.1%) will also remain important. The ground shine, plume shine, and meat consumption pathways are projected to be negligible, with total contribution at 4.8% to the total 30-y risk.

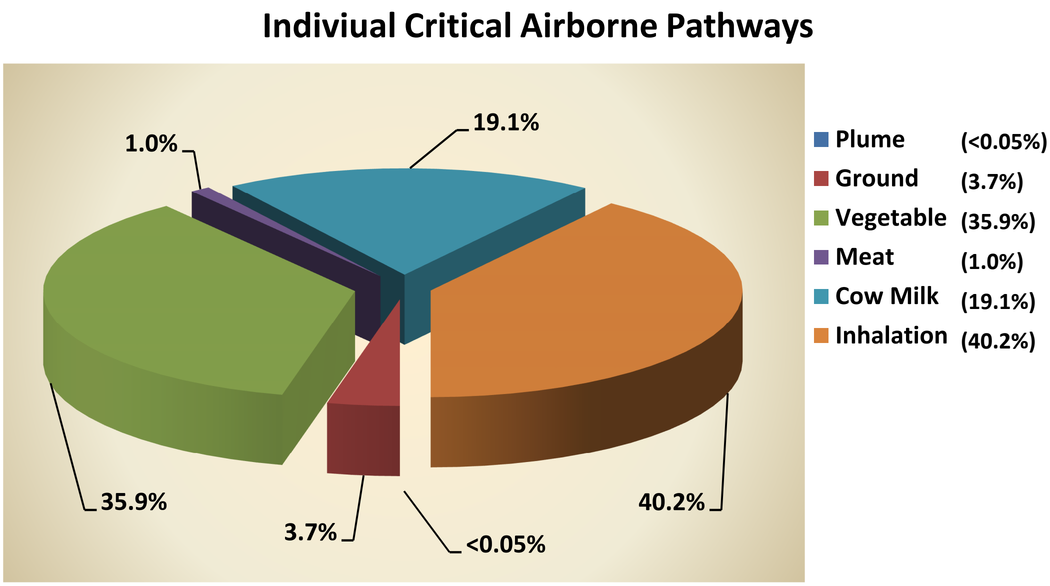

Figure 3-3. Individual Critical Airborne Pathways by Percent of Projected 30-y Risk

3.1.3 *Population Airborne Pathway Dose Comparisons*

As shown in Table 3-2, the cumulative airborne pathway population doses follow a similar trend to the individual risks. However, because of radioactive decay during transport, the shorter-lived radionuclides (such as iodine-131, half-life = 8 d) have less of an impact on the population dose than they do on the site-boundary individual dose and risk. This is why tritium, not iodine-131, is the most critical radionuclide on a cumulative population dose basis.

Table 3-2. Atmospheric Pathway Population Dose Comparisons (person-rem)

Radionuclide (Historical)	Cumulative Risk (1954-2015)	Rank	Radionuclide (Past 10-y)	Projected 30-y Risk (Based on 10-y Dose)
H-3	**2.2E+03**	1	**H-3**	**5.8E+01**
I-131	**9.5E+02**	2	**Cs-137**	**2.9E+00**
Pu-239	**2.1E+02**	3	**Pu-238**	**2.2E+00**
Ar-41	**1.9E+02**	4	**Alpha**	**1.7E+00**
Pu-238	**4.5E+01**	5	**Sr-90**	**1.1E+00**
I-129	**3.7E+01**	6	I-129	8.1E-01
C-14	**3.6E+01**	7	Pu-239	7.9E-01
Kr-88	**2.1E+01**	8	Beta	1.4E-01
Xe-133	**1.9E+01**	9	Kr-85	1.3E-01
Kr-85	**9.1E+00**	10	Am-241	9.7E-02
Beta	**7.2E+00**	11	Eu-154	3.6E-02
Xe-135	**6.9E+00**	12	Co-60	2.7E-02
Alpha	**6.4E+00**	13	Th-232	2.7E-02
Ru-106	**4.4E+00**	14	U-234	1.3E-02
Cm-244	**3.3E+00**	15	Np-237	1.1E-02
Cs-137	**2.2E+00**	16	Tc-99	1.1E-02
Kr-85m	**1.7E+00**	17	C-14	1.0E-02
Ru-103	8.4E-01	18	U-238	7.9E-03
Sr-90	6.0E-01	19	Cm-244	6.1E-03
Am-241	4.5E-01	20	U-235	1.4E-03
Kr-87	1.6E-01	21	Ce-144	1.2E-03
Co-60	7.2E-01	22	**Total**	**6.8E+01**
Nb-95	6.5E-02	23		
Zr-95	5.5E-02	24		
Ce-144	4.7E-02	25		
Ce-141	3.5E-02	26		
Cs-134	3.0E-02	27		
Xe-131m	2.7E-02	28		
U-238	2.4E-02	29		
Cm-242	1.7E-02	30		
U-234	1.6E-02	31		
U-235	1.3E-02	32		
Th-232	9.5E-03	33		
Tc-99	4.3E-03	34		
Np-237	4.0E-03	35		
Total	**3.8E+03**			

Note: *Radionuclides shown in* ***bold*** *exceed a total dose of 1.0 person-rem.*

The projected 30-y population doses, provided in Table 3-2, also follow a similar trend to the individual doses and risks. The critical radionuclides, shown in Figure 3-4**,** are tritium (85.2%), cesium-137 (4.4%), plutonium-238 (3.2%), unidentified alpha (2.5%), and all others (4.6%).

However, because the amount of vegetables produced in the 80-km (50 mile) radius surrounding SRS is not sufficient to feed all of the people living in that area (Jannik et al., 2010), the importance of the vegetable consumption pathway is greatly reduced. On a projected 30-y population dose basis, shown in Figure 3-5, the inhalation pathway (75.1%) becomes more important than in the individual risk projections, the cow milk consumption pathway (16.6%) remains about the same, the vegetable consumption pathway is reduced to 2.6%, and the meat consumption, ground shine, and plume shine pathways all remain below 10.0% of the total projected dose.

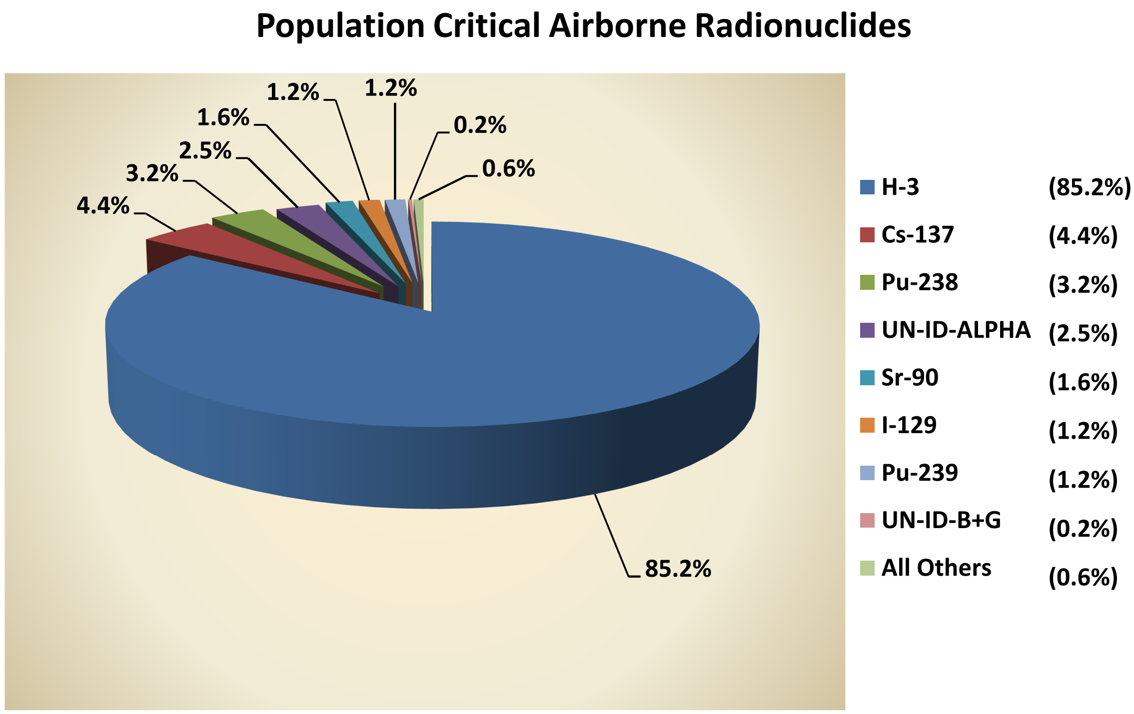

Figure 3-4. Population Critical Airborne Radionuclides by Percent of Projected 30-y Risk

