Contract No.:

This manuscript has been authored by Savannah River Nuclear Solutions (SRNS), LLC under Contract No. DE-AC09-08SR22470 with the U.S. Department of Energy (DOE) Office of Environmental Management (EM).

Paper

SITE SPECIFIC REFERENCE PERSON PARAMETERS AND DERIVED CONCENTRATION STANDARDS FOR THE SAVANNAH RIVER SITE

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Abstract – The U.S. Department of Energy Order 458.1 states that the compliance with the 1 mSv annual dose constraint to a member of the public may be demonstrated by calculating dose to the maximally exposed individual (MEI) or to a representative person. Historically, the MEI concept was used for dose compliance at the Savannah River Site (SRS) using adult dose coefficients and adult male usage parameters. For future compliance, SRS plans to use the representative person concept for dose estimates to members of the public. The representative person dose will be based on the reference person dose coefficients from the DOE Derived Concentration Technical Standard and on usage parameters specific to SRS for the reference and typical person. Usage parameters and dose coefficients were determined for inhalation, ingestion and external exposure pathways. The reference intake for air, water, meat, dairy, freshwater fish, saltwater invertebrates, produce (fruits and vegetables), and grains for the 95th percentile are 17.4 m^3 d^{-1}, 2.19 L d^{-1}, 220.6 g d^{-1}, 674 cm^3 d^{-1}, 66.4 g d^{-1}, 23.0 g d^{-1}, 633.4 g d^{-1} (448.5 g $d^{-1}$and 631.7 g d^{-1}) and 251.3 g d^{-1} respectively. For the 50th percentile: 13.4 m^3 d^{-1}, 0.809 L d^{-1}, 86.4 g d^{-1}, 187 cm^3 d^{-1}, 8.97 g d^{-1}, 3.04 g d^{-1}, 169.5 g d^{-1} (45.9 g $d^{-1}$and 145.6 g d^{-1}), 101.3 g d^{-1} respectively. These parameters for the representative person were used to calculate and tabulate SRS-specific derived concentration standards (DCSs) for the pathways not included in DOE-STD-1196-2011.

Key words: Dosimetry; Environmental; Population Dose; Reference Person

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INTRODUCTION

The U.S. Department of Energy (DOE) Order 458.1 (DOE 2011a) states that compliance with the annual dose limit of 1 mSv to a member of the public may be demonstrated by calculating the dose to the maximally exposed individual (MEI) or to a representative person. Historically, for dose compliance, the Savannah River Site (SRS) has used the MEI concept, which uses adult dose coefficients and adult male usage parameters. Beginning with the 2012 annual site environmental report (ASER), SRS changed to the representative person concept for dose compliance.

The dose to a representative person is based on 1) the SRS-specific reference person usage parameters at the 95th percentile of appropriate national or regional data (Stone and Jannik 2013), 2) the reference person (gender and age averaged) ingestion and inhalation dose coefficients provided in DOE Derived Concentration Technical Standard (DOE-STD-1196-2011) (DOE 2011b), and 3) the external dose coefficients provided in the DC_PAK3 toolbox, which can be accessed on the EPA website.[*] The reference person is weighted based on sex and age and this weighting is based on the six age groups documented in International Commission on Radiological Protection (ICRP) Publication 89 (ICRP 2002). The age groups are: Infant (0 years), 1 year, 5 years, 10 years, 15 years, and Adult and the various age- and gender-specific intake rates were proportioned to correspond with these respective age groupings.

As an extension to the site-specific reference person development, SRS-specific derived concentration standards (DCSs) for all applicable ingestion and inhalation pathways, ground shine, and water submersion also were developed. The DCS is the concentration of a particular

[*] http://www.epa.gov/rpdweb00/federal/techdocs.html.

radionuclide in water, in food, in air, or on the ground that results in a member of the public receiving 1 mSv effective dose following continuous exposure for one year. In DOE (2011b), DCSs were developed for the ingestion of water, inhalation of air, and submersion in air pathways, only. These DCSs are required to be used at all DOE sites in the design and conduct of radiological environmental protection programs (DOE 2011a). DCSs for the following additional pathways were considered and documented: ingestion of meat, dairy, grains, produce (fruits and vegetables), freshwater fish, and saltwater invertebrates, submersion in water, and ground shine. These additional DCSs were developed using the same methods as in DOE (2011b) and will be used at SRS, where appropriate, as screening and reference values and not for dose compliance calculations. Cases of multiple pathways and radionuclides will be screened by use of a sum-of-the-fractions method.

