SANDIA REPORT
SAND2019-13482
Printed November 2019

Sandia National Laboratories

Identification of Top Dose Producing Radionuclides Produced by Research and Test Reactors

Heather M. Pennington, Terrence D. Kraus, Craig M. Tenney, Christopher Faucett and Dusty Brooks

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico
87185 and Livermore,
California 94550

Issued by Sandia National Laboratories, operated for the United States Department of Energy by National Technology & Engineering Solutions of Sandia, LLC.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone:	(865) 576-8401
Facsimile:	(865) 576-5728
E-Mail:	reports@osti.gov
Online ordering:	http://www.osti.gov/scitech

Available to the public from:

U.S. Department of Commerce
National Technical Information Service
5301 Shawnee Rd
Alexandria, VA 22312

Telephone:	(800) 553-6847
Facsimile:	(703) 605-6900
E-Mail:	orders@ntis.gov
Online order:	https://classic.ntis.gov/help/order-methods/

ABSTRACT

Nuclear fission produces more than 1,000 radioactive isotopes, each having different half-lives and producing unique characteristic emissions (e.g., alpha, beta, gamma), which makes it challenging to quickly and accurately assess radiological impacts resulting from sabotage (e.g., atmospheric transport, projected dose). Since many of the radionuclides produced by nuclear fission contribute an insignificant dose compared to other radionuclides, identifying the top dose-producing radionuclides will accelerate and simplify radiological assessments of research and test reactor releases. Here, we identify the fission radionuclides that contribute significant dose, enabling assessors to conduct consistent, simple, rapid and accurate radiological assessments.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the following people, without whom the project could not have been performed. Douglas Shull, IAEA Senior Nuclear Security Officer for support of this study. Nathan Bixler provided significant background information as well as mentoring for the project as a whole. Many thanks to Douglas Osborn, who provided peer review on this report. And special thanks to Susan Jean-Pierre, who provided technical editing of this document.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

This report provides a simplified method and radiological source terms to assess the potential radiological impacts from the explosive sabotage of research and test reactors (RTRs). The radiological assessment of RTR source terms is very complex because more than 1,000 radionuclides are formed by fission processes and many have complex decay chains. Fortunately, many of these radionuclides contribute minimal dose and do not need to be included in the dispersal and dose assessment. This document describes the methodology that was used to determine the top dose-producing radionuclides to enable rapid and consistent radiological assessments.

Because the International Atomic Energy Agency (IAEA) research reactor database includes more than 400 reactors, it was not feasible to generate a simplified source term for each reactor. Therefore, the reactors were grouped into the eight categories shown in Table 2-1 based on fuel type and reactor characteristics, and simplified source terms were developed for the eight reactor types. A two-step process was used to generate the representative radionuclides inventories in the reactor core. First, new cross section libraries were created using transport rigor implemented with time-dependent operation for neutronic depletion (TRITON), a depletion sequence in the standardized computer analyses for licensing evaluation (SCALE) software package [1]. Then, the cross-section libraries were used in Oak Ridge isotope generation automatic rapid processing (ORIGEN-ARP) depletion calculations to create the radionuclide inventories [1]. The following assumptions were made to simplify inventory calculations:

- 50% burnup based on USNRC regulatory limits in NUREGG-1537,
- Aluminum cladding (most common cladding type), and
- 1 kg uranium metal initial loading.

The fraction of the core inventory that could be released by an explosive attack largely is determined by the chemical/physical characteristics of the elements in the inventory. The elements were grouped into seven chemical classes and assigned release fractions as shown in Table 2-2. The radioactivity of each radionuclide in the core inventory was multiplied by the appropriate release fraction to determine the radioactivity of each radionuclide potentially released to the environment by the explosive attack. Particle size distributions (PSDs) were assigned to the radionuclides based on the particle size bins and chemical classes shown in Table 2-3 and Table 2-4, respectively. The deposition velocities in Table 2-7 were used to determine the relative air and ground concentrations for the different particle size bins.

NOTE: Noble gases were assumed **not** to deposit on the ground and were assigned a deposition velocity of 0.0 m/s.

The explosive release atmospheric dispersion (ERAD) model was used to predict integrated air and ground concentrations of each particle size bin at a hypothetical location 400 m downwind and at the plume centerline in a residential setting. Generic atmospheric conditions were assumed, corresponding to a neutral to slightly-stable atmospheric stability class using the atmospheric sounding shown in Table 2-6.

The dose analysis was complicated by the fact that nearly half of the radionuclides in the core inventory, as predicted by the ORIGEN code, have such short half-lives that they are not assigned dose coefficients in the FORTRAN-based dose coefficient file package (DCFPAK) radiological database [2] developed by Oak Ridge National Laboratory (ORNL). Therefore, a detailed analysis

was performed by implementing an instantaneous transformation (radioactive decay) assumption to identify the first progeny that either had assigned dose coefficients or was stable. The number of atoms of the original radionuclide was calculated and assigned to the radioactive progeny and the radioactivity of the progeny then was calculated and its dose was evaluated.

The dose to the adult from each radionuclide in the RTR fuel types was analyzed using the Turbo Federal Radiological Monitoring and Assessment Center (Turbo FRMAC©) code and the methodology specified in [3]. It was necessary to make some minor modifications to the IAEA's methodology, as described in this report, to enable the automation of the dose assessment.

The Turbo FRMAC© code was used to assess the relative dose from each exposure pathway and from each radionuclide in the eight fuel types over the Urgent (0 – 7 d) and Early (0 – 365 d) phases specified by IAEA's guidance. Although IAEA guidance does not include the plume dose (i.e., inhalation and external air submersion) for the Urgent Phase, separate analyses were run for the sake of completeness (one which did not and one which did include the plume dose) to determine the impact of including the plume dose. The total effective dose (TED) over each time phase was calculated by summing the dose from the individual dose pathways, as follows:

- Urgent Phase Total Dose time phase includes:
  - Committed effective dose (CED) from inhalation of the airborne plume,
  - Effective dose (ED) from external exposure (submersion) from the airborne plume,
  - CED from inhalation of resuspended material, and
  - ED from external exposure (groundshine) from the ground-deposited material.
- Urgent Phase Avoidable Dose and Early Phase time phases include:
  - CED from inhalation of resuspended material, and
  - ED from external exposure (groundshine) from the ground-deposited material.

The TED to an adult receptor was calculated assuming that the receptor remained outside 60% of the time and inside a building 40% of the time over the duration of the Urgent and Early Phases. A building protection factor of 2.5 was applied to reduce the calculated external dose while the receptor was inside the building. No respiratory protection factor was applied to modify the inhalation dose while the receptor was inside the building. The defaults inputs specified by [3] for other inputs (e.g., breathing rate, ground roughness factor, lung clearance type, resuspension, weathering) were also applied.

The dose from all progeny radionuclides in each decay chain was attributed to the parent radionuclide of each decay chain. For example, ^{140}La was released as a parent radionuclide and it is also produced by the transmutation of ^{140}Ba. The radiological dose from ^{140}La, as a parent radionuclide, was tracked separately from the radiological dose from ^{140}La formed by the transmutation of ^{140}Ba. The radiological dose attributed to the ^{140}Ba decay chain over each time phase included the dose from the ingrowth and transmutation of ^{140}La.

The dose from each radionuclide and their progeny in the eight fuel types, and over the three different time phases were ranked from highest to lowest to develop the dose rankings. Appendix A, Table A-1–Table A-8 summarize the dose rankings of the radionuclides that contribute more than 99% of the total dose from all radionuclides in the source terms from each fuel type. Each table ranks the radionuclides by the fraction of the total dose from all radionuclides that is contributed by each radionuclide and its progeny over the Urgent and Early Phases. The tables also give the cumulative dose to enable the radiological assessor to determine how many radionuclides must be included to achieve the desired percentage of total dose from all the radionuclides in the RTR source term.

Appendix B, Table B-1 gives the released activities of the top dose-producing radionuclides for each of the eight RTR fuel types. The radionuclide activities in Table B-1 have been adjusted by the release fractions specified in Table 2-2. The core inventory of each radionuclide at reactor shutdown can be calculated by dividing the radionuclide's activity in Table B-1 by the appropriate release fraction in Table 2-2. For example, the core inventory of ^{95}Zr in an RTR burning UZrH fuel is calculated by dividing 1.13+06 MBq (Table B-1) by the Zr release fraction of 0.001 (Table 2-2), which equals 1.13E+09 MBq. The core inventory activities at other times after shutdown can be estimated using standard decay and in-growth methods.

The top dose-producing radionuclides over the different time phases are reasonably consistent across the eight fuel types. Over the Urgent and Early Phases ^{140}Ba, ^{134}Cs, ^{137}Cs, ^{131}I, ^{133}I, ^{134}I, ^{135}I, ^{103}Ru, ^{131m}Te, and ^{132}Te tend to be the most significant dose-producing radionuclides. If the plume dose is included, approximately 20 more radionuclides need to be included in the dose assessment compared to when the plume dose is not included. This analysis shows that the radiological assessment of the RTR source term can be significantly simplified by focusing on the top dose-producing radionuclides.

This report explains how radiological assessors can use our results based on the tools available to them and the desired level of accuracy.

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
ARP	Automatic rapid processing
Bq	Becquerel
CED	Committed effective dose
Ci	Curie
DC	Dose coefficient
DCFPAK	Dose Coefficient File Package
ED	Effective dose
ERAD	Explosive release atmospheric dispersion
GBq	Gigabecquerel
IAEA	International Atomic Energy Agency
MBq	Megabecquerel
OILs	Operational interventional levels
PSD	Particle size distribution
ICRP	International Commission on Radiological Protection
LTSBO	Long-term station black out
NRC	Nuclear Regulatory Commission
ORIGEN	Oak Ridge isotope generation
ORNL	Oak Ridge National Laboratory
RTR	Research and test reactors
SOARCA	State-of-the-art reactor consequence analyses
SCALE	Standardized computer analyses for licensing evaluation
TED	Total effective dose
TISGTR	Thermally-induced steam generator tube rupture
TRIGA	Training, research, isotopes, general atomics
TRITON	Transport rigor implemented with time-dependent operation for neutronic depletion
Turbo FRMAC©	Turbo Federal Radiological Monitoring and Assessment Center; software based upon research performed by the Federal Radiological Monitoring and Assessment Center

1. INTRODUCTION

The radiological assessment of RTR source terms is very complex because of the large number of radionuclides. Many of these radionuclides contribute minimal dose and do not need to be included in the dispersal and dose assessment. This document describes the methodology that was used to determine the top dose-producing radionuclides to enable rapid and consistent radiological assessments.

The steps used to determine the top dose producing radionuclides include:

- The radionuclide inventory from different types of RTRs were identified:
  - The RTR fuel was broken down into eight categories of reactor fuel types.
  - The ORIGEN software was used to predict the radionuclide inventory in the reactor core after normal operations.
- The radionuclide inventory was assumed to be released and atmospherically dispersed in a sabotage scenario:
  - The explosive release atmospheric dispersion (ERAD) model was used to predict integrated air and ground concentrations at downwind locations.
  - From these results, deposition velocities were calculated as a function of particle size for use in subsequent dose assessment calculations.
- Source term doses were assessed:
  - The Turbo FRMAC© [4] health physics code was used to assess the dose from individual radionuclides and their decay products over the Urgent (0 – 7 day) and Early (0 – 365 day) time phases using the methods specified by IAEA [3].
  - The top dose-producing radionuclides were ranked to identify those that contribute more than 99% of the total dose, which defines manageable source terms for reactor dose assessments.

This page left blank

2. METHODS

2.1. ORIGEN Inventory Development

Generating the representative inventories was a two-step process. First, new cross-section libraries were created using TRITON, a depletion sequence in the SCALE software package [1]. Then, the cross-section libraries were used in ORIGEN-ARP depletion calculations to create the radionuclide inventories [1].

With more than 400 reactors in the IAEA research reactor database, it was not feasible to create unique inventories for each reactor. Analysts decided that the fuel neutronics likely would have the largest impact on depletion calculations (as opposed to other reactor characteristics) and so the reactors were grouped by fuel types. The fuel type groups and properties are shown in Table 2-1. The properties were derived from IAEA research reactor literature [5]. Enrichments were chosen based on the most common enrichment for each fuel type.