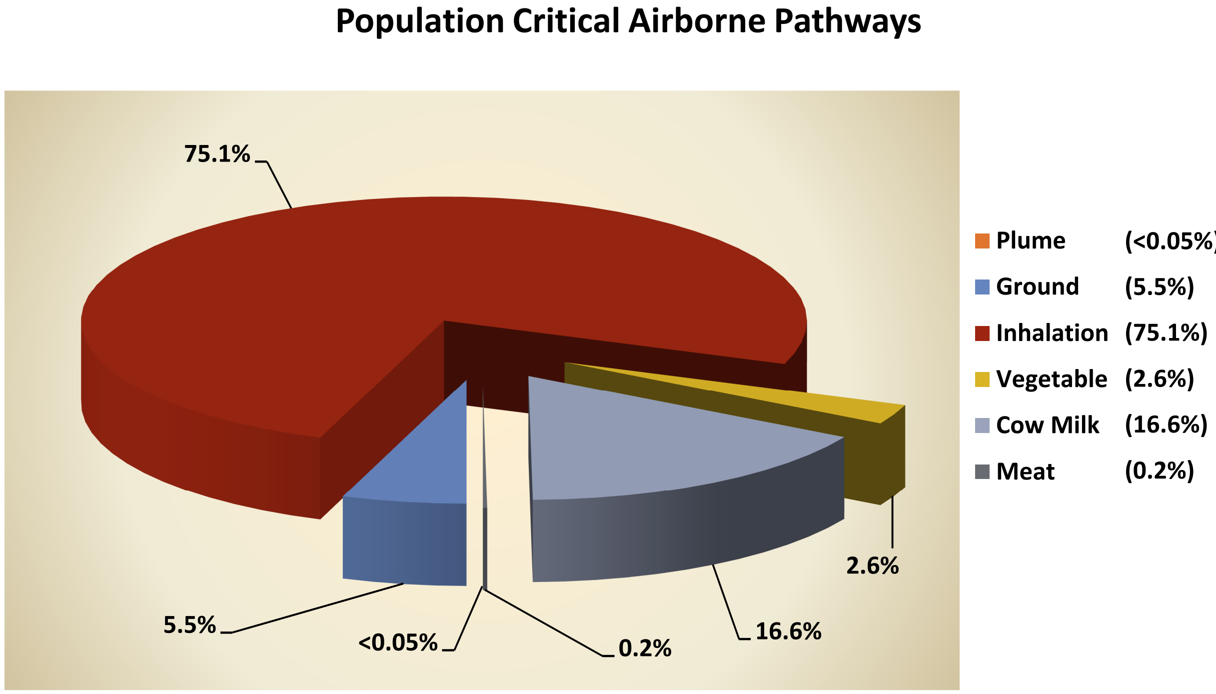

Figure 3-5. Population Critical Airborne Pathways by Percent of Projected 30-y Risk

3.2 Critical Aqueous Radionuclides

In Table 3-3 and Table 3-4, respectively, cumulative (1954-2015) and projected (30-y) individual risk and population dose comparisons are provided for each radionuclide that had a cumulative individual risk over 1.0E-10 or a cumulative population dose over 1.0E-03 person-rem. These tables show the relative importance of each radionuclide measured or calculated to have been released to the Savannah River from SRS. The risks are based on the annual doses calculated, using an average annual Savannah River flow rate of 9,700 cfs.

Table 3-3. Liquid Pathway Individual Risk Comparison

Radionuclide (Historical)	Cumulative Risk (1954-2015)	Rank	Radionuclide (Past 10-y)	Projected 30-y Risk (Based on 10-y Dose)
Cs-137	**1.8E-04**	1	Cs-137	5.7E-07
P-32	**7.8E-05**	2	H-3	3.6E-07
Sr-90	**3.6E-05**	3	Tc-99	2.6E-07
H-3	**1.6E-05**	4	Alpha	2.2E-07
Zn-65	**1.6E-05**	5	Beta	2.2E-07
I-131	**5.7E-06**	6	I-129	2.0E-07
Beta	**5.4E-06**	7	Sr-90	1.2E-07
S-35	**2.2E-06**	8	U-238	1.0E-07
Sr-89	6.5E-07	9	U-234	9.5E-08
Co-60	6.0E-07	10	Am-241	3.1E-08
Alpha	4.6E-07	11	Pu-238	1.9E-08
I-129	4.1E-07	12	U-235	4.4E-09
Ba-La-140	3.9E-07	13	Pu-239	1.8E-09
Y-91	3.7E-07	14	Cm-244	9.5E-10
Np-239	3.6E-07	15	C-14	8.1E-10
Ce-141,144	2.7E-07	16	Zn-65	1.9E-10
Cs-134	2.4E-07	17	Co-60	1.3E-10
Cr-51	2.2E-07	18	**Total**	**2.2E-06**
Zr-95	1.5E-07	19		
Tc-99	1.3E-07	20		
Cm-244	6.7E-08	21		
U-238	5.7E-08	22		
Pu-238	4.2E-08	23		
Pm-147	4.2E-08	24		
U-234	3.4E-08	25		
Am-241	1.1E-08	26		
Pu-239	6.9E-09	27		
Mo-99	3.8E-09	28		
U-235	1.7E-09	29		
Mn-54	1.4E-09	30		
C-14	2.7E-10	31		
Total	**3.4E-04**	32		

Note: *Radionuclides shown in **bold** exceed a total risk of 1.0E-06.*

Table 3-4. Liquid Pathway Population Dose Comparisons (person-rem)

Radionuclide (Historical)	Cumulative Dose (1954-2015)	Rank	Radionuclide (Past 10-y)	Projected 30-y Dose (Based on 10-y Dose)
Zn-65	**1.4E+03**	1	**H-3**	**1.7E+01**
Cs-137	**1.0E+03**	2	**Alpha**	**8.1E+00**
Sr-90	**8.1E+02**	3	**Beta**	**4.8E+00**
H-3	**7.9E+02**	4	**Tc-99**	**4.5E+00**
P-32	**2.7E+02**	5	**I-129**	**3.9E+00**
I-131	**1.4E+02**	6	**Cs-137**	**3.0E+00**
Beta	**1.2E+02**	7	**U-238**	**2.8E+00**
Co-60	**4.1E+01**	8	**Sr-90**	**2.7E+00**
Y-91	**2.2E+01**	9	**U-234**	**2.6E+00**
Sr-89	**2.0E+01**	10	Pu-238	7.1E-01
Alpha	**1.8E+01**	11	Am-241	4.3E-01
Ba-La-140	**1.4E+01**	12	U-235	1.2E-01
Ce-141,144	**1.3E+01**	13	Pu-239	6.6E-02
S-35	**1.2E+01**	14	Cm-244	3.2E-02
Cr-51	**8.6E+00**	15	Zn-65	1.6E-02
Np-239	**8.4E+00**	16	C-14	1.1E-02
Zr-95	**5.0E+00**	17	Co-60	8.7E-03
Cm-244	**3.0E+00**	18	**Total**	**5.1E+01**
Pm-147	**2.6E+00**	19		
Tc-99	**2.3E+00**	20		
Pu-238	**1.6E+00**	21		
U-238	**1.4E+00**	22		
Cs-134	**1.3E+00**	23		
U-234	9.5E-01	24		
Pu-239	2.7E-01	25		
Am-241	1.5E-01	26		
Mo-99	1.2E-01	27		
U-235	4.8E-02	28		
Mn-54	4.3E-02	29		
C-14	3.5E-03	30		
Sb-124,125	2.4E-03	31		
Total	**4.7E+03**	32		