METHODS

During routine, regulated operations at SRS, limited amounts of radioactive materials are released to the environment through atmospheric and liquid pathways. These releases potentially result in a committed dose to offsite people. The principal pathways by which people may be exposed to releases of radioactive materials are inhalation, ingestion of water and foodstuffs, skin absorption and external exposure.

At SRS, the potential effects of routine radioactive releases have been assessed annually since operations began. Since 1972, annual offsite dose estimates have been published in site environmental reports, which are made available to the public. For all routine environmental dose calculations performed since 1978, SRS has used environmental transport models based on codes developed by the U.S. Nuclear Regulatory Commission (NRC) (NRC 1977). The NRC based transport models use DOE accepted methods, consider all significant exposure pathways, and permit detailed analysis of the effects of routine operations.

Reference and Typical Person

Beginning with the 2012 ASER, SRS changed to the representative person concept for dose compliance. The dose to a representative person will be based on the reference person (gender and age averaged) dose coefficients provided in DOE (2011a) and on the SRS-specific reference person usage parameters at the 95th percentile of appropriate national or regional data.

The concept of the reference person began with the introduction of what was known as the standard man. The standard man was first introduced by ICRP Publication 2 (ICRP 1960), which was based on the accepted "average" biological and dosimetric parameters known and used at the time. The purpose of the standard man was to consistently calculate doses to radiation workers and could be reproducible. In 1974, the standard man model was updated to what is known as the reference man model in ICRP Publication 23 (ICRP 1975). This model included improved biokinetic models and better dosimetric models. The reference man model primarily focused on the adult worker and the information for the model is still widely used. The reference man model was updated in ICRP Publication 89 (ICRP 2002) for both the male and female reference person and created six groups of age ranges for specific reference individual values. From this data, the reference person could be determined. The ICRP introduced the Representative Person in ICRP Publication 101, where "the representative person is the equivalent of, and replaces, the average member of the critical group" (ICRP 2005). The ICRP uses the term "equivalent" to show that both methods are valid in calculating dose, though not being numerically equivalent. ICRP Publication 103 (ICRP 2007) formally recommends the use of the representative person.

In DOE (2011a), the use of the representative person is allowed by DOE for dose compliance and defines the reference person as *A hypothetical aggregation of human (male and female) physical and physiological characteristics arrived at by international consensus for the purpose of standardizing radiation dose calculations.* The reference person, therefore, is an age and gender aggregation of the twelve age-specific reference individuals documented in ICRP (2002).

Also in DOE (2011a), the representative person is defined as *An individual receiving a dose that is representative of the more highly exposed individuals in the population. This term is equivalent of, and replaces, "average member of the critical group."* However, in ICRP (2006), the definition is extended to include the *Average value for the more highly exposed group* ***OR*** *the 95th percentile of appropriate national or regional data.* The OR is highlighted for emphasis. At SRS, the reference person who is at the 95th percentile of national usage data will be used as a replacement for the MEI. The appropriate national usage data were taken from the U.S. Environmental Protection Agency's (EPA) Exposure Factors Handbook: 2011 Edition (EPA 2011).

As an extension of the reference person, and to show compliance with collective dose requirements in DOE (2011a), SRS has defined the concept of the "Typical Person." The typical person is a hypothetical reference person that is typical of the entire population group and it is established at the 50th percentile (median) of the national data. These national median data also were taken from EPA (2011). The median (as opposed to the mean) is better suited for skewed distributions, which are typical for human intake rates, to derive at central tendency because it is uninfluenced by extreme values such as 99th percentile intake rates, making the median statistically more robust and sensible (Myers 2002).

Development of Reference and Typical Person Parameters

Several parameters are required for the development of the reference person. Population fractions allows the reference person to be a weighted-average based on age and sex, such that it is an aggregation of male and female from six different age groups. The population fractions were determined using the current U.S. 2010 Census data (2011).