Table 2-1. Research Reactor Fuel Type Groups and Characteristics

Fuel Type	U Density in Fuel Meat (gU/cm^3)	Enrichment (%)	Assumptions
U_3O_8-Al	-	19.9	84.6% U3O8 by weight
UO_2-Al	4.5	19.9	-
$UZrH_x$	-	19.9	1.6 H to Zr ratio
U_3Si_x-Al	4.8	19.9	100% U3Si2-Al
UAl_x-Al	1.6	90	60:40 UAl3 to UAl4
U-metal	-	2	-
UO_2	-	19.9	-
UO_2-Mg	4.5	10	-

After grouping the fuel types, the following assumptions were made to simplify calculations:

- 50% burnup based on USNRC regulatory limits in NUREGG-1537,
- Aluminum cladding as it was the most common cladding type, and
- 1 kg uranium metal initial loading.

The unique fuel materials required new cross-section libraries to be generated using cell TRITON. The TRITON simulations used a fuel pin cell model based on training, research, isotopes, general atomics (TRIGA) reactor fuel pin dimensions provided by a TRIGA reactor operator. The nuclide compositions were calculated using the values and assumptions in Table 2-1. The cross-section libraries then were used with ORIGEN-ARP to generate the nuclide inventories.

Inventories were generated for each fuel type using ORIGEN-ARP. The depletion calculation for each fuel type ran continuously until 50% of the initial U-235 atoms fissioned. In general, research reactors operate for four hours each day with downtime at regular intervals. However, entering such a power history in ORIGEN would have been prohibitive. Because of this, the inventories are conservative as they contain short-lived nuclides that likely would have decayed during non-continuous operation.

2.2. Source Term Assumptions

The radionuclide source term includes the material release fractions and the PSDs. These will be used in the atmospheric dispersion analysis as well as in calculating the dose attributions.

2.2.1. Release Fractions

This study focuses on the explosive sabotage of RTRs. There are two likely outcomes from such an event:

- Scenario 1: A reactor core still contains water and 10% of the core is damaged; fission products from the molten core fraction are released into the pool water. In this case, very little of the material escapes from the water.
- Scenario 2: A reactor core no longer contains water and the release is from the molten fraction of the core. A conservative assumption regarding the radioactive release fractions from the molten core are broken into 4 bins:
    - Noble gases: 100%,
    - I, Te, Cs: 27%,
    - Ba, Sr, Ru: 3% and
    - Other fission products: 0.1 % [6] page 100.

Since there is minimal release in Scenario 1, the release fractions for Scenario 2 are used for this report. Using the Scenario 2 information and the chemical groups and associated member elements from Table 2.1 in [7], Table 2-2 was developed.

Table 2-2. Molten Core Release Fractions

Class Name	Representative	Release Fraction	Member Elements
Noble Gases	Xe	1	He, Ne, Ar, Kr, Xe, Rn, H, N
Halogens	I	0.27	F, Cl, Br, I, At
Chalcogens	Te	0.27	O, S, Se, Te, Po
Alkali Metals	Cs	0.27	Li, Na, K, Rb, Cs, Fr, Cu
Alkaline Earths	Ba	0.03	Be, Mg, Ca, Sr, Ba, Ra, Es, Fm
Platinoids	Ru	0.03	Ru, Rh, Pd, Re, Os, Ir, Pt, Au, Ni
Other Fission Products	-	0.001	Other elements not specified above

2.3. Particle Size Distributions

The mass median aerosol diameter can be broken into different bins [8] page 7-28. Each bin represents a uniform distribution associated with the aerodynamic diameter. This information is used to determine the fraction of the aerosols that belong to each size bin for each chemical class.

Table 2-3. Mass Median Aerosol Diameter Bins

Bin	Mass Median Aerosol Diameter (μm)	Mass Median Aerosol Diameter (μm) As Used for Analysis
1	0.15	0.0001 - 0.15
2	0.29	0.151 - 0.29
3	0.53	0.291 - 0.53
4	0.99	0.531 - 0.99
5	1.8	0.991 - 1.8
6	3.4	1.81 - 3.4
7	6.4	3.41 - 6.4
8	11.9	6.41 - 11.9
9	22.1	11.91 - 22.1
10	41.2	22.11 - 41.2

The proportion of activity for each radionuclide class that is assigned to each bin in Table 2-3 is based on previous research on PSDs for accident scenarios at United States commercial nuclear power boiling water (Peach Bottom) and pressurized water (Surry) reactors [8, 9]. The accident scenarios for both reactor types span multiple conditions including multiple types of station blackout and loss of coolant accidents. These were assumed to cover a sufficiently broad range of conditions to be representative of a plausible PSD for this analysis. Each scenario from these studies had a different PSD specified as in Table 2-4 (see Appendix C for all the scenario results).

The distribution used for this analysis was identified by choosing a single table from the set of tables used in the Surry and Peach Bottom research, Appendix C, that is most biased toward smaller particle sizes [8, 9]. The sum over the radionuclide classes within each bin was calculated for each scenario. This sum represents the total activity in each bin for each of the Peach Bottom and Surry accident scenarios. The sums are plotted together in Figure 2-1, which shows that the total activity is distributed differently over particle sizes depending on the accident scenario. The activity in the Surry unmitigated thermally-induced steam generator tube rupture (TISGTR) scenario is concentrated toward larger particle size bins (Bins 5 and 6), whereas the activity in the Peach Bottom long-term station black out (LTSBO) scenario is concentrated toward smaller particle size bins (Bin 2 and 4).

The PSD most biased toward smaller particle sizes is the distribution for the Peach Bottom unmitigated LTSBO scenario (green in Figure 2-1). This PSD, shown in Table 2-4, was used for this study.

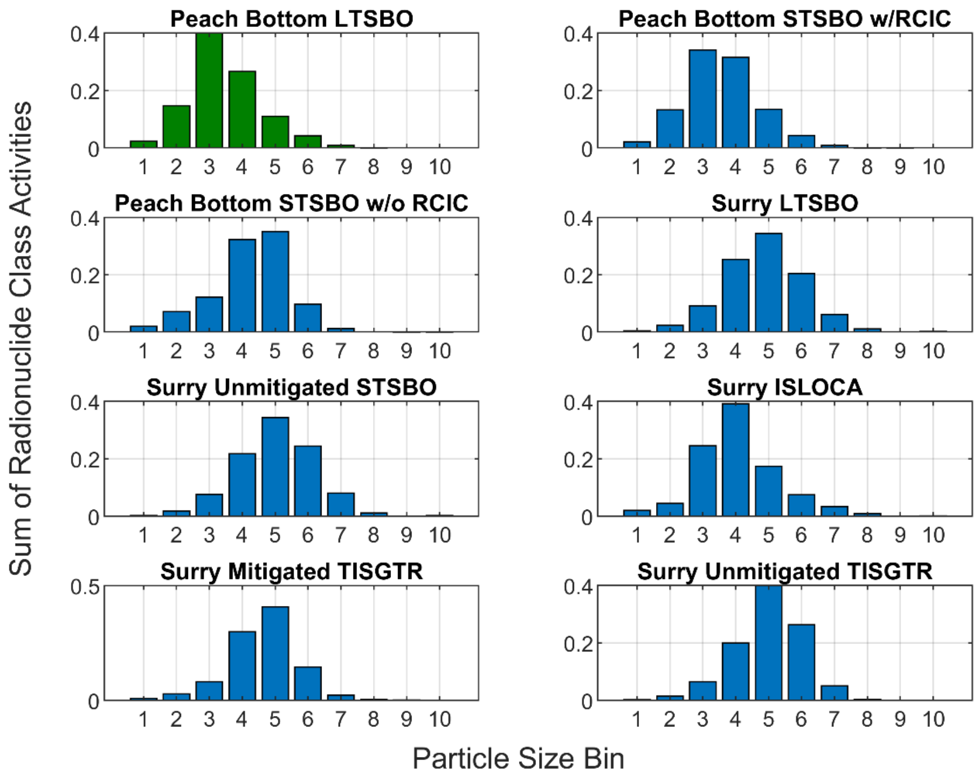

Figure 2-1. Total Activity Calculated Over Radionuclide Classes for Different Light Water Reactor Accident Scenarios

The radionuclide activities were partitioned into the 10 PSD bins based on the nine chemical classes shown in Table 2-4. Table 2-5 shows the element members of each chemical class.

Table 2-4. Fraction of Radionuclide Activities Assigned to PSD Bins by Chemical Class

Chemical Class	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6	Bin 7	Bin 8	Bin 9	Bin 10
Xe	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cs	1.17E-01	1.60E-01	3.30E-01	3.06E-01	5.75E-02	1.80E-02	7.10E-03	2.50E-03	9.00E-04	4.00E-04
Ba	4.12E-02	2.23E-01	4.45E-01	2.27E-01	4.86E-02	1.11E-02	3.00E-03	5.00E-04	1.00E-04	1.00E-04
I	2.31E-02	1.50E-01	5.22E-01	2.58E-01	3.33E-02	1.02E-02	2.70E-03	5.00E-04	1.00E-04	0.0
Te	2.86E-02	1.37E-01	4.60E-01	2.78E-01	6.43E-02	2.49E-02	5.90E-03	9.00E-04	2.00E-04	1.00E-04
Ru	3.93E-02	1.51E-01	3.60E-01	2.68E-01	1.21E-01	4.84E-02	1.04E-02	1.10E-03	2.00E-04	1.00E-04
Mo	1.55E-01	1.64E-01	2.56E-01	3.26E-01	6.49E-02	2.02E-02	8.70E-03	3.30E-03	1.20E-03	5.00E-04
Ce	3.06E-02	1.93E-01	4.36E-01	2.43E-01	7.08E-02	2.18E-02	4.70E-03	5.00E-04	1.00E-04	1.00E-04
La	2.35E-02	1.47E-01	3.99E-01	2.66E-01	1.11E-01	4.33E-02	8.90E-03	7.00E-04	0.0	0.0

Table 2-5. Elements by Chemical Class

Chemical Class	Elements
Xe	Ar, H, He, Kr, N, Ne, Rn, Xe,
Cs	Ag, Cs, Cu, Fr, K, Li, Na, Rb
Ba	Ba, Be, Ca, Es, Fm, Mg, Ra, Sr
I	As, At, Bi, Br, Cd, Cl, F, Hg, I, Pb, Sb, Tl, Zn
Te	O, Po, S, Se, Te
Ru	Au, Ir, Ni, Os, Pd, Pt, Re, Rh, Ru
Mo	Ag, Co, Fe, Ga, Ge, In, Mn, Mo, Nb, Sn, Tc, U
Ce	Ce, Pa, Pu, Np, Th, Zr
La	Am, Bk, Cf, Cm, Cr, Dy, Er, Eu, Gd, Ho, La, Lu, Nd, Pm, Pr, Sm, Tb, Tm, Y

2.4. Atmospheric Dispersion

The radionuclide inventory was assumed to be released and atmospherically dispersed in a sabotage scenario. The ERAD model was used to predict integrated air and ground concentrations at downwind locations. From these results, deposition velocities were calculated as a function of particle size and location for use in the dose assessment calculations described in Section 2.5.2.

Ten ERAD calculations were performed, one for each particle size bin listed in Table 2-3. A monodisperse PSD was assumed for each of the ten ERAD calculations, with the particle aerodynamic diameter set to the mass median aerosol diameter of the corresponding bin.

Each ERAD model calculation used the following settings and assumptions:

- The initial release was a non-buoyant, 1 meter radius sphere located one meter above ground level.
- Generic atmospheric conditions were assumed, corresponding to neutral to slightly-stable atmospheric stability classes. [10] The data corresponding to the atmospheric sounding used in these calculations is shown in Table 2-6.
- There was no precipitation at the time of the event.
- Each calculation was normalized to an arbitrary release activity (e.g., 1 Ci or 1 GBq) for a non-specific radionuclide. Results were scaled in subsequent dose calculations for specific radionuclide release amounts.
- Roughness length was set to 1.1 m, to correspond to a residential setting [11].

Table 2-6. Atmospheric Sounding Used in Atmospheric Dispersion Calculations

Pressure (Pa)	Height (m)	Temperature (K)	Dew Point (K)	Wind Direction (degrees)	Wind Speed (m/s)
101000	1	288	275	180	3.0
99000	125	287	271	185	4.0
97500	250	286	271	185	5.0

Pressure (Pa)	Height (m)	Temperature (K)	Dew Point (K)	Wind Direction (degrees)	Wind Speed (m/s)
96000	450	284	267	175	6.0
95500	500	283	270	190	8.0
89900	1000	282	269	170	10.0
84600	1500	278	266	185	11.0
79500	2000	275	263	190	10.0
74700	2500	272	260	160	10.0
70100	3000	269	257	225	13.0
65800	3500	265	252	228	13.5
61700	4000	262	249	231	14.5
57800	4500	259	246	234	16.0
54000	5000	256	243	237	18.0
50500	5500	252	239	240	20.5
47200	6000	249	236	243	23.5

2.5. Dose Analysis

The DCFPAK database explicitly ignores radionuclides known to have a short half-life. Since many of these radionuclides decay into other radionuclides, we tested whether any of these decayed radionuclides contributes a significant dose, which would warrant their inclusion in our final calculations.