Note: *Radionuclides shown in **bold** exceed a total dose of 1.0 person-rem.*

3.2.1 *Individual Liquid Pathway Risk Comparison*

Because they were released in relatively large quantities and/or have large bioaccumulation factors in freshwater fish, cesium-137, phosphorus-32, strontium-90, tritium, zinc-65, iodine-131, unidentified beta, and sulfur-35 were the most critical radionuclides at SRS, on a cumulative (1954-2015) individual risk basis. The cumulative risks for each of these radionuclides were determined to be greater than 1.0E-06. Most of the releases of these radionuclides to SRS streams and seepage basins occurred during the early years of operations (prior to 1970), and this usually was the result of abnormal operating events, such as fuel failures, cooling coil leaks, or faulty storage containers (Carlton, 1998). Cesium-137 was the most critical radionuclide from 1954-2015. During the 1970s, physical and administrative controls (e.g., filters, redesigned fuel rods, and disassembly basin heat exchangers) were implemented to lessen the offsite impact of most fission and activation products (Carlton et al., 1992). During subsequent years, tritium, which cannot be practically filtered from effluent streams, increased in relative importance.

As shown in Figure 3-6, over the past 10-y, direct process liquid discharges of tritium account for about 20% or less of the total amount of tritium released to the Savannah River from SRS. The remainder is legacy tritium that is migrating out of site seepage basins and the Solid Waste Disposal Facility (SRS, 2015). As seen in Figure 3-6, total aqueous tritium releases from SRS continue a general downward trend, which will decrease its importance in the future.

On a projected 30-y risk basis, no radionuclides exceed a risk of 1.0E-06, but cesium-137, tritium, technetium-99, alpha, beta, iodine-129, uranium-238, and strontium-90 all exceed a potential risk of 1.0E-07. In Figure 3-7, critical aqueous radionuclides are presented by percent contribution to the total projected 30-y risk. As shown, cesium-137 (25.8%) and tritium (16.2%) are projected to be the most critical radionuclides. However, as anticipated in Jannik (1997), technetium-99 (11.9%) and iodine-129 (8.9%), which are long-lived and highly mobile in the environment, have become more important on a percentage risk basis as site aqueous tritium releases have declined. Strontium-90, which has a 29-y half-life, continues to be important (5.7% of projected risk) at SRS because of its mobility in the environment. Unidentified alpha and beta releases are conservatively included in the assessment, and they account for 10.0% and 9.8% of the projected risk, respectively. Most of these unidentified releases are probably naturally occurring radionuclides (such as uranium, thorium, and potassium-40), but they are not subtracted out of the effluent release totals. The dose and risk from the unidentified alpha and beta releases are based on the dose factors for plutonium-239 and strontium-90, respectively.

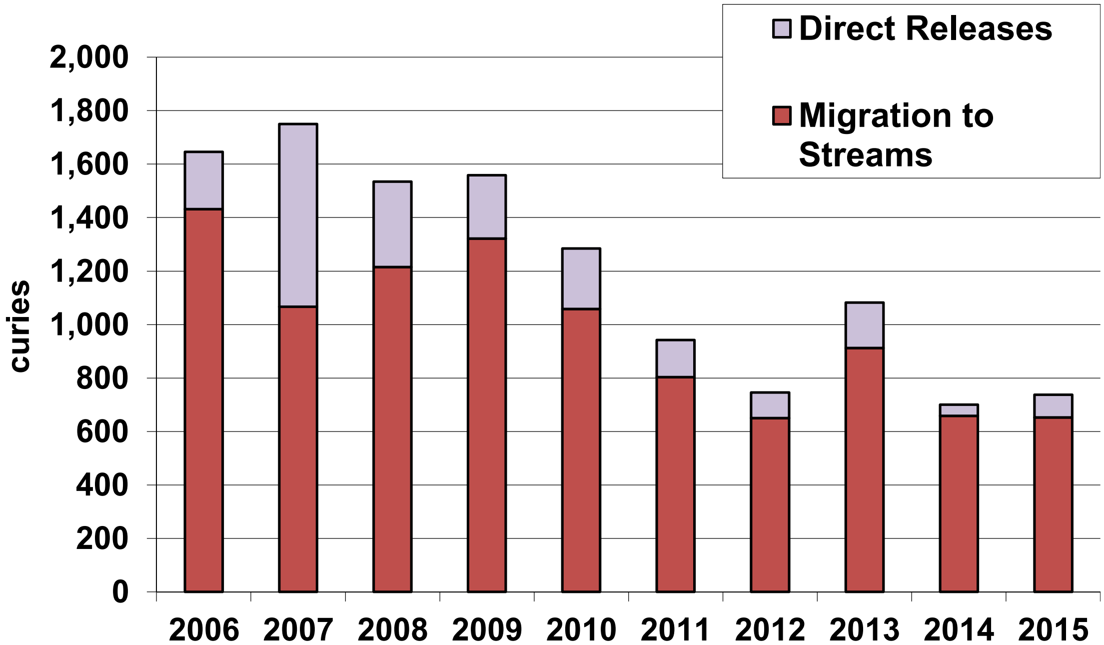

Figure 3-6. Ten-Year History of Tritium Releases to SRS Streams

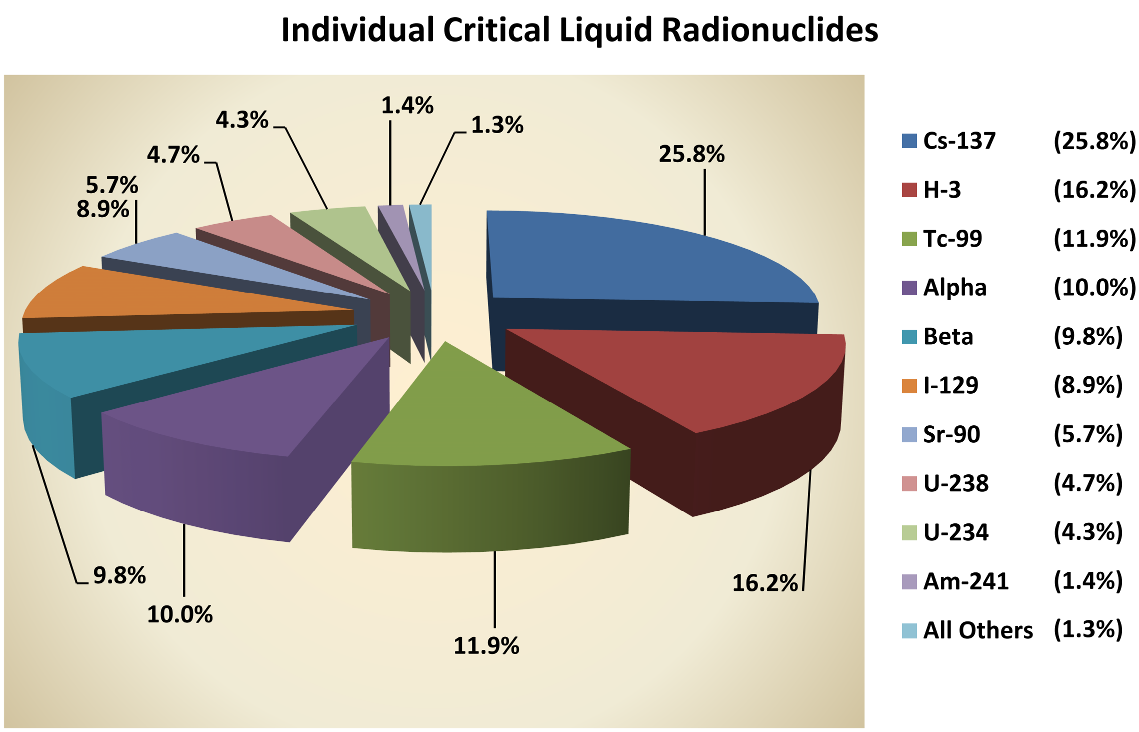

Figure 3-7. Individual Critical Aqueous Radionuclides by Percent of Projected 30-y Risk