Population data for the US as a whole and for the South Carolina (SC) and Georgia (GA) counties surrounding the SRS (within an 80 km radius) are shown in Table 1. In the population fractions presented, people living in the surrounding SC/GA counties are slightly younger and more female than the general US population.

There are many pathways an individual member of the public may be exposed to radioactive materials. In the DOE (2011b), the pathways analyzed were ingestion of water, inhalation of air, and external exposure from immersion in air. The pathways for food and water ingestion, inhalation, and external exposure by immersion in air, submersion in water, and ground shine were analyzed for this work. As previously discussed, for each pathway, 95th and 50th percentile intake rates were taken from EPA (2011) and used for the reference person and typical person scenarios, respectively.

The water ingestion intake rates are given as an example in Table 2. The daily 95% reference person and 50% typical person intake rates convert to about 800 L y^{-1} and 300 L y^{-1}, respectively. The previous SRS MEI and average-population intake rates from "Land and Water use Characteristics and Human Health Input Parameters for use in Environmental Dosimetry and

Risk Assessments as the Savannah River Site." (Jannik et al. 2010) were 730 L y^{-1} and 337 L y^{-1}, respectively.

External doses can be received from immersion in air, submersion in water or ground shine. For immersion in air, individuals are exposed 365.25 d y^{-1}. Exposure time from submersion in water is determined by the type of activity; boating and swimming. For boating, the maximum time per year is 44 hours per year and the average time is 22 hours per year. The maximum annual exposure time for swimming is 14 hours and the average time is 7 hours. Exposure factors for these exposures are taken from Jannik et al. (2010). Ground shine is the external dose received from radioactive material deposited on the ground. The exposure time is conservatively set at 365.25 d y^{-1}. An additional ground shine pathway includes exposure to Savannah River sediment. To calculate dose from shoreline pathways, the ground-shine dose coefficient is multiplied by a dose reduction factor. Because SRS is located along the Savannah River, the river-shoreline dose reduction factor of 0.2 is used as recommended in EPA (1993). External dose coefficients for immersion in air, submersion in water and ground shine were taken from the DC_PAK3 toolbox[†] and are compiled in Stone and Jannik (2013).

Derived Concentration Standards (DCS)

DCS are a concentration of a radionuclide in a medium that results in a member of the public receiving 1 mSv effective dose following continuous exposure for one year. The pathways water ingestion, air inhalation and immersion in air were developed in DOE (2011b), These DCSs are recommended by DOE (2011a) for use at all DOE sites in the design and conduct of radiological environmental protection programs. Using the same methods as in DOE-STD-1196-2011, additional pathways were considered and documented for DCSs. These pathways include

[†] http://www.epa.gov/rpdweb00/federal/techdocs.html

ingestion of meat, dairy, grains, produce (fruits and vegetables), seafood, submersion in water and ground shine. These DCSs will be used at SRS, where appropriate, as screening and reference values.

Reference intake rates and reference dose coefficients are calculated using the population fractions and intake rates for each associated age group for both male and female. The reference intake rate is calculated by summing the male intake rate multiplied by the male population fraction and the female intake rate multiplied by the female population fraction of each age group shown here in eqn 1,

$$IR_{ref} = \sum_{n=1}^{6}(U_M(n) * f_M(n) + U_F(n) * f_F(n) \quad (1)$$

Where, IR_{ref} (kg d^{-1} or L d^{-1}), is the reference intake rate. "U" is the age specific intake rate (kg d^{-1} or L d^{-1}) and "f" is the population fraction of that particular age group. The subscripts, "M" and "F," denote male and female parameters, respectively. Reference dose coefficients are calculated using the reference intake rate as seen in eqn 2.

$$DC_{ref} = \frac{\sum_{n=1}^{6}[(U_M(n) * f_M(n) + U_F(n) * f_F(n)) * DC_n]}{IR_{ref}} \quad (2)$$

Where, DC_{ref} (Sv Bq^{-1}) is the reference dose coefficient. DC_n (Sv Bq^{-1}) is the dose coefficient of a particular age group, n. IR_{ref} (kg d^{-1} or L d^{-1}) is the reference intake rate. "U" is the age specific intake rate (kg d^{-1} or L d^{-1}) and "f" is the population fraction of that particular age group. The subscripts, "M" and "F," denote male and female parameters, respectively. The dose coefficients are taken from DOE (2011b).