2.5.1. Analysis of Dose from Short-Lived Radionuclides Not Included in the Radiological Database

The ORIGEN code was used to predict the fission product inventory at the end of a 100-day irradiation period for representative RTR fuels by uranium oxide (UO_2) reactor fuel. The ORIGEN-predicted core inventory included 1,154 radionuclides, including 620 radionuclides that are included in DCFPAK [2] (developed by ORNL to enable electronic access to the full set of ingestion, inhalation, and external exposure dose coefficients). The ORIGEN output also included 534 radionuclides that are not included in the DCFPAK database. A primary factor that determines whether a radionuclide is included in DCFAK is its half-life. Radionuclides with very short half-lives are not included in the database because they generally are considered to have little dosimetric consequence following releases into the environment.

A thorough analysis was performed to evaluate the dose from the radionuclides that are not included in the DCFFPAK database to determine if any of these radionuclides and their progeny produce significant dose in comparison to the radionuclides that are included in the database. The decay chains of the radionuclides not included in the database were tracked to identify what radioactive and/or stable decay products are formed by their transmutation so that the dose from these nuclides also could be evaluated. An instantaneous decay assumption then was applied to the radionuclides not included in DCFPAK to identify the first decay product that is radioactive and included in the database or is stable (not radioactive).

For example, ^{149}Ba (half-life = 0.34 s) is not included in DCFPAK. ^{149}Ba transforms to ^{149}La (half-life = 1.05 s) which also is not in DCFPAK. ^{149}La transforms to ^{149}Pa (half-life = 138 s) which also is not in DCFPAK, but it transforms to ^{149}Nd (half-life = 6,220 s) which is included in DCFPAK. Thus, all the ^{149}Ba atoms were assumed to transform instantly into ^{149}Nd atoms and the activity of ^{149}Nd was calculated using Equation 2-1.

$$Bq_{Nd149} = N_{Ba149} \times \lambda_{Nd149}$$ **Equation 2-1**

Where:

- Bq_{Nd149} = the radioactivity of ^{149}Nd formed by the transformation of all ^{149}Ba atoms (Bq), $d{*}s^{-1}$,
- N_{Ba149} = the number of atoms of ^{149}Ba predicted by the ORIGEN code and represents the number of ^{149}Nd atoms, and
- λ_{Nd149} = the ^{149}Nd decay constant, s^{-1}

This process was used to assign activities to the progeny of the radionuclides not included in the DCFPAK database and their activities then were added to the radionuclides included in DCFPAK to develop the complete fission source term inventory. The Turbo FRMAC© [4] software code was used to estimate the relative dose of the individual radionuclides and their decay products from the external (submersion in an airborne cloud, groundshine) and inhalation (airborne plume and resuspended material) exposure pathways. The radionuclides then were ranked by magnitude of the dose from all pathways to identify the top dose-producing radionuclides not explicitly included in the DCFPAK database. This analysis revealed that ^{146}Ce is the top dose-producing radionuclide not included in DCFPAK and its decay product (i.e., ^{146}Pr) is projected to produce approximately 0.01% of the total dose from all the fission radionuclides predicted by the ORIGEN code. Therefore, since none of the short-lived radionuclides excluded in DCFPAK nor their decay products contribute significant dose, these radionuclides were not included in the final dose analyses discussed below.

2.5.2. Analysis of Dose from Radionuclides Included in the Radiological Database

Analyses were performed to identify and rank the top dose-producing radionuclides to simplify the complex task of evaluating the RTR source terms. The ORIGEN runs described in Section 2.1 produced radionuclide source terms (i.e., radionuclide and activity) for eight different RTR fuel types. The dose to the adult from each radionuclide in the RTR fuel types was analyzed using the Turbo FRMAC© code and the methodology specified in [3]. The following modifications to IAEAs guidance were applied:

- Although the IAEA guidance utilizes the International Commission on Radiological Protection (ICRP) 26-based dosimetry models and dose coefficients (DCs) [12], the ICRP 60-based models and DCs [13] were used instead because the ICRP 60 DCFPAK database includes dose coefficients for more than 100 additional radionuclides not included in the ICRP 26 DCFPAK database. Using the ICRP 60 DCFPAK database enabled a much more complete dose analysis.

- Tables 10 and 12 of [3] recommend using the adult's CED and the infant's ED from external exposure. The mixing of age groups significantly increases the complexity of the dose calculation and was deemed unnecessary for this report's purpose of identifying the top dose-producing radionuclides. This is especially true since the ED to the adult and infant from a given radionuclide are essentially the same. Therefore, this analysis considered the adult's TED (CED plus ED).
- Tables 10 and 12 of [3] also recommend including the inadvertent ingestion rate of an infant in the TED analysis. The mixing of age groups combined with the high variability of inadvertent ingestion rates led the authors to decide this was unnecessary for identifying the top dose-producing radionuclides. Therefore, this analysis considered only the adult's TED (CED from inhalation plus ED).

The atmospheric dispersion modeling described in Section 2.3 was used to determine the relative integrated air ($Bq*s/m^3$) and ground (Bq/m^2) concentrations that a hypothetical member of the public was subjected to at a location 400 m downwind and in the center of the plume. The deposition velocity (m/s) was calculated for each PSD bin by dividing the ground concentration by the integrated air activity concentration. The deposition velocities in Table 2-7 were used to determine the relative air and ground concentrations for the PSD bins to support the dose calculations.

NOTE: Noble gases were assumed **not** to deposit on the ground and were assigned a deposition velocity of 0.0 m/s.

Table 2-7. Deposition Velocity by PSD Bin

Bin	Deposition Velocity m/s
1	0.020
2	0.020
3	0.020
4	0.020
5	0.020
6	0.020
7	0.020
8	0.020
9	0.060
10	0.200

The radionuclides activities predicted by the ORIGEN code for each fuel type were multiplied by the release fractions in Table 2-2 to estimate the source terms that were released to the environment from each fuel type. The activity of each radionuclide was partitioned into the PSDs using the assumptions in Table 2-3–Table 2-5. The deposition velocity assumptions in Table 2-7 were applied to determine the relative integrated air and ground concentrations of each radionuclide.

The Turbo FRMAC© code was used to assess the relative dose from each exposure pathway and from each radionuclide in the eight fuel types over the Urgent (0 – 7 d) and Early (0 – 365 d) phases specified by [3]. Although IAEA guidance does not include the plume dose (i.e., inhalation and external air submersion) for the Urgent Phase, separate analyses were run for the sake of completeness (one which did not and one which did include the plume dose) to determine the impact of including the plume dose. The TED over each time phase was calculated by summing the dose from the individual dose pathways, as follows:

- Urgent Phase Total Dose time phase includes:
  - CED from inhalation of the airborne plume,
  - ED from external exposure (submersion) from the airborne plume,
  - CED from inhalation of resuspended material, and
  - ED from external exposure (groundshine) from the ground-deposited material.
- Urgent Phase Avoidable Dose and Early Phase time phases include:
  - CED from inhalation of resuspended material, and
  - ED from external exposure (groundshine) from the ground-deposited material.

The TED to a hypothetical adult receptor located 400 m downwind was calculated assuming that the receptor remained outside 60% of the time and inside a building 40% of the time over the duration of the Urgent and Early Phases. A building protection factor of 2.5 was applied to reduce the calculated external dose while the receptor was inside the building. No respiratory protection factor was applied to modify the inhalation dose while the receptor was inside the building. The default inputs specified by [3] for other inputs (e.g., breathing rate, ground roughness factor, lung clearance type, resuspension, weathering) were also applied.

The dose from all progeny radionuclides in each decay chain was attributed to the parent radionuclide of each decay chain. For example, ^{140}La was released as a parent radionuclide and it is also produced by the transmutation of ^{140}Ba. The radiological dose from ^{140}La, as a parent radionuclide, was tracked separately from the radiological dose from ^{140}La formed by the transmutation of ^{140}Ba. The radiological dose attributed to the ^{140}Ba decay chain over each time phase included the dose from the ingrowth and transmutation of ^{140}La.

This page left blank

3. RESULTS

3.1. Determination of the Top Radiological Dose Producing Radionuclides

The doses from each radionuclide and their progeny in the eight fuel types, and over the different time phases were ranked from highest to lowest to develop the dose rankings. Appendix A, Table A-1–Table A-8 summarize the dose rankings of the radionuclides that contribute more than 99% of the total dose from all radionuclides in the source terms from each fuel type. Each table ranks the radionuclides by the fraction of the total dose from all radionuclides that is contributed by each individual radionuclide and its progeny over the Urgent and Early Phases. The tables also give the cumulative dose to enable the radiological assessor to determine how many radionuclides must be included to achieve the desired percentage of total dose from all the radionuclides in the RTR source term.

Appendix B, Table B-1 gives the released activities of the top dose-producing radionuclides for each of the eight RTR fuel types. The radionuclide activities in Table B-1 have been adjusted by the release fractions specified in Table 2-2. The core inventory of each radionuclide at reactor shutdown can be calculated by dividing the radionuclide's activity in Table B-1 by the appropriate release fraction in Table 2-2. For example, the core inventory of ^{95}Zr in an RTR burning UZrH fuel is calculated by dividing 1.13+06 MBq (Table B-1) by the Zr release fraction of 0.001 (Table 2-2), which equals 1.13E+09 MBq. The core inventory activities at other times after shutdown can be estimated using standard decay and in-growth methods.

The top dose-producing radionuclides over the different time phases are reasonably consistent across the eight fuel types. Over the Urgent and Early Phases ^{140}Ba, ^{134}Cs, ^{137}Cs, ^{131}I, ^{133}I, ^{134}I, ^{135}I, ^{103}Ru, ^{131m}Te, and ^{132}Te tend to be the most significant dose-producing radionuclides. If the plume dose is included, approximately 20 more radionuclides need to be included in the dose assessment compared to when the plume dose is not included. This analysis shows that the radiological assessment of the RTR source term can be significantly simplified by focusing on the top dose-producing radionuclides.

3.2. How to Use This Information

Radiological assessors can use the data in this report in two different ways:

- Ready access to ORIGEN or similar tools: Able to estimate the activities of the radionuclide inventory in the core of their RTR based on the usage history; see Section 3.2.1.
- No access to ORIGEN or similar tools: Cannot estimate the activities of the radionuclide inventory in the core of their RTR based on the usage history; see Section 3.2.2.

The radiological assessors should select the list of radionuclides to include in their assessment based on the appropriate RTR fuel type in Appendix A. The assessor also can decide what percentage of total dose is appropriate for their assessment. For example, if the RTR utilizes UO_2 fuel and the assessor wants to include more than 99% of the total dose from all radionuclides over the Urgent Phase, then they should include 48 radionuclides (Table A-1). However, if the assessor believes that including at least 90% of the total dose is suitable, then they should include 17 radionuclides in the assessment (Table A-1).

3.2.1. Using Data in this Report with RTR-Specific Core Inventory

The assessor should complete the following steps if they have access to software tools that predict the RTR's core radionuclide inventory based on the reactor's usage history.

1. Estimate the core inventories (activities) for each of the top dose-producing radionuclides for the RTR fuel type (see Appendix A) and RTR's burn-up history using the available software code.

NOTE: The data in Appendix A, Table A-1–Table A-8 can be used to select the required radionuclides to attain the desired percentage of total dose from all the radionuclides included in the RTR core inventory.

---

2. Estimate the activity of each radionuclide which may be released to the environment: Multiply the core inventory activity of the radionuclides from Step 1 by the release fractions from Table 2-2.
3. Assign particles size distributions to all particulate (non-noble gas) radionuclides based on available time and resources:
   a. If time and the necessary resources are available, the radionuclide activities from Step 2 should be partitioned into the appropriate PSD bins using the information in Table 2-3 and Table 2-4, or

   b. If adequate time and resources are not available, assign all particulate radionuclides a PSD recommended by the International Commission on Radiological Protection, ICRP 1994 [14].

      - 5 μm activity median aerodynamic diameter (AMAD),
      - Geometric standard deviation of 2.47,
      - Particle density of 3 g/cm^3, and
      - Particle shape factor of 1.5,
      - or,

   c. If Steps 3.a or 3.b cannot be executed, assign all particulate radionuclides a 1 μm (monodispersed) PSD.