3.2.2 *Critical Liquid Exposure Pathways*

As noted, cesium-137 was the most critical radionuclide on a cumulative basis (especially during the years 1954-1975), and because the fish consumption pathway accounts for about 90% of the dose from cesium-137, it is by far the most critical pathway during this period. For the projected 30-y individual risk, the critical liquid pathways are presented by percent contribution to the risk in Figure 3-8.

For the past 10-y, and therefore on a 30-y projected basis, the irrigated food ingestion pathway is now the critical pathway at SRS, accounting for about 57.8% of the projected risk (Figure 3-8). Of the 30-y projected risk, the fish consumption pathway accounts for 27.3%, and the water ingestion pathway accounts for 14.6%. The combined recreation pathways (swimming, boating, and shoreline) account for less than 1.0% of the liquid pathway individual risk.

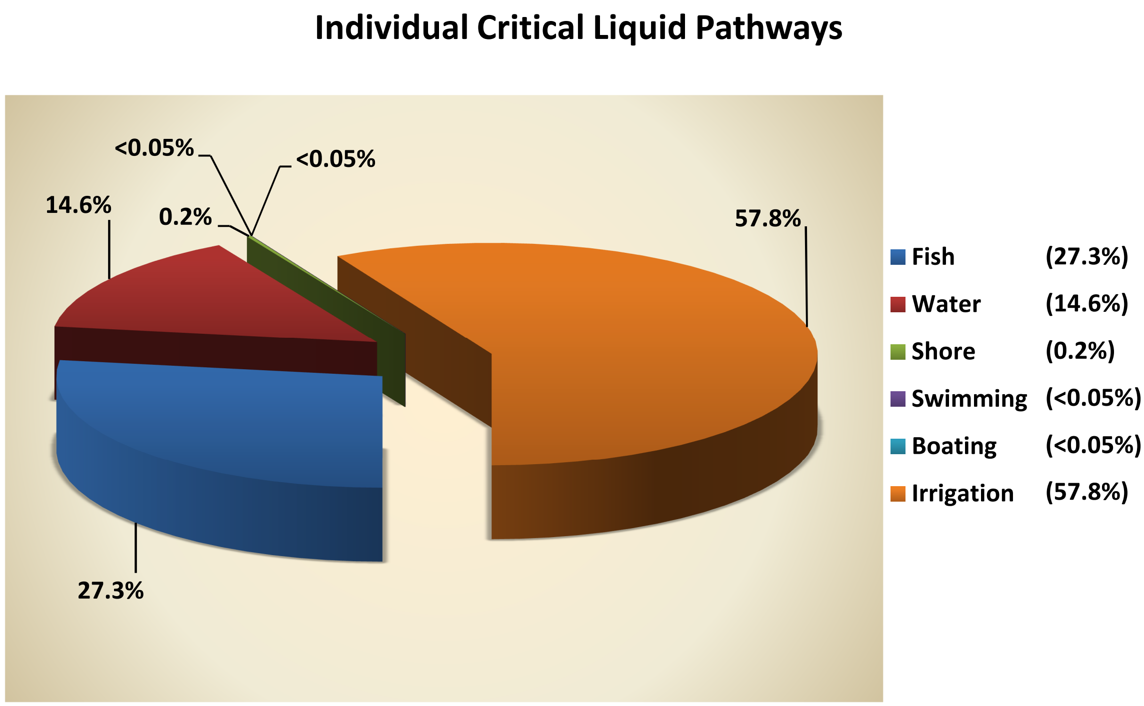

Figure 3-8. Individual Critical Liquid Pathways by percent of Projected 30-y Risk

3.2.3 *Population Liquid Pathway Dose Comparisons*

As shown in Table 3-4, the liquid pathway population doses follow a similar trend to the individual risks. However, zinc-65, which has an extremely large bioaccumulation factor (50,000 L/kg) in saltwater invertebrates, was the most critical radionuclide for the cumulative (1954-2015) population dose. In addition, the short-lived radionuclides (such as phosphorus-32 and sulfur-35) have less of an impact on the population dose than they do on the site-boundary individual dose and risk.

The projected 30-y population doses (Table 3-4) also follow a similar trend to the individual doses and risks. However, because of the three downriver drinking water plants, the drinking water pathway (50.5% of projected 30-y dose) is more important than the irrigated food ingestion (41.1%), fish consumption (8.0%), or recreation (<1%) pathways (Figure 3-9). As shown in Figure 3-10, tritium (33.4%) and unidentified alpha (15.8%) are the most critical radionuclides, based on the projected 30-y population doses. They are followed by unidentified beta (9.5%), technetium-99 (8.9%), iodine-129 (7.7%), cesium-137 (5.8%), uranium-238 (5.5%), strontium-90 (5.4%), uranium-234 (5.2%), and all others (2.8%).

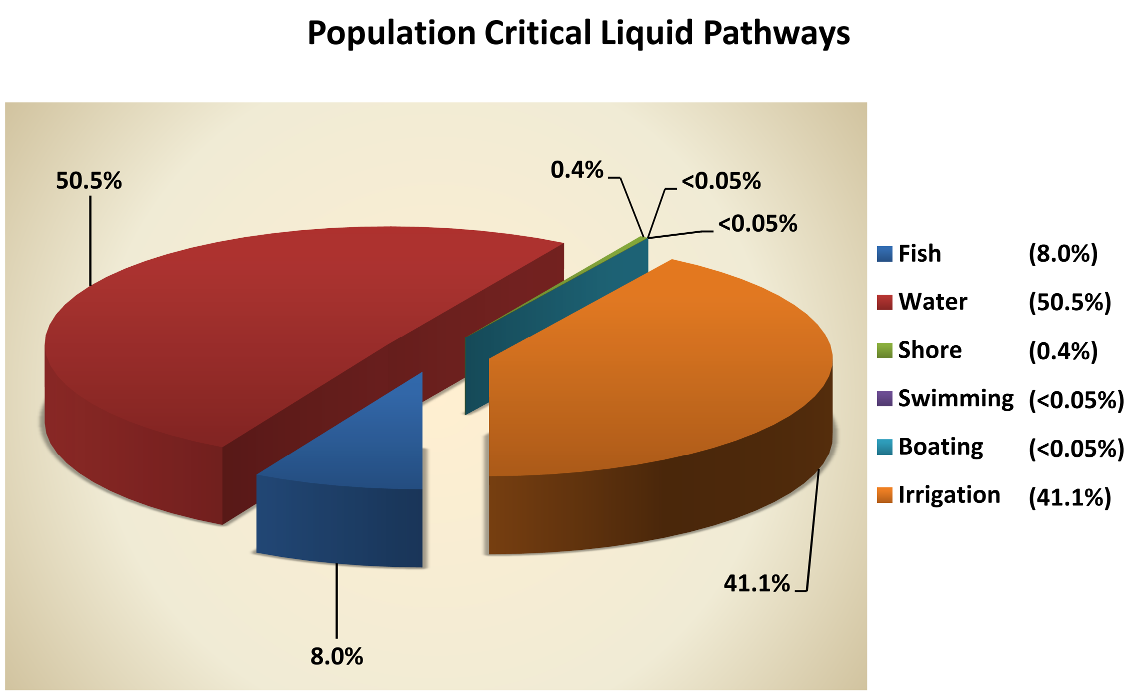

Figure 3-9. Population Critical Liquid Pathways by percent of Projected 30-y Risk