The DCS's for each pathway of ingestion are calculated in a similar manner and ar calculated using eqn 3.

$$DCS_{ing} = \frac{EC}{t * IR_{ref} * DC_{ref}} \qquad (3)$$

Where, DCS_{ing} (kg d^{-1} or L d^{-1}), is the derived concentration for a specific ingestion pathway and radionuclide. Four parameters are needed to calculate the DCS. The dose constraint is the dose an individual will receive when exposed to the DCS. This dose is the annual dose limit (EC) recommended and used by DOE of 1 mSv. The reference intake (IR_{ref}) discussed previously is calculated for the ingestion pathway of interest in the units of volume or mass per day (kg d^{-1} or L d^{-1}). The reference dose coefficient (DC_{ref}) is calculated as shown previously and used to convert the dose of the constraint into an activity (Sv Bq^{-1}). The DCS is calculated over the course of a year or 365.25 days(t). The derived concentrations are calculated using eqn 3. Depending on the type of food being ingested, the DCS will result in units of activity per unit volume or unit mass.

The inhalation DCS is calculated similarly to that of the ingestion DCS, where the inhalation reference intake rate is used in place of the ingestion reference intake rate. The reference-inhalation intake rate is calculated using eqn 1 and the reference-inhalation dose coefficient is calculated using eqn 2.

The DCS for both air immersion and water submersion are calculated by eqn 4, where the dose constraint (EC) is the annual dose limit of 1 mSv. The dose coefficient is in units of Sv-m^3 per Bq-sec, and time over the course of a year (t) is 3.1536×10^7 seconds. The dose coefficients are from the DC_PAK3 toolbox.

$$DCS = \frac{EC}{t * DC} \quad (4)$$

The calculation of the DCS for ground shine is similar to that of air and water submersion and eqn 4 can be used. The units of the DCS are in activity per unit area (Bq cm^{-2}); the dose coefficient is in units of Sv m^2 per Bq-sec.

RESULTS

The following is a summary of the SRS-specific Reference Person (95^{th} percentile) and Typical Person (50^{th} percentile) intake rates. Comparisons to the previous MEI and average population values are provided, as is an example of how the overall dose estimates will be affected.

Reference Intake Comparisons

The reference intake values calculated changed from the values that were previously used, which are listed in Jannik et al. (2010). Table 3 compares previously used intake rates with new reference intake rates.

The 95^{th} percentile values showed no change or slight increases except for inhalation and leafy vegetables, which decreased by 20% and 28%, respectively, from the previous adult male (MEI) values. However, for the 50^{th} percentile values there was a noticeable decrease in all of the intake rates because of the effect of age and gender weighting and use of the median as opposed to the mean.

Comparison of Internal Dose Calculations

Using the reference intakes in Table 3 and the internal dose coefficients for tritium oxide from DOE (2011b), dose calculations were performed for a unit concentration (1 Bq L^{-1} or 1 Bq kg^{-1}) and are compared to the previous dose values in Table 4. Tritium oxide typically accounts for over 99% of the total releases from SRS.

In general, the reference-person dose coefficients are larger than the previously used ICRP (1995) adult dose coefficients. For tritium oxide, the difference is about 17% more for ingestion and 7% more for inhalation. Therefore, for the 95% intake parameters that increased (Table 3) the dose difference is even larger (Table 4). For the 50% intake parameters (which all decreased), the percentage dose difference is smaller.

Comparison of External Dose Coefficients

Using the existing exposure times from Jannik et al. (2010) and the external dose coefficients for ^{137}Cs (including ^{137m}Ba) from the DC_PAK3 toolbox, dose calculations were performed for a unit concentration (1 Bq m^{-2} or 1 Bq m^{-3}) and compared to the current dose values in Table 5. There are only minor changes due to minor differences in the updated ICRP (2008) decay data. ^{137}Cs is an important beta-gamma emitter at SRS.