NOTE: All noble gases should be entered as gases.

---

4. Use an atmospheric dispersion code to estimate the downwind integrated air and ground concentrations, to convert the radionuclides activities into projected doses (TED) over the time phase of interest, and to draw contours at the desired operational interventional levels (OILs) specified by [3] or local jurisdictions.

3.2.2. Using Data in this Report with the Core Inventory Provided in this Report

The assessor should complete the following steps if they DO NOT have access to software tools that predict the RTR's core radionuclide inventory based on the reactor's usage history.

1. Use the core inventory data in Appendix B, Table B-1 for the appropriate RTR reactor fuel to estimate the core inventory of the top dose-producing radionuclides.

NOTE: See the NOTE in Section 3.2.1, Step 1 for guidance on selecting the appropriate radionuclides.

2. Follow Section 3.2.1, Steps 3 and 4.

4. CONCLUSIONS

The data in this report shows that the radiological assessment of the RTR core inventory can be significantly simplified and accelerated by focusing on only those radionuclides that contribute significant dose following their release to the environment. There is no need to assess the entire radionuclide inventory because most of the radionuclides produce insignificant dose. For example, out of the 1,154 radionuclides the ORIGEN code predicts would be present in the UO_2-fueled RTR core inventory at the time of shutdown, 48 radionuclides and their progeny would contribute more than 99% of the total dose.

This page left blank

5. REFERENCES

[1] W. A. Wieselquist, "SCALE | ORNL," Oak Ridge National Laboratory, [Online]. Available: https://www.ornl.gov/scale. [Accessed 16 July 2019].

[2] K. Eckerman, R. Leggett and et al., "Dose Coefficient Factor Package," Oak Ridge National Laboratory, Oak Ridge, TN., 2015.

[3] IAEA, "Operational Intervention Levels for Reactor Emergencies, and Methodology for their Derivation," EPR_NPP_OILs, Vienna: International Atomic Energy Agency (IAEA), Vienna, March 2017.

[4] J. Fulton and et al., "Turbo FRMAC© Assessment Software Package," Sandia National Laboratories, Albuquerque, NM., 2019.

[5] IAEA, Research Reactor Core Conversion Guidebook Volume 4: Fuels (Appendicies I-K), Vienna, 1992.

[6] IAEA, "Safety Reports Series No. 53 Derivation of the Source Term and Analysis of the Radiological Consequences of Research Reactor Accidents. Vienna: International Atomic Energy Agency (IAEA)," International Atomic Energy Agency, Vienna, 2008.

[7] L. L. Humphries, B. A. Beeny, C. Faucett, F. Gelbard, T. Haskin, D. L. Louie and J. Phillips, "MELCOR Computer Code Manuals Vol.2: Reference Manual Version 2.2.11932," Sandia National Laboratories, Albuquerque, November 2018.

[8] N. Bixler, R. Gauntt, J. Jones and M. Leonard, "State-of-the-Art Reactor Consequence Analyses Project Volume 1: Peach Bottom Integrated Analysis," Office of Nuclear Regulatory Research, May 2013.

[9] Sandia National Laboratories, "State-of-the-Art Reactor Consequence Analysis Project Volum 2: Surry Integrated Analysis," 2013.

[10] J. E. Till and H. R. Meyer, "Radiological Assessment: A Textbook on Environmental Dose Analysis," U.S. Nuclear Regulatory Commission, NUREG/CR-3322.

[11] F. V. Hansen, "Surface Roughness Lengths," Army Research Laboratory, Adelphi, MD, August 1993.

[12] International Commission on Radiological Protection, "Recommendations of the International Commission on Radiological Protection, ICRP Publication 26," ICRP, Ottawa, Ontario, Canada, 1977.

[13] International Commission on Radiological Protection, "Recommendations of the International Commission on Radiological Protection, ICRP Publication 60," ICRP, Ottawa, Ontario, Canada, 1990.

[14] International Commission on Radiological Protection, "Human Respiratory Tract Model for Radiological Protection," ICRP Publication 66, Ottawa, Ontario, Canada, 1994.

This page left blank

APPENDIX A. TOP DOSE-PRODUCING RADIONUCLIDES BY FUEL TYPE AND TIME PHASE

Table A-1–Table A-8 rank the top dose-producing radionuclides from the eight RTR fuel types that produce more than 99% of the TED from all radionuclides in the RTR core. The dose rankings are given for the Urgent (0 – 7 d) and Early (0 – 365 d) time phases. The TED over each phase was calculated by summing the dose from the individual dose pathways, as follows:

- Urgent Phase Total Dose time phase includes:
    - CED from inhalation of the airborne plume,
    - ED from external exposure (submersion) from the airborne plume,
    - CED from inhalation of resuspended material, and
    - ED from external exposure (groundshine) from the ground-deposited material.
- Urgent Phase Avoidable Dose and Early Phase time phases includes:
    - CED from inhalation of resuspended material, and
    - ED from external exposure (groundshine) from the ground-deposited material.

Table A-1. UO_2 Fuel Top Dose Producing Radionuclide Summary

Dose Rank	Urgent Phase-Total Dose			Urgent Phase-Avoidable Dose			Early Phase		
	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose
1	te-132	3.69E-01	36.88%	te-132	5.31E-01	53.13%	te-132	2.97E-01	29.66%
2	i-131	1.36E-01	50.53%	ba-140	9.78E-02	62.92%	cs-134	1.99E-01	49.58%
3	i-133	8.50E-02	59.03%	i-131	8.37E-02	71.29%	ba-140	1.78E-01	67.40%
4	ba-140	8.13E-02	67.16%	i-133	7.45E-02	78.74%	i-131	7.69E-02	75.09%
5	i-135	5.11E-02	72.28%	i-135	6.18E-02	84.92%	ru-103	5.40E-02	80.50%
6	i-134	2.01E-02	74.28%	te-131m	1.93E-02	86.84%	cs-137	3.75E-02	84.25%
7	cs-134	2.00E-02	76.28%	i-132	1.91E-02	88.76%	i-133	3.34E-02	87.59%
8	i-132	1.88E-02	78.16%	ru-103	1.61E-02	90.37%	i-135	2.68E-02	90.27%
9	sr-89	1.84E-02	79.99%	cs-134	1.40E-02	91.76%	cs-136	1.39E-02	91.66%
10	ru-103	1.59E-02	81.58%	i-134	1.39E-02	93.15%	sr-89	1.08E-02	92.74%
11	kr-89	1.45E-02	83.04%	te-134	1.25E-02	94.40%	zr-95	1.06E-02	93.79%
12	te-131m	1.43E-02	84.47%	cs-136	1.02E-02	95.42%	te-131m	9.74E-03	94.77%
13	xe-138	1.34E-02	85.81%	te-133m	7.10E-03	96.13%	i-132	8.30E-03	95.60%
14	cs-138	1.33E-02	87.14%	cs-138	6.78E-03	96.81%	ru-106	8.28E-03	96.43%
15	te-134	1.20E-02	88.34%	sr-91	4.59E-03	97.27%	i-134	6.02E-03	97.03%
16	kr-88	1.17E-02	89.51%	sr-89	3.15E-03	97.58%	te-134	5.44E-03	97.57%
17	cs-137	1.13E-02	90.64%	cs-137	2.59E-03	97.84%	te-133m	3.11E-03	97.88%
18	te-133m	8.87E-03	91.52%	sr-92	2.03E-03	98.05%	cs-138	2.94E-03	98.18%
19	ru-106	7.61E-03	92.28%	rb-89	1.76E-03	98.22%	te-129m	2.45E-03	98.42%
20	cs-136	7.25E-03	93.01%	la-140	1.65E-03	98.39%	sr-91	2.11E-03	98.63%
21	rb-89	6.10E-03	93.62%	br-82	1.27E-03	98.51%	nb-95	2.07E-03	98.84%
22	cs-140	5.38E-03	94.16%	zr-95	1.16E-03	98.63%	ce-144	9.62E-04	98.94%
23	rb-90	4.91E-03	94.65%	te-133	1.07E-03	98.74%	sr-90	8.84E-04	99.02%
24	sr-90	4.02E-03	95.05%	ru-106	9.14E-04	98.83%			
25	sr-91	3.87E-03	95.44%	te-129m	9.12E-04	98.92%			
26	kr-87	3.49E-03	95.79%	i-130	7.68E-04	99.00%			
27	te-129m	3.22E-03	96.11%	np-239	7.18E-04	99.07%			
28	te-133	3.03E-03	96.41%						
29	pu-238	2.81E-03	96.69%						
30	xe-137	2.57E-03	96.95%						
31	sr-92	2.11E-03	97.16%						
32	rb-88	1.73E-03	97.33%						
33	ce-144	1.46E-03	97.48%						
34	rb-90m	1.45E-03	97.62%						
35	cs-139	1.39E-03	97.76%						

Table A-1. UO_2 Fuel Top Dose Producing Radionuclide Summary

Dose Rank	Urgent Phase-Total Dose			Urgent Phase-Avoidable Dose			Early Phase		
	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose
36	br-84	1.33E-03	97.90%						
37	pu-241	1.30E-03	98.03%						
38	zr-95	1.23E-03	98.15%						
39	te-131	1.20E-03	98.27%						
40	la-140	1.15E-03	98.38%						
41	xe-135m	9.82E-04	98.48%						
42	np-239	9.56E-04	98.58%						
43	br-82	8.50E-04	98.66%						
44	sr-93	8.19E-04	98.74%						
45	se-83	7.96E-04	98.82%						
46	y-91	7.68E-04	98.90%						
47	ru-105	6.94E-04	98.97%						
48	i-130	6.05E-04	99.03%						

Table A-2. U Fuel Top Dose Producing Radionuclide Summary

Dose Rank	Urgent Phase-Total Dose			Urgent Phase-Avoidable Dose			Early Phase		
	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose
1	te-132	4.40E-01	43.99%	te-132	5.95E-01	59.50%	te-132	5.15E-01	51.48%
2	i-133	1.09E-01	54.91%	i-133	8.98E-02	68.48%	ba-140	1.45E-01	65.97%
3	i-131	1.09E-01	65.84%	i-135	7.56E-02	76.05%	i-131	8.96E-02	74.92%
4	i-135	6.66E-02	72.50%	i-131	6.29E-02	82.34%	i-133	6.24E-02	81.17%
5	ba-140	4.54E-02	77.04%	ba-140	5.13E-02	87.47%	i-135	5.09E-02	86.26%
6	i-134	2.54E-02	79.57%	te-131m	2.61E-02	90.08%	ru-103	2.46E-02	88.72%
7	i-132	2.34E-02	81.91%	i-132	2.23E-02	92.31%	te-131m	2.05E-02	90.76%
8	te-131m	2.07E-02	83.98%	i-134	1.65E-02	93.96%	i-132	1.50E-02	92.26%
9	cs-138	1.64E-02	85.61%	te-134	1.41E-02	95.36%	i-134	1.11E-02	93.37%
10	xe-138	1.64E-02	87.25%	te-133m	8.10E-03	96.17%	te-134	9.46E-03	94.32%
11	kr-89	1.46E-02	88.71%	cs-138	7.86E-03	96.96%	cs-137	7.90E-03	95.11%
12	te-134	1.44E-02	90.15%	ru-103	4.73E-03	97.43%	cs-134	7.34E-03	95.84%
13	kr-88	1.18E-02	91.33%	sr-91	4.52E-03	97.88%	te-133m	5.50E-03	96.39%
14	te-133m	1.08E-02	92.41%	sr-92	2.06E-03	98.09%	cs-138	5.29E-03	96.92%
15	cs-140	6.42E-03	93.05%	np-239	2.03E-03	98.29%	cs-136	3.61E-03	97.28%
16	rb-89	6.18E-03	93.67%	cs-136	1.71E-03	98.46%	sr-89	3.30E-03	97.61%
17	ru-103	4.97E-03	94.17%	rb-89	1.68E-03	98.63%	sr-91	3.22E-03	97.93%
18	rb-90	4.88E-03	94.66%	ru-105	1.35E-03	98.77%	zr-95	3.15E-03	98.25%
19	sr-91	4.06E-03	95.06%	te-133	1.30E-03	98.90%	ru-106	3.13E-03	98.56%
20	te-133	3.92E-03	95.45%	te-131	7.55E-04	98.97%	np-239	1.56E-03	98.72%
21	sr-89	3.86E-03	95.84%	la-140	7.34E-04	99.05%	sr-92	1.39E-03	98.86%
22	kr-87	3.59E-03	96.20%				rb-89	1.16E-03	98.97%
23	xe-137	3.27E-03	96.53%				te-129m	1.02E-03	99.08%
24	np-239	2.88E-03	96.81%						
25	sr-92	2.28E-03	97.04%						
26	ru-106	1.98E-03	97.24%						
27	rb-88	1.75E-03	97.42%						
28	cs-139	1.71E-03	97.59%						
29	cs-137	1.63E-03	97.75%						
30	te-131	1.61E-03	97.91%						
31	rb-90m	1.57E-03	98.07%						
32	br-84	1.42E-03	98.21%						
33	ru-105	1.40E-03	98.35%						
34	xe-135m	1.37E-03	98.49%						
35	cs-136	1.29E-03	98.62%						