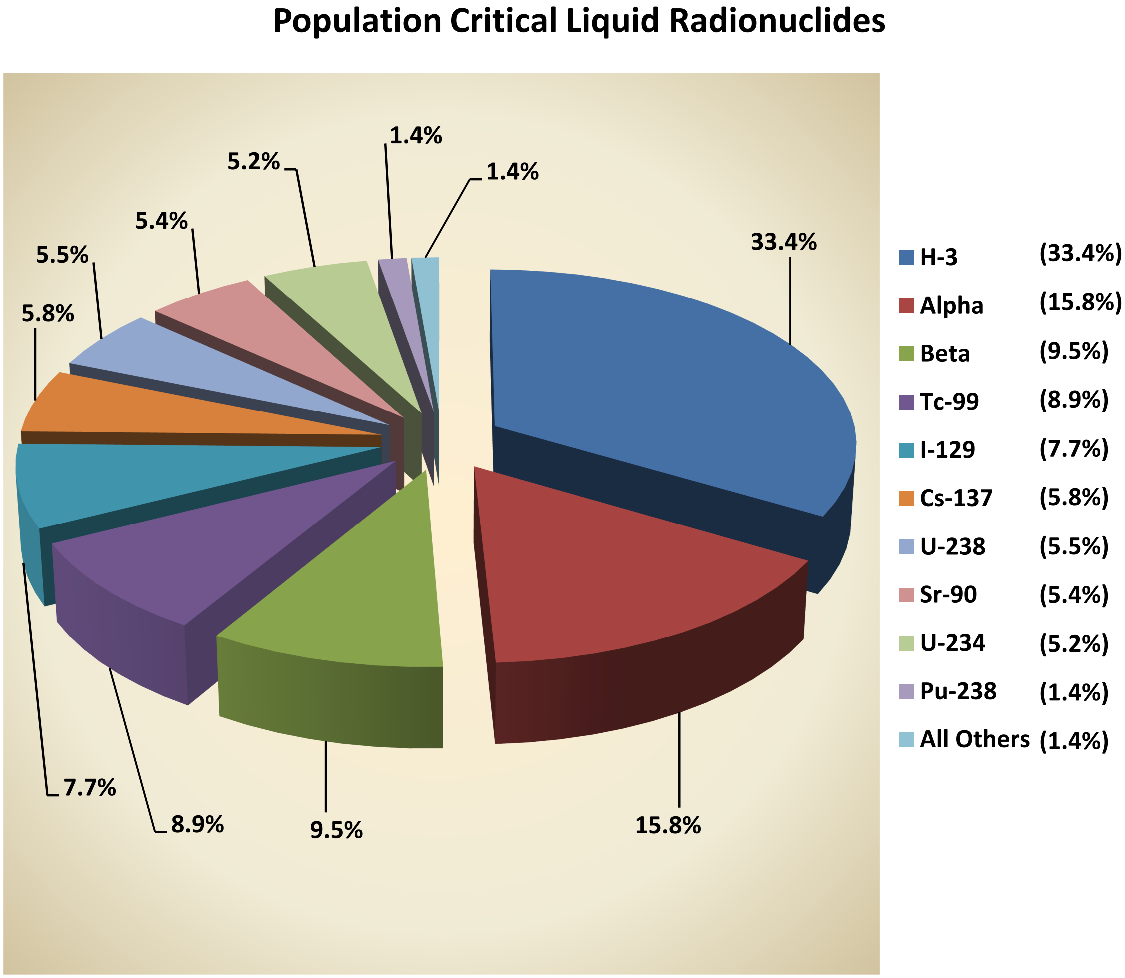

Figure 3-10. Population Critical Aqueous Radionuclides by Percent of Projected 30-y Risk

3.3 Non-typical Exposure Pathways

Non-typical exposure pathways, not included in the standard calculations of the dose to the RP, are considered and quantified separately. These pathways apply to relatively low probability or unique exposure scenarios.

3.3.1 *Critical Subpopulations*

Within 80 km of SRS, there are no known sensitive subpopulations (e.g., native Americans) with unique lifestyles or diets that should be considered separately from the standard consumption/exposure pathways.

3.3.2 *Onsite-Hunter Deer, Hog, and Turkey Consumption Pathway*

Controlled hunts of deer and feral hogs are conducted at SRS for approximately six weeks each year. Hunt participants are volunteers who are chosen by a lottery. Before any harvested animal is released to a hunter, SRS personnel perform a field analysis for cesium-137 concentrations. Like fish, deer and hogs have a high bioaccumulation factor for cesium. Since 1992, the estimated dose from the consumption of the harvested deer and hog meat has been determined for each hunter. The hunter-dose calculation is based on the assumption that the hunter individually consumes the entire edible portion of the animals he harvested from SRS.

A background concentration of 3.25 pCi/g is subtracted out, before the hunter dose is calculated. This background value was established in Shine (2012). The value was based on deer concentrations measured at other large government facilities in GA and SC (Fort Gordon, Fort Stewart and Fort Jackson). These facilities are similar to SRS, in that the global fallout from weapons testing remains somewhat unmitigated by farming and other anthropogenic activities. However, because the physical half-life of cesium-137 is 30-y, and its effective (physical plus ecological) half-life in the SRS area has been shown to be about 14-15 y (Paller et al., 2008), it is recommended that a SRS-specific background concentration be re-established and confirmed on a periodic basis. A similar background level specific for hogs has not been yet been determined. It is recommended that a cesium-137 background concentration, based on hogs harvested from the regional military bases, be established.

The maximum onsite-hunter doses from 2006 through 2015 are shown in Table 3-5. The 30-y projected risk for this pathway (3.2E-04) is based on the 10-y average. However, it should be noted that the same hunter seldom receives the maximum potential dose for more than one year. The maximum annual dose from the onsite-hunter deer and hog consumption pathway typically exceeds all standard individual pathways combined. As shown in Table 3-5, this dose exceeds all other sportsman-dose scenarios. Therefore, deer consumption by the onsite hunter is the critical exposure pathway for SRS.

Table 3-5. Maximum Sportsman Doses and Projected 30-y Risks (2006-2015)

Year	Onsite Hunter (mrem)	Offsite Hunter (mrem)	Sav. Swamp (Offsite) Hunter (mrem)	Creek Mouth Fisherman (mrem)	Sav. Swamp (Offsite) Fisherman (mrem)
2006	22.0	8.9	9.6	0.24	0.52
2007	9.0	2.3	4.8	0.24	0.50
2008	13.0	7.7	8.6	0.11	0.37
2009	8.4	1.5	4.4	0.35	0.38
2010	12.4	0.4	3.3	0.22	0.40
2011	14.7	0.8	3.6	0.07	0.35
2012	14.5	1.1	4.0	0.22	0.17
2013	5.0	2.5	6.2	0.21	0.28
2014	18.3	3.2	6.1	0.28	0.23
2015	12.9	4.9	7.8	0.28	0.04
30-y Risk (unitless)	3.4E-04	8.7E-05	1.5E-04	5.8E-06	9.1E-06

Since 2006, a special turkey hunt for the mobility impaired has been held on site. Because of the relatively small size of the turkeys (as compared to deer and hogs), and because the cesium-137 concentrations measured in the field are usually below the detection limit of about 1.0 pCi/g, the doses from the turkey consumption pathway are much lower than from deer and hog. Like hogs, a cesium-137 background level specific for turkeys has not been determined. It is recommended that one be established for SRS.