Example Derived Concentration Standards

Using the reference person parameters developed DCS's were calculated for each radionuclide and exposure pathway (Stone and Jannik 2013). Example DCS's for ^{3}H, ^{90}Sr, ^{137}Cs, and ^{239}Pu are in Table 6.

DISCUSSION AND CONCLUSION

SRS-specific reference person intake parameters have been developed and are now used as input for calculating dose to the representative person. The external pathway exposure parameters remained unchanged from Jannik et al. (2010). However, the external exposure dose coefficients were updated to those that incorporate the ICRP 107 decay data. In addition, the SRS-specific derived concentration standards for all applicable exposure pathways have been calculated and provided for reference.

Use of Reference Person Parameters and Dose Coefficients

The SRS-specific reference person intake parameters will be used in conjunction with the reference person ingestion and inhalation dose coefficients to calculate the representative person dose at SRS. This representative person dose will be used for demonstrating compliance with the DOE (2011a) public dose limit of 1 mSv y^{-1}.

Use of SRS-Specific Derived Concentration Standards

In DOE (2011b), DCSs were developed for the ingestion of water, inhalation of air and submersion in air pathways. DCSs for the following additional pathways were considered and documented: ingestion of meat, dairy, grains, produce (fruits and vegetables), seafood, submersion in water and ground shine. These additional DCSs were developed using the same methods as in DOE (2011b) and will be used at SRS, where appropriate, as screening and reference values.

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FOOTNOTES

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‡http://www.epa.gov/rpdweb00/federal/techdocs.html.

§ http://www.epa.gov/rpdweb00/federal/techdocs.html

Table 1

Table 1. U.S. and SC/GA 2010 population fractions

Age Group	Age (y)	US 2010		SC/GA Counties 2010	
		Male	Female	Male	Female
new born	x<1	0.006524	0.006251	0.006770	0.006511
1 year	1≤x<3	0.013354	0.012800	0.013421	0.013240
5 year	3≤x<7	0.026979	0.025833	0.027484	0.026269
10 year	7≤x<12	0.033949	0.032489	0.034591	0.033192
15 year	12≤x<17	0.034765	0.033087	0.035017	0.033156
Adult	17 and older	0.376036	0.397933	0.369306	0.401043

Table 2

Table 2. Water Ingestion Intake Rates (L d^{-1})

Age Group	Age x, (y)	50%		95%	
		Male	Female	Male	Female
New Born	x<1	0.364	0.364	1.1195	1.1195
1 year	1≤x<3	0.3295	0.3295	0.98	0.98
5 year	3≤x<7	0.438	0.438	1.2	1.2
10 year	7≤x<12	0.503	0.503	1.409	1.409
15 year	12≤x<17	0.663	0.49725	1.96	1.47
Adult	17 and older	1.04175	0.781313	2.808	2.106
Reference Person (Age and Gender Combined)		0.81		2.2	

Table 3

Table 3 Comparison of Reference and Typical Person Intakes with Current Intakes

Pathway	Units	95th Percentile Reference Person	Current MEI	Difference
Air	$m3\ y^{-1}$	6400	8000	-20.0%
Water	$L\ y^{-1}$	800	730	9.6%
Meat	$kg\ y^{-1}$	81	81	0.0%
Leafy Vegetables	$kg\ y^{-1}$	31	43	-27.9%
Other Produce	$kg\ y^{-1}$	289	276	0.5%
Milk/Dairy	$L\ y^{-1}$	260	230	13%
Freshwater Fish	$kg\ y^{-1}$	24	19	26.3%
Saltwater Invertebrate	$kg\ y^{-1}$	9.0	8	12.5%
Pathway	**Units**	**50th Percentile Typical Person**	**Current Avg.**	**Difference**
Air	$m3\ y^{-1}$	5000	5548	-9.9%
Water	$L\ y^{-1}$	300	337	-11.0%
Meat	$kg\ y^{-1}$	32	43	-26.3%
Leafy Vegetables	$kg\ y^{-1}$	11	21	-47.6%
Other Produce	$kg\ y^{-1}$	89	163	-45.4%
Milk/Dairy	$L\ y^{-1}$	69	120	-42.3%
Freshwater Fish	$kg\ y^{-1}$	3.7	9	-58.9%
Saltwater Invertebrate	$kg\ y^{-1}$	1.5	2	-25.0%