Table A-2. U Fuel Top Dose Producing Radionuclide Summary

Dose Rank	Urgent Phase-Total Dose			Urgent Phase-Avoidable Dose			Early Phase		
	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose
36	te-129m	9.24E-04	98.71%						
37	sr-93	9.14E-04	98.80%						
38	se-83	8.80E-04	98.89%						
39	ba-142	6.37E-04	98.95%						
40	ba-141	5.83E-04	99.01%						

Table A-3. U_3O_8_Al Fuel Top Dose Producing Radionuclide Summary

	Urgent Phase-Total Dose			Urgent Phase-Avoidable Dose			Early Phase		
Dose Rank	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose
1	te-132	3.69E-01	36.89%	te-132	5.317E-01	53.17%	te-132	3.01E-01	30.07%
2	i-131	1.36E-01	50.54%	ba-140	9.916E-02	63.09%	cs-134	1.88E-01	48.83%
3	i-133	8.54E-02	59.08%	i-131	8.375E-02	71.47%	ba-140	1.83E-01	67.14%
4	ba-140	8.24E-02	67.32%	i-133	7.480E-02	78.95%	i-131	7.79E-02	74.93%
5	i-135	5.13E-02	72.45%	i-135	6.200E-02	85.15%	ru-103	5.45E-02	80.39%
6	i-134	2.02E-02	74.46%	te-131m	1.943E-02	87.09%	cs-137	3.84E-02	84.22%
7	i-132	1.88E-02	76.34%	i-132	1.912E-02	89.00%	i-133	3.40E-02	87.62%
8	sr-89	1.87E-02	78.21%	ru-103	1.604E-02	90.61%	i-135	2.73E-02	90.35%
9	cs-134	1.86E-02	80.07%	i-134	1.395E-02	92.00%	cs-136	1.18E-02	91.53%
10	ru-103	1.58E-02	81.66%	cs-134	1.297E-02	93.30%	sr-89	1.12E-02	92.65%
11	kr-89	1.48E-02	83.13%	te-134	1.263E-02	94.56%	zr-95	1.09E-02	93.74%
12	te-131m	1.44E-02	84.58%	cs-136	8.558E-03	95.42%	te-131m	9.95E-03	94.73%
13	xe-138	1.35E-02	85.92%	te-133m	7.178E-03	96.13%	i-132	8.41E-03	95.57%
14	cs-138	1.34E-02	87.26%	cs-138	6.836E-03	96.82%	ru-106	8.08E-03	96.38%
15	te-134	1.21E-02	88.47%	sr-91	4.654E-03	97.28%	i-134	6.13E-03	96.99%
16	kr-88	1.19E-02	89.66%	sr-89	3.218E-03	97.60%	te-134	5.55E-03	97.55%
17	cs-137	1.14E-02	90.80%	cs-137	2.613E-03	97.87%	te-133m	3.18E-03	97.87%
18	te-133m	8.97E-03	91.70%	sr-92	2.060E-03	98.07%	cs-138	3.01E-03	98.17%
19	ru-106	7.33E-03	92.43%	rb-89	1.793E-03	98.25%	te-129m	2.41E-03	98.41%
20	rb-89	6.20E-03	93.05%	la-140	1.667E-03	98.42%	sr-91	2.16E-03	98.62%
21	cs-136	6.08E-03	93.66%	zr-95	1.184E-03	98.54%	nb-95	2.14E-03	98.84%
22	cs-140	5.40E-03	94.20%	br-82	1.145E-03	98.65%	ce-144	9.89E-04	98.94%
23	rb-90	4.99E-03	94.70%	te-133	1.074E-03	98.76%	sr-90	9.13E-04	99.03%
24	sr-90	4.10E-03	95.11%	te-129m	8.840E-04	98.85%			
25	sr-91	3.92E-03	95.50%	ru-106	8.804E-04	98.93%			
26	kr-87	3.54E-03	95.85%	i-130	7.172E-04	99.01%			
27	te-129m	3.13E-03	96.17%						
28	te-133	3.03E-03	96.47%						
29	xe-137	2.58E-03	96.73%						
30	pu-238	2.46E-03	96.97%						
31	sr-92	2.13E-03	97.19%						
32	rb-88	1.75E-03	97.36%						
33	rb-90m	1.48E-03	97.51%						
34	ce-144	1.48E-03	97.66%						
35	cs-139	1.40E-03	97.80%						

Table A-3. U_3O_8_Al Fuel Top Dose Producing Radionuclide Summary

Dose Rank	Urgent Phase-Total Dose			Urgent Phase-Avoidable Dose			Early Phase		
	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose
36	br-84	1.34E-03	97.93%						
37	pu-241	1.26E-03	98.06%						
38	zr-95	1.25E-03	98.18%						
39	te-131	1.20E-03	98.30%						
40	la-140	1.16E-03	98.42%						
41	xe-135m	9.85E-04	98.52%						
42	np-239	9.39E-04	98.61%						
43	sr-93	8.27E-04	98.70%						
44	se-83	8.01E-04	98.78%						
45	y-91	7.83E-04	98.85%						
46	br-82	7.66E-04	98.93%						
47	ru-105	6.71E-04	99.00%						
48	i-130	5.65E-04	99.05%						

Table A-4. U_3Six_Al Fuel Top Dose Producing Radionuclide Summary

Dose Rank	Urgent Phase-Total Dose			Urgent Phase-Avoidable Dose			Early Phase		
	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose
1	te-132	3.69E-01	36.90%	te-132	5.321E-01	53.21%	te-132	3.04E-01	30.43%
2	i-131	1.36E-01	50.54%	ba-140	1.005E-01	63.25%	ba-140	1.88E-01	49.20%
3	i-133	8.57E-02	59.11%	i-131	8.371E-02	71.63%	cs-134	1.77E-01	66.94%
4	ba-140	8.35E-02	67.46%	i-133	7.512E-02	79.14%	i-131	7.88E-02	74.82%
5	i-135	5.14E-02	72.60%	i-135	6.218E-02	85.36%	ru-103	5.48E-02	80.30%
6	i-134	2.03E-02	74.62%	te-131m	1.939E-02	87.30%	cs-137	3.91E-02	84.21%
7	sr-89	1.91E-02	76.53%	i-132	1.912E-02	89.21%	i-133	3.45E-02	87.66%
8	i-132	1.88E-02	78.41%	ru-103	1.594E-02	90.80%	i-135	2.77E-02	90.43%
9	cs-134	1.74E-02	80.15%	i-134	1.402E-02	92.20%	sr-89	1.15E-02	91.58%
10	ru-103	1.57E-02	81.72%	te-134	1.273E-02	93.48%	zr-95	1.12E-02	92.70%
11	kr-89	1.51E-02	83.23%	cs-134	1.213E-02	94.69%	cs-136	1.01E-02	93.71%
12	te-131m	1.44E-02	84.67%	te-133m	7.254E-03	95.42%	te-131m	1.00E-02	94.71%
13	xe-138	1.36E-02	86.03%	cs-136	7.228E-03	96.14%	i-132	8.51E-03	95.56%
14	cs-138	1.35E-02	87.37%	cs-138	6.888E-03	96.83%	ru-106	7.76E-03	96.34%
15	te-134	1.22E-02	88.60%	sr-91	4.733E-03	97.30%	i-134	6.24E-03	96.96%
16	kr-88	1.21E-02	89.81%	sr-89	3.285E-03	97.63%	te-134	5.66E-03	97.53%
17	cs-137	1.15E-02	90.95%	cs-137	2.629E-03	97.89%	te-133m	3.25E-03	97.85%
18	te-133m	9.07E-03	91.86%	sr-92	2.092E-03	98.10%	cs-138	3.06E-03	98.16%
19	ru-106	6.96E-03	92.56%	rb-89	1.829E-03	98.28%	te-129m	2.37E-03	98.40%
20	rb-89	6.32E-03	93.19%	la-140	1.688E-03	98.45%	sr-91	2.23E-03	98.62%
21	cs-140	5.44E-03	93.73%	zr-95	1.201E-03	98.57%	nb-95	2.19E-03	98.84%
22	cs-136	5.13E-03	94.25%	te-133	1.075E-03	98.68%	ce-144	1.01E-03	98.94%
23	rb-90	5.09E-03	94.75%	br-82	1.019E-03	98.78%	sr-90	9.39E-04	99.03%
24	sr-90	4.16E-03	95.17%	te-129m	8.600E-04	98.87%			
25	sr-91	3.99E-03	95.57%	ru-106	8.364E-04	98.95%			
26	kr-87	3.60E-03	95.93%	nb-95	6.958E-04	99.02%			
27	te-129m	3.04E-03	96.23%						
28	te-133	3.03E-03	96.54%						
29	xe-137	2.59E-03	96.80%						
30	sr-92	2.16E-03	97.01%						
31	pu-238	2.16E-03	97.23%						
32	rb-88	1.79E-03	97.41%						
33	rb-90m	1.51E-03	97.56%						
34	ce-144	1.50E-03	97.71%						
35	cs-139	1.41E-03	97.85%						

Table A-4. U_3Six_Al Fuel Top Dose Producing Radionuclide Summary

Dose Rank	Urgent Phase-Total Dose			Urgent Phase-Avoidable Dose			Early Phase		
	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose
36	br-84	1.35E-03	97.99%						
37	zr-95	1.27E-03	98.11%						
38	te-131	1.20E-03	98.23%						
39	la-140	1.18E-03	98.35%						
40	pu-241	1.15E-03	98.46%						
41	xe-135m	9.85E-04	98.56%						
42	np-239	8.83E-04	98.65%						
43	sr-93	8.38E-04	98.74%						
44	se-83	8.10E-04	98.82%						
45	y-91	7.97E-04	98.90%						
46	br-82	6.82E-04	98.96%						
47	ru-105	6.41E-04	99.03%						

Table A-5. UAlx_Al Fuel Top Dose Producing Radionuclide Summary

	Urgent Phase-Total Dose			Urgent Phase-Avoidable Dose			Early Phase		
Dose Rank	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose
1	te-132	2.92E-01	29.24%	te-132	4.657E-01	46.57%	cs-134	5.39E-01	53.92%
2	i-131	1.08E-01	40.08%	ba-140	8.516E-02	55.08%	te-132	1.32E-01	67.12%
3	cs-134	9.64E-02	49.72%	cs-134	7.438E-02	62.52%	ba-140	7.88E-02	75.00%
4	i-133	7.00E-02	56.72%	i-131	7.351E-02	69.87%	cs-137	7.57E-02	82.58%
5	ba-140	6.40E-02	63.13%	i-133	6.778E-02	76.65%	i-131	3.43E-02	86.00%
6	i-135	4.17E-02	67.30%	i-135	5.573E-02	82.22%	cs-136	3.28E-02	89.29%
7	cs-137	4.05E-02	71.35%	cs-136	4.742E-02	86.96%	ru-103	2.66E-02	91.94%
8	cs-136	3.05E-02	74.40%	i-132	1.651E-02	88.62%	i-133	1.54E-02	93.49%
9	pu-238	2.30E-02	76.70%	ru-103	1.559E-02	90.17%	i-135	1.23E-02	94.72%
10	sr-89	2.27E-02	78.97%	te-131m	1.523E-02	91.70%	zr-95	8.05E-03	95.52%
11	i-134	1.67E-02	80.65%	i-134	1.280E-02	92.98%	sr-89	7.50E-03	96.27%
12	sr-90	1.57E-02	82.22%	te-134	1.200E-02	94.18%	ru-106	6.76E-03	96.95%
13	i-132	1.47E-02	83.69%	cs-137	1.028E-02	95.21%	te-131m	3.91E-03	97.34%
14	kr-89	1.40E-02	85.09%	te-133m	6.744E-03	95.88%	i-132	3.64E-03	97.70%
15	ru-103	1.39E-02	86.48%	cs-138	6.374E-03	96.52%	i-134	2.82E-03	97.98%
16	xe-138	1.14E-02	87.62%	sr-91	4.769E-03	97.00%	nb-95	2.65E-03	98.25%
17	cs-138	1.13E-02	88.75%	sr-89	4.311E-03	97.43%	te-134	2.65E-03	98.51%
18	kr-88	1.12E-02	89.87%	sr-92	2.079E-03	97.63%	sr-90	1.94E-03	98.71%
19	ru-106	1.11E-02	90.98%	rb-89	1.866E-03	97.82%	te-133m	1.50E-03	98.86%
20	te-134	1.04E-02	92.02%	zr-95	1.744E-03	98.00%	ce-144	1.48E-03	99.00%
21	te-131m	1.02E-02	93.04%	br-82	1.710E-03	98.17%	cs-138	1.41E-03	99.15%
22	te-133m	7.63E-03	93.81%	nb-95	1.701E-03	98.34%			
23	rb-89	5.84E-03	94.39%	ru-106	1.469E-03	98.48%			
24	rb-90	4.74E-03	94.87%	la-140	1.442E-03	98.63%			
25	cs-140	4.65E-03	95.33%	pu-238	1.265E-03	98.75%			
26	ce-144	4.02E-03	95.73%	te-129m	1.003E-03	98.85%			
27	sr-91	3.64E-03	96.10%	te-133	9.717E-04	98.95%			
28	kr-87	3.31E-03	96.43%	i-130	8.959E-04	99.04%			
29	te-129m	3.21E-03	96.75%						
30	te-133	2.48E-03	97.00%						
31	xe-137	2.13E-03	97.21%						
32	sr-92	1.95E-03	97.40%						
33	zr-95	1.67E-03	97.57%						
34	rb-88	1.66E-03	97.74%						
35	rb-90m	1.35E-03	97.87%						