3.3.3 *Offsite-Hunter Deer and Hog Consumption Pathway*

This pathway assumes that deer and hogs that had resided on SRS moved offsite, prior to being harvested. The estimated doses are based on the maximum annual meat consumption rate of 81 kg/y (Jannik et al., 2016) and on the average concentration of cesium-137 in all of the deer and hogs harvested during the annual onsite hunts. A background concentration of 0.5 pCi/g is subtracted out, before the offsite hunter dose is calculated. This background is the median offsite deer concentration determined by SCDHEC for South Carolina deer, from 2008 through 2012 (SCDHEC, 2013).

The maximum deer and hog offsite hunter doses, from 2006 through 2015, are shown in Table 3-5. The 30-y projected risk for this pathway (8.7E-05) is based on the 10-y average. This pathway typically exceeds all standard individual pathways combined.

3.3.4 *Savannah River Swamp Hunter Soil Exposure Pathway*

The potential dose to an offsite recreational hunter, exposed to SRS legacy contamination in Savannah River Swamp soil, on the privately owned Creek Plantation, is estimated using the RESRAD code (Yu et al., 2001). It was assumed that this recreational sportsman hunted for 120 hours during the year (8 hours/day for 15 days) at the location of maximum radionuclide contamination.

Using the worst-case radionuclide concentrations from the most recent comprehensive survey, the potential dose to a hunter, from a combination of 1) external exposure to the contaminated soil, 2) incidental ingestion of the soil, and 3) incidental inhalation of re-suspended soil, is estimated and added to the maximum offsite hunter, to obtain the combined “Savannah River Swamp Offsite Hunter” dose. The maximum doses (from 2006 through 2015) for this pathway are shown in Table 3-5. The 30-y projected risk for this pathway (1.5E-04) is based on the 10-y average. This pathway typically exceeds all standard individual pathways combined, and it is the second most critical pathway at SRS.

3.3.5 *Fish Consumption Pathway*

In EPA (1991), two fish-consumption pathways are considered – the recreational and the subsistence fisherman scenarios. In Burger et al. (1999), it was shown that some people who fish on the Savannah River reportedly eat a subsistence level (>50 kg/y) of fish each year, but not necessarily on fish caught exclusively from the Savannah River. Also, a majority of the fisherman interviewed in Burger et al., 1999 were located above SRS, especially around the New Savannah Bluff Lock and Dam (located near Augusta, Georgia). In the 2002 and 2008 GA Department of Natural Resources Creel Surveys, the average success rate for catching fish in the lower Savannah River is about 0.25 kg of whole fish per hour. This equates to over 14 hours per kg of edible fish.

Therefore, because of 1) SRS's relatively remote location, and 2) the relatively low productivity of the lower Savannah River (especially for game fish), the recreational fisherman, as opposed to the subsistence fisherman, is considered the more reasonable scenario and should continue to be used for individual and fisherman dose assessments at SRS.

During 1991 and 1992, a U.S. House of Representatives Appropriations Committee requested that SRS develop a plan to evaluate risk to the public from fish collected from the Savannah River. In response to this request, SRS developed (in conjunction with EPA, GDNR, and SCDHEC) the SRS Fish Monitoring Plan, which is reviewed and updated every year, as needed. Among the reporting requirements of this plan are 1) assessing radiological risk from the consumption of Savannah River fish, and 2) presenting a summary of the results in the SRS Annual Site Environmental Report.

In the dose and risk calculations performed as part of the SRS Fish Monitoring Plan, it is conservatively assumed that the recreational "Creek Mouth Fisherman" fishes for a single species of fish from the mouth of the worst-case SRS stream. Since 1992, samples of fish have been systematically taken from the mouths of the five SRS streams, and the subsequent recreational fisherman doses and 30-y risks have been estimated using a maximum consumption rate of 24 kg/y (Table 2.3). The results are shown graphically in Figure 3-11. The doses from this pathway for the past 10-y (2006-2015) are provided in the Table 3-5 column labeled "Creek Mouth Fisherman."

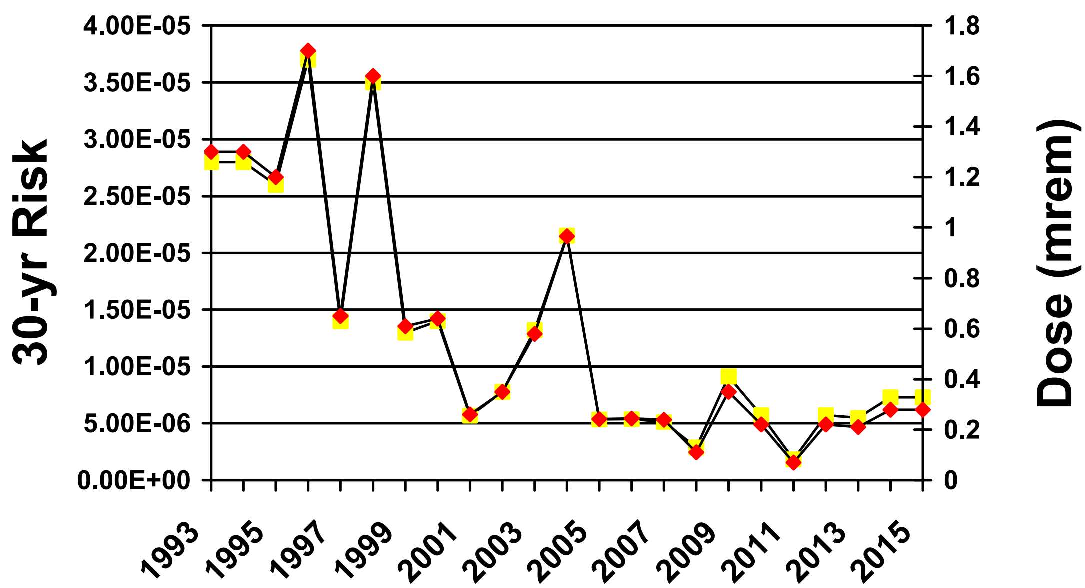

Figure 3-11. Maximum Fisherman Doses and Projected 30-y Risks (1992-2015)

According to the SRS Fish Monitoring Plan, all non-negative radioanalytical results are included in the average radionuclide concentrations, only, if at minimum, one of the three composites (by species) is significant. Cesium-137 is typically the critical radionuclide for the fish consumption pathway. However, when measured above detection levels, strontium-90, iodine-129, and technetium-99 can add significantly to the dose (40 to 50%). Tritium, which does not bioaccumulate in fish, remains at an equilibrium concentration between the water in which fish live and the fish flesh. The dose from tritium in fish has been, and will continue to be, less than 1% of the estimated total fisherman dose. Therefore, it is recommended that tritium in fish flesh be discontinued as an analyte.

No fish species (such as smelt) that are commonly eaten whole exist in the Savannah River. No known critical sub-populations occur in the SRS area that routinely eat whole fish as a common practice. In Burger et al., 1999, a majority of the Savannah River fisherman interviewed reportedly have eaten "whole fish." However, "whole fish" was not defined, nor was the frequency of this practice. However, for the species commonly fished for in the Savannah River (*see GDNR Creel Surveys*), the non-edible portion is in fact non-edible and avoided most of the time. Therefore, the dose/risk from the fish consumption pathway will continue to be based only on the edible portion of the fish.

As shown in Table 3-5, the 30-y projected Creek Mouth Fisherman fish consumption pathway risk, which is based on the 10-y average dose, is 5.8E-06, which is more than the 2.2E-06 projected risks for the standard individual liquid pathways combined (Table 3-3).