Table 4

Table 4 Comparison of Representative and Typical Doses with Current Dose Calculations for Unit Concentrations of Tritium Oxide

95%			
Pathways	Representative Dose (Sv)	Previous Dose (Sv)	Difference
Air	$1.85x10^{-7}$	$2.16x10^{-7}$	-14.22%
Water	$1.68x10^{-8}$	$1.31x10^{-8}$	27.85%
Meat	$1.70x10^{-9}$	$1.46x10^{-9}$	16.67%
Total Produce	$6.72x10^{-9}$	$5.74x10^{-9}$	17.03%
Milk/Dairy	$5.46x10^{-9}$	$4.14x10^{-9}$	31.88%
Freshwater Fish	$5.04x10^{-10}$	$3.42x10^{-10}$	47.37%
Saltwater Invertebrate	$1.89x10^{-10}$	$1.44x10^{-10}$	31.25%

50%			
Pathways	Typical Dose (Sv)	Previous Dose (Sv)	Difference
Air	$1.45x10^{-7}$	$1.50x10^{-7}$	-3.37%
Water	$6.30x10^{-9}$	$6.07x10^{-9}$	3.86%
Meat	$6.72x10^{-10}$	$7.74x10^{-10}$	-13.18%
Total Produce	$2.10x10^{-9}$	$3.31x10^{-9}$	-36.59%
Milk/Dairy	$1.45x10^{-9}$	$2.16x10^{-9}$	-32.92%
Freshwater Fish	$7.77x10^{-11}$	$1.62x10^{-10}$	-52.04%
Saltwater Invertebrate	$3.15x10^{-11}$	$3.60x10^{-11}$	-12.50%

Table 5

Table 5 External dose calculation comparisons (Sv)

Pathway	Updated Dose	Current Dose	Difference
Air Immersion	8.51×10^{-7}	9.08×10^{-7}	-6.30%
Water Submersion	1.84×10^{-9}	1.97×10^{-9}	-6.72%
Ground Shine	1.83×10^{-8}	1.85×10^{-8}	-1.05%

Table 6

Table 6 Example Derived Concentration Standards for each exposure pathway

Nuclide	Water Ingestion (Bq L^{-1})	Meat Ingestion (Bq kg^{-1})	Dairy Ingestion (Bq L^{-1})	Freshwater Fish Ingestion (Bq kg^{-1})	Saltwater Shellfish Ingestion (Bq kg^{-1})	Produce Ingestion (Bq kg^{-1})	Air Inhalation (Bq m^{-3})	Ground Shine (Bq m^{-2})	Air Immersion (Bq m^{-3})	Water Submersion (Bq m^{-3})
H-3	5.92×10^{4}	5.88×10^{5}	1.82×10^{5}	2.16×10^{6}	5.95×10^{6}	1.47×10^{5}	8.10×10^{3}	N/A	N/A	N/A
Sr-90	3.45×10^{1}	3.43×10^{2}	1.06×10^{2}	1.26×10^{3}	3.47×10^{3}	8.57×10^{1}	3.99×10^{0}	1.93×10^{7}	3.23×10^{5}	2.91×10^{8}
Cs-137	9.35×10^{1}	9.28×10^{2}	2.88×10^{2}	3.42×10^{3}	9.40×10^{3}	2.32×10^{2}	3.40×10^{1}	1.01×10^{7}	3.37×10^{5}	3.02×10^{8}
Pu-239	4.32×10^{0}	4.29×10^{1}	1.33×10^{1}	1.58×10^{2}	4.34×10^{2}	1.07×10^{1}	3.10×10^{3}	1.04×10^{8}	8.41×10^{6}	3.73×10^{9}

Daniel Stone is an Environmental Dosimetry Intern in the Environmental Sciences and Biotechnology Division at the Savannah River National Laboratory in Aiken, South Carolina. He recently received his master's degree in Radiation Health Physics from Oregon State University. His research interests include environmental dosimetry, internal and external dosimetry, radiobiology and radioecology.

A site specific reference person is developed for the Savannah River Site to demonstrate compliance of doses to members of the public.