Table A-5. UAlx_Al Fuel Top Dose Producing Radionuclide Summary

Dose Rank	Urgent Phase-Total Dose			Urgent Phase-Avoidable Dose			Early Phase		
	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose
36	br-84	1.23E-03	97.99%						
37	nb-95	1.19E-03	98.11%						
38	cs-139	1.18E-03	98.23%						
39	br-82	1.04E-03	98.34%						
40	y-91	1.03E-03	98.44%						
41	xe-135	1.02E-03	98.54%						
42	rb-86	9.94E-04	98.64%						
43	te-131	9.57E-04	98.73%						
44	la-140	9.11E-04	98.83%						
45	xe-135m	7.60E-04	98.90%						
46	sr-93	7.42E-04	98.98%						
47	se-83	7.24E-04	99.05%						

Table A-6. UO_2_Al Fuel Top Dose Producing Radionuclide Summary

Dose Rank	Urgent Phase-Total Dose			Urgent Phase-Avoidable Dose			Early Phase		
	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose
1	te-132	3.69E-01	36.89%	te-132	5.317E-01	53.17%	te-132	3.01E-01	30.07%
2	i-131	1.36E-01	50.54%	ba-140	9.916E-02	63.09%	cs-134	1.88E-01	48.83%
3	i-133	8.54E-02	59.08%	i-131	8.375E-02	71.47%	ba-140	1.83E-01	67.14%
4	ba-140	8.24E-02	67.32%	i-133	7.480E-02	78.95%	i-131	7.79E-02	74.93%
5	i-135	5.13E-02	72.45%	i-135	6.200E-02	85.15%	ru-103	5.45E-02	80.39%
6	i-134	2.02E-02	74.46%	te-131m	1.943E-02	87.09%	cs-137	3.84E-02	84.22%
7	i-132	1.88E-02	76.34%	i-132	1.912E-02	89.00%	i-133	3.40E-02	87.62%
8	sr-89	1.87E-02	78.21%	ru-103	1.604E-02	90.61%	i-135	2.73E-02	90.35%
9	cs-134	1.86E-02	80.07%	i-134	1.395E-02	92.00%	cs-136	1.18E-02	91.53%
10	ru-103	1.58E-02	81.66%	cs-134	1.297E-02	93.30%	sr-89	1.12E-02	92.65%
11	kr-89	1.48E-02	83.13%	te-134	1.263E-02	94.56%	zr-95	1.09E-02	93.74%
12	te-131m	1.44E-02	84.58%	cs-136	8.558E-03	95.42%	te-131m	9.95E-03	94.73%
13	xe-138	1.35E-02	85.92%	te-133m	7.178E-03	96.13%	i-132	8.41E-03	95.57%
14	cs-138	1.34E-02	87.26%	cs-138	6.836E-03	96.82%	ru-106	8.08E-03	96.38%
15	te-134	1.21E-02	88.47%	sr-91	4.654E-03	97.28%	i-134	6.13E-03	96.99%
16	kr-88	1.19E-02	89.66%	sr-89	3.218E-03	97.60%	te-134	5.55E-03	97.55%
17	cs-137	1.14E-02	90.80%	cs-137	2.613E-03	97.87%	te-133m	3.18E-03	97.87%
18	te-133m	8.97E-03	91.70%	sr-92	2.060E-03	98.07%	cs-138	3.01E-03	98.17%
19	ru-106	7.33E-03	92.43%	rb-89	1.793E-03	98.25%	te-129m	2.41E-03	98.41%
20	rb-89	6.20E-03	93.05%	la-140	1.667E-03	98.42%	sr-91	2.16E-03	98.62%
21	cs-136	6.08E-03	93.66%	zr-95	1.184E-03	98.54%	nb-95	2.14E-03	98.84%
22	cs-140	5.40E-03	94.20%	br-82	1.145E-03	98.65%	ce-144	9.89E-04	98.94%
23	rb-90	4.99E-03	94.70%	te-133	1.074E-03	98.76%	sr-90	9.13E-04	99.03%
24	sr-90	4.10E-03	95.11%	te-129m	8.840E-04	98.85%			
25	sr-91	3.92E-03	95.50%	ru-106	8.804E-04	98.93%			
26	kr-87	3.54E-03	95.85%	i-130	7.172E-04	99.01%			
27	te-129m	3.13E-03	96.17%						
28	te-133	3.03E-03	96.47%						
29	xe-137	2.58E-03	96.73%						
30	pu-238	2.46E-03	96.97%						
31	sr-92	2.13E-03	97.19%						
32	rb-88	1.75E-03	97.36%						
33	rb-90m	1.48E-03	97.51%						
34	ce-144	1.48E-03	97.66%						
35	cs-139	1.40E-03	97.80%						

Table A-6. UO_2_Al Fuel Top Dose Producing Radionuclide Summary

Dose Rank	Urgent Phase-Total Dose			Urgent Phase-Avoidable Dose			Early Phase		
	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose
36	br-84	1.34E-03	97.93%						
37	pu-241	1.26E-03	98.06%						
38	zr-95	1.25E-03	98.18%						
39	te-131	1.20E-03	98.30%						
40	la-140	1.16E-03	98.42%						
41	xe-135m	9.85E-04	98.52%						
42	np-239	9.39E-04	98.61%						
43	sr-93	8.27E-04	98.70%						
44	se-83	8.01E-04	98.78%						
45	y-91	7.83E-04	98.85%						
46	br-82	7.66E-04	98.93%						
47	ru-105	6.71E-04	99.00%						
48	i-130	5.65E-04	99.05%						

Table A-7. UO2_Mg Fuel Top Dose Producing Radionuclide Summary

Dose Rank	Urgent Phase-Total Dose			Urgent Phase-Avoidable Dose			Early Phase		
	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose
1	te-132	3.91E-01	39.08%	te-132	5.491E-01	54.91%	te-132	3.77E-01	37.66%
2	i-131	1.48E-01	53.92%	ba-140	9.313E-02	64.22%	ba-140	2.09E-01	58.52%
3	i-133	8.89E-02	62.81%	i-131	8.876E-02	73.10%	i-131	1.00E-01	68.54%
4	ba-140	7.94E-02	70.75%	i-133	7.598E-02	80.70%	cs-134	7.25E-02	75.79%
5	i-135	5.35E-02	76.11%	i-135	6.313E-02	87.01%	ru-103	4.84E-02	80.63%
6	i-134	2.09E-02	78.19%	te-131m	2.172E-02	89.18%	i-133	4.19E-02	84.82%
7	i-132	2.01E-02	80.21%	i-132	2.000E-02	91.18%	i-135	3.37E-02	88.19%
8	te-131m	1.65E-02	81.86%	i-134	1.408E-02	92.59%	cs-137	2.37E-02	90.55%
9	kr-89	1.41E-02	83.28%	te-134	1.244E-02	93.84%	te-131m	1.35E-02	91.90%
10	xe-138	1.38E-02	84.66%	ru-103	1.174E-02	95.01%	i-132	1.07E-02	92.97%
11	cs-138	1.38E-02	86.04%	te-133m	7.198E-03	95.73%	sr-89	8.57E-03	93.82%
12	te-134	1.23E-02	87.26%	cs-138	6.868E-03	96.42%	zr-95	8.15E-03	94.64%
13	sr-89	1.22E-02	88.48%	cs-136	4.759E-03	96.89%	cs-136	7.97E-03	95.44%
14	ru-103	1.19E-02	89.67%	sr-91	4.391E-03	97.33%	i-134	7.51E-03	96.19%
15	kr-88	1.14E-02	90.81%	cs-134	4.133E-03	97.74%	te-134	6.64E-03	96.85%
16	te-133m	9.23E-03	91.73%	sr-89	2.036E-03	97.95%	ru-106	6.52E-03	97.50%
17	cs-134	6.07E-03	92.34%	sr-92	1.964E-03	98.14%	te-133m	3.87E-03	97.89%
18	rb-89	5.96E-03	92.94%	rb-89	1.679E-03	98.31%	cs-138	3.66E-03	98.26%
19	cs-137	5.94E-03	93.53%	la-140	1.563E-03	98.47%	sr-91	2.48E-03	98.50%
20	cs-140	5.45E-03	94.08%	cs-137	1.328E-03	98.60%	te-129m	2.06E-03	98.71%
21	ru-106	5.01E-03	94.58%	np-239	1.148E-03	98.72%	sr-92	1.05E-03	98.82%
22	rb-90	4.75E-03	95.05%	te-133	1.083E-03	98.82%	nb-95	1.00E-03	98.92%
23	sr-91	3.79E-03	95.43%	br-82	9.327E-04	98.92%	rb-89	9.19E-04	99.01%
24	cs-136	3.47E-03	95.78%	ru-105	8.584E-04	99.00%			
25	kr-87	3.41E-03	96.12%	zr-95	7.297E-04	99.08%			
26	te-133	3.14E-03	96.43%						
27	xe-137	2.68E-03	96.70%						
28	te-129m	2.26E-03	96.93%						
29	sr-92	2.08E-03	97.14%						
30	sr-90	2.05E-03	97.34%						
31	rb-88	1.69E-03	97.51%						
32	np-239	1.57E-03	97.67%						
33	rb-90m	1.49E-03	97.81%						
34	cs-139	1.44E-03	97.96%						
35	br-84	1.29E-03	98.09%						

Table A-7. UO2_Mg Fuel Top Dose Producing Radionuclide Summary

Dose Rank	Urgent Phase-Total Dose			Urgent Phase-Avoidable Dose			Early Phase		
	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose
36	te-131	1.26E-03	98.21%						
37	pu-241	1.20E-03	98.33%						
38	la-140	1.12E-03	98.45%						
39	xe-135m	1.07E-03	98.55%						
40	ru-105	8.51E-04	98.64%						
41	sr-93	8.18E-04	98.72%						
42	ce-144	7.97E-04	98.80%						
43	zr-95	7.91E-04	98.88%						
44	se-83	7.81E-04	98.96%						
45	br-82	6.40E-04	99.02%						