3.3.6 *Savannah River Swamp Fisherman Soil Exposure Pathway*

The potential dose to a recreational fisherman, exposed to SRS legacy contamination in Savannah River Swamp soil, on the privately owned Creek Plantation, was estimated using the RESRAD code (Yu et al., 2001). It was assumed that this recreational sportsman fished the South Carolina bank of the Savannah River, near the mouth of Steel Creek, for 250 hours during the year.

Using the radionuclide concentrations in soil measured at this location, the potential dose to a fisherman from a combination of 1) external exposure to the contaminated soil, 2) incidental ingestion of the soil, and 3) incidental inhalation of re-suspended soil is estimated and added to the maximum offsite fisherman dose, to obtain the combined "Savannah River Swamp Offsite Fisherman" dose. The maximum doses from 2006 through 2015 for this pathway are shown in Table 3-5. The 30-y projected risk for this pathway (9.1E-06) is based on the 10-y average. This pathway typically exceeds all standard individual pathways combined, and it is the fourth most critical pathway at SRS.

3.3.7 *Other Non-typical Wildlife Consumption Pathways*

Other SRS aquatic, terrestrial, and riparian animals (such as waterfowl, amphibians, raccoons, beavers, rabbits, and reptiles) may leave the site and be consumed by people in the surrounding areas. Over the years, these animals have been extensively studied by researchers of the Savannah River Ecology Laboratory (SREL). For a complete listing of related publications, refer to the SREL website (http://www.srel.edu).

However, because they travel over much larger ranges and are widely hunted and consumed by people, waterfowl are typically of most concern to SRS stakeholders. In 1986, in support of the site's Comprehensive Cooling Water Study, SREL issued a final report of a multiyear study of waterfowl at SRS (Mayer et al., 1986). This study concluded that offsite consumption of waterfowl posed a minor risk to offsite hunters. Part of the reason for this conclusion is that waterfowl have been shown to have a relatively rapid elimination rate for cesium upon leaving a contaminated area. In Fendley et al., 1976, the biological half-life for wood ducks was shown to average 5.6 d with a range of 3.2 to 9.3 d.

Georgia and South Carolina have a flourishing population of alligators, which is managed through a regulated hunting season. At SRS, alligators are abundant in the Savannah River, its swamp and tributaries, L-Lake, Par Pond, and other reservoirs on the site (SREL, 2014). Even though SRS is closed to public access and alligator hunting is prohibited on the site, larger alligators can leave the site's boundaries and move onto public lands where they could be harvested (Brisbin et al., 1992, 1997). SRS analyzes donated samples from alligators harvested by local hunters in the Savannah River or other locations adjacent to the site. In 2013, samples were analyzed from two alligators. Both animals were harvested from the Savannah River (one near Little Hell Landing in South Carolina; the other south of Plant Vogtle in Georgia). The alligator cesium-137 results were compared to results from edible fish. Based upon the samples from 2010, 2011, and 2013, the level of cesium-137 observed in alligator are consistent with observations from fish collected in the Savannah River.

In addition, insufficient data exist to accurately or practically determine reasonable maximum consumption rates and concentrations to calculate potential doses from non-typical wildlife consumption pathways. However, doses and risks from these less common consumption pathways are considered to be bounded by those determined from the deer/hog consumption pathways.

3.3.8 *Goat Milk Consumption Pathway*

Goats are raised on some farms in the SRS vicinity. It has been shown that the annual individual dose would increase about 10% if goat milk were substituted for the customary cow milk pathway (SRS, 2014). Most of this difference is from tritium oxide, because the transfer factor (fraction of the daily intake of the nuclide that appears in each liter of milk) for tritium oxide is 17 times more for goat milk than for cow milk (NRC, 1977b). However, because goat milk consumption is far less common and seldom a long-term substitute for cow milk, cow milk will remain the primary parameter for the milk consumption pathway.

3.4 SRS Performance Assessments and Composite Analysis

In response to DOE (1999), several Performance Assessments and a Comprehensive Composite Analysis have been completed at SRS. These reports document the potential pathways and likely radionuclides of concern, after operations cease at SRS. These reports have not been updated since the last revision of this report, and the critical pathways and radionuclides of concern remain the same as in Jannik and Scheffler (2011).

3.4.1 *Performance Assessments*

Four major Performance Assessments (PAs) have been completed at SRS (WSRC, 2008; LWO, 2009; SRR, 2010; SRR, 2011). These assessments are very conservative, in that they must consider a hypothetical intruder living on the waste site and the concentrations in groundwater at 100 m. In addition to the hypothetical intruder, the PAs have a point of compliance at the site boundary for potential airborne releases from the facilities. However, neither of these pathways is directly applicable to the near-term individual doses documented in the SRS environmental report, but they do give an indication of the critical radionuclides in the distant future (100-10,000 y).

3.4.1.1 *E-Area Low Level Waste Facility*

The critical radionuclides identified in the E-Area LLW Facility PA (WSRC, 2008) were iodine-129, tritium, carbon-14, and technetium-99, mainly from the drinking water pathway.

3.4.1.2 *Saltstone Disposal Facility*

The critical radionuclides identified in the Saltstone Disposal Facility PA (LWO, 2009) were radium-226, iodine-129, technetium-99, neptunium-237, and protactinium-231, with radium-226 and iodine-129 being the principal contributors to the projected dose within 10,000 y. Water ingestion (47%), fish ingestion (16%), and vegetable ingestion (37%) were identified as the critical pathways in this assessment.

3.4.1.3 *F-Tank Farm*

The critical radionuclides identified in the F-Tank Farm PA (SRR, 2010) were radium-226, technetium-99, neptunium-237, and cesium-135, with radium-226 and neptunium-237 being the principal contributors to the projected dose greater than 10,000 y. Water ingestion (64%) and vegetable ingestion (29%) were identified as the critical pathways leading to the highest dose within 10,000 y.

3.4.1.4 *H-Tank Farm*

The critical radionuclides identified in the H-Tank Farm PA (SRR, 2011) were radium-226, technetium-99, niobium-93m, neptunium-237, carbon-14, and cesium-135, with technetium-99 being the principal contributor to the projected dose greater than 10,000 y. Water ingestion (73%) and vegetable ingestion (20%) were identified as the critical pathways leading to the highest dose within 10,000 y.

3.4.2 *Composite Analysis*

A sitewide Composite Analysis (CA) also is required by DOE (1999). DOE views a CA as a planning tool relative to the end-state radiological protection of the public. As such, a CA is not a tool to evaluate current or near term (<2025) compliance, but rather it is a long-term management and planning tool.

The CA includes the following three additional exposure pathways that are not included in the SRS site environmental report (SER): ingestion of garden soil, external irradiation from garden soil, and inhalation of garden dust. These additional CA exposure pathways were found to be insignificant contributors to the overall CA dose (SRNL, 2010). A comparison of the types of dose projections provided by the SER and CA is provided in Table 3-6.

Table 3-6. Comparison of SER and CA Dose Pathways

CA Exposure Pathway	SER Individual	SER Irrigation	SER Creek-Mouth Fisherman
Ingestion of surface water	X		
Ingestion of vegetables, beef, and milk		X	
Ingestion of garden soil			
External irradiation from garden soil			
Inhalation of garden dust			
Ingestion of fish	X		X
External irradiation from shoreline	X		
External irradiation while boating	X		
External irradiation while swimming	X		

As shown in Table 3-7 (taken from SRNL, 2011), the near-term (30-y) critical radionuclides and associated pathways identified in the CA are cesium-137 (fish consumption), tritium (water consumption), iodine-129 (food consumption), and chlorine-36 (food consumption).