Table A-8. UZrH Fuel Top Dose Producing Radionuclide Summary

Dose Rank	Urgent Phase-Total Dose			Urgent Phase-Avoidable Dose			Early Phase		
	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose
1	te-132	3.71E-01	37.12%	te-132	5.354E-01	53.54%	te-132	3.45E-01	34.47%
2	i-131	1.37E-01	50.78%	ba-140	1.071E-01	64.25%	ba-140	2.25E-01	56.98%
3	ba-140	8.89E-02	59.67%	i-131	8.383E-02	72.63%	i-131	8.88E-02	65.87%
4	i-133	8.75E-02	68.42%	i-133	7.674E-02	80.30%	ru-103	6.14E-02	72.00%
5	i-135	5.22E-02	73.64%	i-135	6.315E-02	86.62%	cs-134	6.02E-02	78.02%
6	sr-89	2.15E-02	75.79%	i-132	1.914E-02	88.53%	cs-137	4.74E-02	82.76%
7	i-134	2.08E-02	77.88%	te-131m	1.893E-02	90.43%	i-133	3.97E-02	86.73%
8	i-132	1.88E-02	79.75%	ru-103	1.584E-02	92.01%	i-135	3.16E-02	89.89%
9	kr-89	1.67E-02	81.42%	i-134	1.441E-02	93.45%	sr-89	1.46E-02	91.35%
10	ru-103	1.56E-02	82.99%	te-134	1.330E-02	94.78%	zr-95	1.39E-02	92.73%
11	xe-138	1.41E-02	84.40%	te-133m	7.607E-03	95.54%	te-131m	1.10E-02	93.84%
12	te-131m	1.41E-02	85.80%	cs-138	7.130E-03	96.25%	i-132	9.59E-03	94.80%
13	cs-138	1.39E-02	87.19%	sr-91	5.165E-03	96.77%	i-134	7.21E-03	95.52%
14	kr-88	1.34E-02	88.53%	sr-89	3.697E-03	97.14%	ru-106	6.73E-03	96.19%
15	te-134	1.28E-02	89.81%	cs-134	3.654E-03	97.51%	te-134	6.66E-03	96.86%
16	cs-137	1.23E-02	91.04%	cs-137	2.832E-03	97.79%	cs-136	4.01E-03	97.26%
17	te-133m	9.51E-03	91.99%	cs-136	2.554E-03	98.04%	te-133m	3.84E-03	97.64%
18	rb-89	6.97E-03	92.69%	sr-92	2.265E-03	98.27%	cs-138	3.57E-03	98.00%
19	cs-140	5.67E-03	93.26%	rb-89	2.018E-03	98.47%	nb-95	2.75E-03	98.27%
20	rb-90	5.63E-03	93.82%	la-140	1.792E-03	98.65%	sr-91	2.73E-03	98.55%
21	ru-106	5.36E-03	94.35%	zr-95	1.321E-03	98.78%	te-129m	2.46E-03	98.79%
22	cs-134	5.23E-03	94.88%	te-133	1.086E-03	98.89%	ce-144	1.25E-03	98.92%
23	sr-90	4.68E-03	95.35%	te-129m	7.952E-04	98.97%	sr-90	1.19E-03	99.04%
24	sr-91	4.35E-03	95.78%	nb-95	7.777E-04	99.05%			
25	kr-87	3.95E-03	96.18%						
26	te-133	3.06E-03	96.48%						
27	te-129m	2.81E-03	96.76%						
28	xe-137	2.65E-03	97.03%						
29	sr-92	2.34E-03	97.26%						
30	rb-88	1.97E-03	97.46%						
31	cs-136	1.81E-03	97.64%						
32	rb-90m	1.66E-03	97.81%						
33	ce-144	1.65E-03	97.97%						
34	br-84	1.46E-03	98.12%						
35	cs-139	1.46E-03	98.26%						

Table A-8. UZrH Fuel Top Dose Producing Radionuclide Summary

Dose Rank	Urgent Phase-Total Dose			Urgent Phase-Avoidable Dose			Early Phase		
	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose	Radio-nuclide	Fraction of Total Dose	Percent of Cum-ulative Dose
36	zr-95	1.39E-03	98.40%						
37	la-140	1.25E-03	98.53%						
38	te-131	1.20E-03	98.65%						
39	xe-135m	9.81E-04	98.75%						
40	sr-93	8.98E-04	98.84%						
41	y-91	8.91E-04	98.93%						
42	se-83	8.66E-04	99.01%						

This page left blank

APPENDIX B. RELEASED ACTIVITIES OF TOP DOSE-PRODUCING RADIONUCLIDES BY RTR FUEL TYPE

Table B-1. Released Activities of Top Dose-Producing Radionuclides by RTR Fuel Type

Radio-nuclide	Release Activity by Research and Test Reactor Fuel Type							
	UO_2	U	U_3O_8_Al	U_3Six_Al	UAlx_Al	UO_2_Al	UO_2_Mg	UZrH
	(MBq)	(MBq)	(MBq)	(MBq)	(MBq)	(MBq)	(MBq)	(MBq)
Ba-140	4.86E+07	2.59E+07	4.84E+07	4.82E+07	4.06E+07	4.84E+07	4.82E+07	4.72E+07
Ba-141	-	5.01E+07	-	-	-	-	-	-
Br-82	1.24E+06	4.66E+07	1.09E+06	9.58E+05	1.60E+06	1.09E+06	9.45E+05	-
Br-84	5.83E+07	5.97E+07	5.77E+07	5.75E+07	5.71E+07	5.77E+07	5.76E+07	5.71E+07
Ce-144	3.07E+05	-	3.06E+05	3.05E+05	8.96E+05	3.06E+05	1.70E+05	3.08E+05
Cs-134	6.44E+06	1.56E+05	5.88E+06	5.40E+06	3.29E+07	5.88E+06	1.99E+06	1.50E+06
Cs-136	4.30E+06	7.31E+05	3.54E+06	2.94E+06	1.91E+07	3.54E+06	2.09E+06	9.54E+05
Cs-137	2.83E+06	3.91E+05	2.81E+06	2.78E+06	1.08E+07	2.81E+06	1.51E+06	2.75E+06
Cs-138	4.39E+08	5.17E+08	4.35E+08	4.30E+08	3.96E+08	4.35E+08	4.63E+08	4.09E+08
Cs-139	4.13E+08	4.85E+08	4.09E+08	4.05E+08	3.73E+08	4.09E+08	4.34E+08	3.85E+08
Cs-140	3.66E+08	4.17E+08	3.61E+08	3.58E+08	3.35E+08	3.61E+08	3.77E+08	3.42E+08
I-130	2.48E+06	-	2.28E+06	-	2.78E+06	2.28E+06	-	-
I-131	2.05E+08	1.57E+08	2.01E+08	1.98E+08	1.72E+08	2.01E+08	2.26E+08	1.82E+08
I-132	3.13E+08	3.72E+08	3.07E+08	3.02E+08	2.59E+08	3.07E+08	3.41E+08	2.78E+08
I-133	4.53E+08	5.56E+08	4.47E+08	4.41E+08	3.96E+08	4.47E+08	4.82E+08	4.14E+08
I-134	5.21E+08	6.29E+08	5.15E+08	5.09E+08	4.61E+08	5.15E+08	5.51E+08	4.80E+08
I-135	4.31E+08	5.36E+08	4.24E+08	4.18E+08	3.72E+08	4.24E+08	4.58E+08	3.90E+08
Kr-87	5.43E+08	5.33E+08	5.41E+08	5.42E+08	5.46E+08	5.41E+08	5.38E+08	5.46E+08
Kr-88	7.44E+08	7.19E+08	7.43E+08	7.45E+08	7.55E+08	7.43E+08	7.38E+08	7.55E+08
Kr-89	9.40E+08	8.98E+08	9.39E+08	9.42E+08	9.59E+08	9.39E+08	9.28E+08	9.57E+08
La-140	1.65E+06	7.48E+05	1.64E+06	1.64E+06	1.39E+06	1.64E+06	1.63E+06	1.59E+06
Nb-95	6.97E+05	-	6.96E+05	6.92E+05	1.68E+06	6.96E+05	2.84E+05	7.10E+05
Np-239	7.23E+06	2.08E+07	6.97E+06	6.45E+06	-	6.97E+06	1.20E+07	-
Pu-238	3.76E+02	-	3.24E+02	2.79E+02	3.26E+03	3.24E+02	-	-
Pu-241	8.22E+03	-	7.87E+03	7.05E+03	-	7.87E+03	7.71E+03	-
Rb-86	-	-	-	-	2.14E+06	-	-	-
Rb-88	2.04E+08	1.97E+08	2.03E+08	2.04E+08	2.07E+08	2.03E+08	2.02E+08	2.06E+08
Rb-89	2.67E+08	2.59E+08	2.67E+08	2.68E+08	2.71E+08	2.67E+08	2.65E+08	2.71E+08
Rb-90	2.71E+08	2.57E+08	2.71E+08	2.72E+08	2.78E+08	2.71E+08	2.66E+08	2.76E+08
Rb-90m	5.18E+07	5.36E+07	5.20E+07	5.22E+07	5.11E+07	5.20E+07	5.40E+07	5.26E+07
Ru-103	2.51E+07	7.49E+06	2.45E+07	2.40E+07	2.33E+07	2.45E+07	1.90E+07	2.19E+07
Ru-105	1.61E+07	3.09E+07	1.53E+07	1.44E+07	-	1.53E+07	2.01E+07	-
Ru-106	1.28E+06	3.18E+05	1.21E+06	1.13E+06	1.98E+06	1.21E+06	8.56E+05	8.01E+05

Table B-1. Released Activities of Top Dose-Producing Radionuclides by RTR Fuel Type

Radio-nuclide	Release Activity by Research and Test Reactor Fuel Type							
	UO_2	U	U_3O_8_Al	U_3Six_Al	UAlx_Al	UO_2_Al	UO_2_Mg	UZrH
	(MBq)	(MBq)	(MBq)	(MBq)	(MBq)	(MBq)	(MBq)	(MBq)
Se-83	2.78E+07	2.93E+07	2.75E+07	2.73E+07	2.68E+07	2.75E+07	2.77E+07	2.68E+07
Sr-89	2.64E+07	5.30E+06	2.65E+07	2.66E+07	3.46E+07	2.65E+07	1.78E+07	2.75E+07
Sr-90	2.79E+05	-	2.79E+05	2.79E+05	1.15E+06	2.79E+05	1.44E+05	2.88E+05
Sr-91	3.76E+07	3.76E+07	3.74E+07	3.74E+07	3.74E+07	3.74E+07	3.74E+07	3.75E+07
Sr-92	3.90E+07	4.02E+07	3.88E+07	3.87E+07	3.82E+07	3.88E+07	3.92E+07	3.85E+07
Sr-93	4.19E+07	4.46E+07	4.16E+07	4.14E+07	4.02E+07	4.16E+07	4.25E+07	4.08E+07
Te-129m	4.60E+06	1.26E+06	4.38E+06	4.18E+06	4.85E+06	4.38E+06	3.27E+06	3.55E+06
Te-131	1.83E+08	2.33E+08	1.80E+08	1.76E+08	1.54E+08	1.80E+08	1.95E+08	1.62E+08
Te-131m	3.35E+07	4.61E+07	3.32E+07	3.25E+07	2.54E+07	3.32E+07	3.93E+07	2.92E+07
Te-132	3.06E+08	3.48E+08	3.01E+08	2.96E+08	2.57E+08	3.01E+08	3.29E+08	2.73E+08
Te-133	2.31E+08	2.85E+08	2.27E+08	2.23E+08	2.00E+08	2.27E+08	2.42E+08	2.07E+08
Te-133m	2.41E+08	2.79E+08	2.39E+08	2.37E+08	2.19E+08	2.39E+08	2.54E+08	2.29E+08
Te-134	4.44E+08	5.07E+08	4.39E+08	4.35E+08	4.07E+08	4.39E+08	4.59E+08	4.18E+08
Xe-135	-	-	-	-	6.04E+08	-	-	-
Xe-135m	3.21E+08	4.29E+08	3.16E+08	3.11E+08	2.63E+08	3.16E+08	3.55E+08	2.85E+08
Xe-137	1.52E+09	1.85E+09	1.51E+09	1.49E+09	1.34E+09	1.51E+09	1.62E+09	1.40E+09
Xe-138	1.51E+09	1.77E+09	1.50E+09	1.48E+09	1.37E+09	1.50E+09	1.58E+09	1.41E+09
Y-91	1.01E+06	-	1.01E+06	1.02E+06	1.43E+06	1.01E+06	-	1.04E+06
Zr-95	1.13E+06	2.20E+05	1.12E+06	1.12E+06	1.62E+06	1.12E+06	7.34E+05	1.13E+06

APPENDIX C. RELEASE FRACTION TABLES FROM REACTOR ACCIDENT STUDIES

The U.S. Nuclear Regulatory Commission (NRC), the nuclear power industry, and the international nuclear energy research community have conducted considerable research over the last several decades to examine severe reactor accident phenomena. The NRC initiated the state-of-the-art reactor consequence analyses (SOARCA) project to develop best consequence estimates for potential severe reactor accidents for two pilot plants: the Peach Bottom Atomic Power Station in Pennsylvania and the Surry Power Station in Virginia.

Table C-1. Peach Bottom Unmitigated Long-Term Station Blackout Release Fractions [8]

Class	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6	Bin 7	Bin 8	Bin 9	Bin 10
Xe	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000
Cs	0.1171	0.1602	0.3303	0.3061	0.0575	0.0180	0.0071	0.0025	0.0009	0.0004
Ba	0.0412	0.2230	0.4450	0.2275	0.0486	0.0111	0.0030	0.0005	0.0001	0.0001
I	0.0231	0.1503	0.5219	0.2579	0.0333	0.0102	0.0027	0.0005	0.0001	0.0000
Te	0.0286	0.1370	0.4603	0.2779	0.0643	0.0249	0.0059	0.0009	0.0002	0.0001
Ru	0.0393	0.1512	0.3597	0.2682	0.1214	0.0484	0.0104	0.0011	0.0002	0.0001
Mo	0.1553	0.1638	0.2563	0.3259	0.0649	0.0202	0.0087	0.0033	0.0012	0.0005
Ce	0.0306	0.1930	0.4357	0.2427	0.0708	0.0218	0.0047	0.0005	0.0001	0.0001
La	0.0235	0.1473	0.3990	0.2664	0.1109	0.0433	0.0089	0.0007	0.0000	0.0000

Table C-2. Peach Bottom Short-Term Station Blackout with Reactor Core Isolation Cooling Blackstart Release Fractions [8]

Class	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6	Bin 7	Bin 8	Bin 9	Bin 10
Xe	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000
Cs	0.1704	0.1914	0.2388	0.2874	0.0796	0.0169	0.0094	0.0039	0.0017	0.0005
Ba	0.0303	0.1751	0.4211	0.3035	0.0581	0.0084	0.0023	0.0008	0.0003	0.0001
I	0.0322	0.1958	0.4343	0.2527	0.0634	0.0164	0.0040	0.0008	0.0003	0.0001
Te	0.0499	0.1770	0.3605	0.2675	0.0987	0.0353	0.0088	0.0016	0.0005	0.0001
Ru	0.0501	0.1443	0.2997	0.3035	0.1406	0.0480	0.0114	0.0017	0.0005	0.0001
Mo	0.2081	0.1901	0.1871	0.2966	0.0834	0.0167	0.0108	0.0047	0.0021	0.0006
Ce	0.0188	0.1393	0.4164	0.3264	0.0786	0.0164	0.0034	0.0005	0.0001	0.0001
La	0.0218	0.1333	0.3404	0.3148	0.1352	0.0442	0.0093	0.0008	0.0001	0.0000

Table C-3. Peach Bottom Short-Term Station Blackout with Reactor Core Isolation Cooling Blackstart Release Fractions [8]

Class	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6	Bin 7	Bin 8	Bin 9	Bin 10
Xe	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000
Cs	0.0288	0.2922	0.2076	0.2174	0.1847	0.0587	0.0089	0.0012	0.0002	0.0003
Ba	0.0178	0.0546	0.1120	0.3364	0.3641	0.0994	0.0135	0.0018	0.0002	0.0001
I	0.0282	0.5160	0.2181	0.1261	0.0864	0.0217	0.0023	0.0003	0.0003	0.0006
Te	0.0393	0.3360	0.2596	0.2010	0.1225	0.0376	0.0034	0.0004	0.0001	0.0001
Ru	0.0323	0.0946	0.1503	0.2915	0.2935	0.1127	0.0209	0.0036	0.0005	0.0003
Mo	0.0300	0.1217	0.1995	0.2859	0.2584	0.0880	0.0141	0.0020	0.0002	0.0002
Ce	0.0219	0.0558	0.1024	0.3281	0.3666	0.1076	0.0151	0.0021	0.0002	0.0002
La	0.0203	0.0724	0.1218	0.3231	0.3501	0.0976	0.0127	0.0016	0.0002	0.0002

Table C-4. Surry Long-Term Station Blackout Release Fractions [9]

Class	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6	Bin 7	Bin 8	Bin 9	Bin 10
Xe	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01
Cs	1.7E-03	1.3E-02	6.2E-02	2.0E-01	3.4E-01	2.5E-01	1.1E-01	2.4E-02	2.3E-03	1.1E-03
Ba	6.9E-03	3.6E-02	1.4E-01	3.7E-01	3.5E-01	9.0E-02	1.5E-02	2.5E-03	2.5E-04	3.6E-04
I	6.5E-03	3.2E-02	1.2E-01	3.3E-01	3.6E-01	1.3E-01	1.9E-02	2.0E-03	3.2E-04	1.4E-03
Te	7.5E-03	3.5E-02	1.3E-01	3.5E-01	3.4E-01	1.1E-01	1.9E-02	2.4E-03	2.4E-04	1.3E-03
Ru	8.8E-03	3.7E-02	1.4E-01	3.2E-01	3.1E-01	1.3E-01	2.7E-02	1.0E-02	3.4E-03	1.4E-02
Mo	2.4E-04	3.9E-03	2.8E-02	1.0E-01	2.7E-01	3.3E-01	2.0E-01	6.3E-02	8.5E-03	3.8E-04
Ce	7.5E-03	3.2E-02	1.2E-01	2.9E-01	3.3E-01	1.7E-01	3.6E-02	8.0E-03	1.7E-03	8.0E-03
La	4.9E-03	2.4E-02	9.2E-02	2.5E-01	3.4E-01	2.0E-01	6.2E-02	1.2E-02	1.3E-03	2.9E-03

Table C-5. Surry Unmitigated Short-Term Station Blackout Release Fractions [9]

Class	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6	Bin 7	Bin 8	Bin 9	Bin 10
Xe	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01
Cs	1.2E-03	1.0E-02	5.3E-02	1.7E-01	3.3E-01	2.9E-01	1.2E-01	2.1E-02	1.2E-03	1.2E-03
Ba	7.0E-03	3.6E-02	1.4E-01	3.4E-01	3.2E-01	1.2E-01	2.7E-02	3.6E-03	2.6E-04	4.4E-03
I	6.2E-03	2.9E-02	1.1E-01	2.7E-01	3.4E-01	2.0E-01	4.0E-02	2.5E-03	2.0E-04	2.4E-03
Te	4.0E-03	2.3E-02	9.5E-02	2.7E-01	3.6E-01	1.9E-01	4.6E-02	4.7E-03	2.3E-04	1.5E-03
Ru	5.2E-03	2.7E-02	1.1E-01	2.8E-01	3.4E-01	1.8E-01	4.1E-02	6.9E-03	1.7E-03	1.4E-02
Mo	2.5E-04	4.2E-03	3.1E-02	1.1E-01	2.9E-01	3.4E-01	1.8E-01	3.7E-02	2.4E-03	9.4E-05
Ce	5.1E-03	2.6E-02	1.0E-01	2.6E-01	3.4E-01	2.0E-01	4.9E-02	6.9E-03	1.3E-03	9.5E-03
La	3.1E-03	1.8E-02	7.6E-02	2.2E-01	3.4E-01	2.5E-01	8.1E-02	1.2E-02	8.0E-04	2.7E-03

Table C-6. Surry Interfacing Systems Loss-of-Coolant Accident Release Fractions [9]

Class	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6	Bin 7	Bin 8	Bin 9	Bin 10
Xe	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01
Cs	9.4E-03	2.6E-02	7.0E-02	2.7E-01	4.0E-01	1.8E-01	4.0E-02	2.6E-03	4.3E-05	5.5E-04
Ba	2.2E-02	4.7E-02	1.4E-01	2.9E-01	3.2E-01	1.4E-01	3.1E-02	2.5E-03	7.7E-05	2.6E-03
I	9.2E-03	2.4E-02	7.6E-02	2.8E-01	4.0E-01	1.7E-01	3.9E-02	2.5E-03	4.3E-05	6.2E-04
Te	1.3E-02	3.0E-02	8.7E-02	2.8E-01	3.8E-01	1.7E-01	3.7E-02	2.5E-03	4.6E-05	5.4E-04
Ru	1.1E-02	3.1E-02	9.7E-02	2.9E-01	3.8E-01	1.6E-01	3.3E-02	2.1E-03	3.5E-05	4.8E-04
Mo	1.0E-02	2.5E-02	6.1E-02	2.3E-01	3.8E-01	2.2E-01	6.4E-02	8.9E-03	7.4E-04	3.9E-04
Ce	7.9E-03	3.3E-02	2.2E-01	4.0E-01	1.9E-01	8.6E-02	4.1E-02	1.3E-02	1.3E-03	6.0E-03
La	2.1E-02	4.5E-02	2.5E-01	3.9E-01	1.7E-01	7.6E-02	3.4E-02	9.3E-03	8.1E-04	2.2E-03

Table C-7. Surry Mitigated Thermally-Induced Steam Generator Tube Rupture Release Fractions [9]

Class	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6	Bin 7	Bin 8	Bin 9	Bin 10
Xe	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01
Cs	2.4E-02	3.9E-02	6.3E-02	2.1E-01	3.5E-01	2.2E-01	7.7E-02	2.3E-02	4.4E-03	6.6E-04
Ba	1.3E-02	1.9E-02	5.5E-02	2.4E-01	4.2E-01	2.0E-01	4.5E-02	1.2E-02	2.4E-03	3.7E-04
I	3.5E-02	5.0E-02	6.4E-02	2.1E-01	3.5E-01	2.0E-01	6.8E-02	2.0E-02	3.7E-03	5.9E-04
Te	1.5E-02	2.7E-02	5.7E-02	2.2E-01	3.7E-01	2.2E-01	7.3E-02	2.2E-02	4.2E-03	6.1E-04
Ru	1.6E-03	5.3E-03	3.9E-02	2.2E-01	4.2E-01	2.2E-01	6.3E-02	1.9E-02	3.5E-03	4.4E-04
Mo	1.6E-02	5.2E-02	6.9E-02	3.0E-01	4.1E-01	1.2E-01	2.8E-02	6.9E-03	1.3E-03	1.9E-04
Ce	1.3E-03	8.5E-03	7.3E-02	2.8E-01	4.2E-01	1.8E-01	3.0E-02	7.0E-03	2.0E-03	2.7E-04
La	8.7E-03	2.8E-02	8.1E-02	3.0E-01	4.1E-01	1.5E-01	2.4E-02	5.3E-03	1.4E-03	1.9E-04

Table C-8. Surry Unmitigated Thermally-Induced Steam Generator Tube Rupture Release Fractions [9]

Class	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6	Bin 7	Bin 8	Bin 9	Bin 10
Xe	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.0E-01
Cs	4.8E-03	1.6E-02	5.9E-02	1.9E-01	4.0E-01	2.7E-01	5.1E-02	5.5E-03	7.8E-04	1.2E-04
Ba	6.4E-03	2.6E-02	8.1E-02	2.4E-01	3.8E-01	2.3E-01	4.4E-02	2.9E-03	2.3E-04	4.0E-05
I	1.1E-02	2.8E-02	6.8E-02	2.0E-01	3.5E-01	2.5E-01	7.6E-02	1.1E-02	1.4E-03	2.2E-04
Te	8.6E-03	2.6E-02	7.1E-02	2.0E-01	3.6E-01	2.6E-01	7.2E-02	7.6E-03	6.9E-04	1.1E-04
Ru	1.8E-03	6.3E-03	4.2E-02	2.2E-01	4.2E-01	2.2E-01	6.4E-02	1.9E-02	3.5E-03	4.4E-04
Mo	4.0E-03	1.9E-02	6.6E-02	1.8E-01	3.3E-01	2.9E-01	1.0E-01	1.1E-02	3.3E-04	8.3E-05
Ce	4.2E-03	2.2E-02	9.2E-02	2.5E-01	3.6E-01	2.0E-01	5.7E-02	1.4E-02	2.4E-03	2.4E-04
La	2.3E-03	1.5E-02	6.5E-02	2.0E-01	4.0E-01	2.6E-01	5.1E-02	3.7E-03	2.5E-04	2.8E-05

This page left blank

DISTRIBUTION

Hardcopy—External

Number of Copies	Name	Company Name and Company Mailing Address

Hardcopy—Internal

Number of Copies	Name	Org.	Mailstop

Email—External

Name	Company Email Address	Company Name
Doug Shull	D.SHULL@iaea.org	International Atomic Energy Agency

Email—Internal

Name	Org.	Sandia Email Address
David Ek	6811	drek@sandia.gov
Nathaniel Foust	10668	nefoust@sandia.gov
Nathan Bixler	8852	nbixler@sandia.gov
Gregory Baum	6812	gabaum@sandia.gov
Dominic Martinez	6812	dmartin@sandia.gov
Technical Library	01177	libref@sandia.gov