Table 3-7. CA Primary Radionuclides/Sources Contributing to Peak Dose

(Those producing a maximum dose ≥0.01 mrem/y)

Radionuclide	Source	Peak Dose (mrem/y)	Timing of Peak
Cs137	LTR Streambed	4.110	2011
Cs137	FMB Streambed	2.740	2011
Cs137	SC/PB Streambed	0.420	2011
Cs137	UTR Streambed	0.100	2011
Cs137	SR Swamp	0.043	2011
H3	K-Area GOU	0.150	2011
H3	FMB GOU	0.015	2011
H3	P-Reactor (concrete)	0.015	2032
H3	264-H	0.015	2039
H3	HAMN	0.061	2041
H3	E-Area CIG	0.021	2043
H3	232-H	0.011	2045
H3	HAOM	0.020	2060
I129	ORWBG fast	0.014	2011
I129	Old F-Area Seepage Basin	0.025	2021
I129	ORWBG slow	0.160	2024
I129	P-Reactor (surface)	0.012	2033
I129	E-Area Slit Trench Central	0.013	2049
I129	Z-Area Vault 4	0.027	2050
I129	LLRWDF FMB	0.018	2085
I129	MWMF	0.130	2115
I129	LLRWDF UTR	0.018	2125
I129	H-Area Seepage Basin	0.100	2240
Cl36	P-Reactor (surface)	0.099	2032
Cl36	L-Reactor (surface)	0.072	2038
Cl36	R-Reactor (surface)	0.045	2043
Cl36	K-Reactor (surface)	0.053	2055
Cl36	C-Reactor (surface)	0.057	2145
Tc99	Z-Area Vault 4	0.048	2115
Nb94	C-Reactor SS	0.150	2155
Nb94	NRCDA Pad 2	0.035	2215
Nb93m	TPBAR	0.021	2310
Np237	H-Area Canyon	1.040	2815
Ra226	E-Area ILV	0.016	4750
Ni59	ORWBG	0.028	5000
Nb93m	NRCDA Pad 1	0.066	12050

The critical radionuclides in the distant future (>100 y) were identified as iodine-129, chlorine-36, technetium-99, carbon-14, niobium-94, niobium-93m (daughter of zirconium-93), neptunium-237, radium-226, and nickel-59. Because of recommendations in Jannik (1997), several of these long-lived radionuclides (iodine-129, technetium-99, and neptunium-237) were previously added to the SRS environmental monitoring program radionuclide analytical suite. They are currently being measured at the applicable SRS-effluent and environmental surveillance locations. The others have not been routinely analyzed. This is because they are not projected to reach human exposure locations for many years. However, consideration should be given to periodically analyzing for these radionuclides, as well as for cesium-135 and protactinium-231 (the additional long-lived radionuclides identified as important in the four PAs).

In Table 3-7, chlorine-36 is shown as a fairly near-term dose contributor. However, all of the chlorine-36 is associated with the reactor buildings which will undergo in-situ disposal (which consists of grouting and sealing the reactor buildings). These barriers were conservatively not accounted for in the CA modeling. In the future, all of the long-lived radionuclides (Table 3-7) may become more important on a percentage of dose/risk basis, but as shown, the total dose consequence should remain small.

4.0 CONCLUSIONS

During the operational history of SRS, many different radionuclides have been released from site facilities. However, as shown in this analysis (Table 3-1 and Table 3-3), only a relatively small number of the released radionuclides have been significant contributors to doses/risks to offsite people.

For the airborne pathway, only iodine-131, tritium, argon-41, iodine-129, plutonium-239, and carbon-14 were determined to exceed a risk of 1.0E-06 on a cumulative individual risk basis. However, no radionuclides exceeded a cumulative risk of 1.0E-04. The most critical pathways associated with the airborne pathway individual cumulative risks were food consumption, inhalation, and plume shine.

For the liquid pathway, cesium-137, phosphorus-32, strontium-90, zinc-65, tritium, iodine-131, unidentified beta, and sulfur-35 were determined to exceed a risk of 1.0E-06 on a cumulative individual risk basis. Only cesium-137 exceeded a cumulative risk of 1.0E-04. The most critical pathways associated with the liquid pathway individual cumulative risks were fish consumption and drinking water ingestion.

For the next 30 years, if site missions and operations remain constant, only tritium is projected to exceed an atmospheric pathway individual risk of 1.0E-07 All other airborne radionuclides are projected to have negligible (<1.0E-07) 30-y risks. The critical pathways associated with the airborne pathway individual projected risks are inhalation and vegetation consumption, with milk consumption becoming more important, as iodine-129 becomes a higher percentage of the dose.

On a 30-y risk basis, no liquid pathway radionuclides are projected to exceed a risk of 1.0E-06. However, cesium-137 (while decreasing) remains reasonably close (5.7E-07), and tritium, technetium-99, unidentified alpha and beta, iodine-129, strontium-90, and uranium-238 all exceed 1.0E-07. All other liquid pathway radionuclides have negligible (<1.0E-07) projected 30-y risks. By considering the irrigation of foodstuffs with Savannah River water, the most critical pathway associated with the liquid pathway individual projected risk is the consumption of irrigated food, followed by fish consumption, then drinking water ingestion.

The SRS-specific, non-typical exposure pathways are not included in the standard RP dose calculations, because they apply to relatively low-probability (creek-mouth fisherman) or unique (onsite deer and hog hunters) exposure scenarios. However, they are assessed separately.

The maximum annual dose from the onsite-hunter deer/hog consumption pathway typically exceeds all standard RP pathways combined, and it exceeds all other sportsman dose scenarios. The 30-y projected risk (assuming the maximum dose occurs to the same hunter) from this pathway is 3.4E-04. Therefore, deer/hog consumption by the onsite hunter is the critical exposure pathway for SRS, with cesium-137 being the critical radionuclide.

The offsite deer/hog hunter and the associated Savannah River Swamp offsite hunter are the next most critical exposure pathways at SRS. The projected 30-y risks for these pathways are 8.7E-05 and 1.5E-04, respectively. The creek-mouth fisherman and the associated Savannah River Swamp (Steel Creek) offsite fisherman are the next most critical pathways at SRS. The projected 30-y risks for these pathways are 5.8E-06 and 9.1E-06, respectively.

The following recommendations and considerations were identified during this assessment:

- In the SRS PA's and CA, the following long-lived radionuclides were identified as being important in long-term dose projections (>100 y): iodine-129, chlorine-36, technetium-99, niobium-94, niobium-93m, neptunium-237, radium-226, nickel-59, cesium-135, carbon-14, and protactinium-231. Because of recommendations in Jannik (1997), several of these long-lived radionuclides (iodine-129, technetium-99, carbon-14 and neptunium-237) were previously added to the SRS environmental monitoring program radionuclide analytical suite. But the remainder of these radionuclides has not been routinely analyzed for in SRS effluent or environmental samples. Consideration should be given to periodically analyzing for these radionuclides in aqueous surveillance samples.

- Because of the reduced releases of atmospheric tritium at SRS (Figure 3-2), the frequency of detection of tritium-in-air at the site boundary air-surveillance sampling stations has also been reduced (Abbott et al., 2016). It is recommended that the data quality objectives for the site's air-surveillance stations be reconsidered, to determine if they are still located at the proper distances and directions from the major onsite sources.

- A regional cesium-137 background level for hogs has not been yet been determined. It is recommended that a cesium-137 background concentration, based on hogs harvested from the nearby military bases, be established.

- Like hogs, a cesium-137 background level for turkeys has not been determined. It is recommended that one be established for SRS.

- Tritium, which does not bioaccumulate in fish, remains at an equilibrium concentration between the water in which fish live and the fish flesh. The dose from tritium in fish has been, and will continue to be, less than 1% of the estimated total fisherman dose. Therefore, it is recommended that tritium in fish flesh be discontinued as an analyte.

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