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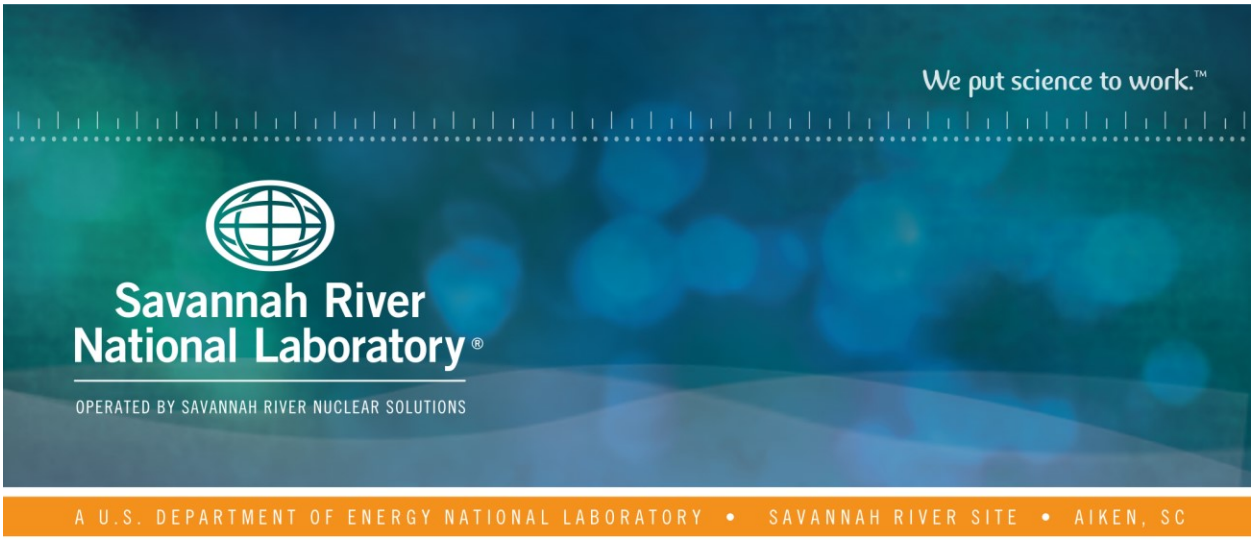

Determination of Reportable Radionuclides for Defense Waste Processing Facility (DWPF) Sludge Batch 9 (Macrobatch 11)

C.L. Trivelpiece, W.P. Kubilius, D.P. Diprete

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PREFACE OR ACKNOWLEDGEMENTS

The authors would like to acknowledge the great efforts of the SRNL shielded cells staff that worked on preparing the sample for further analysis and physical characterization. Their expertise and proficiency at cell operations makes this work possible. The authors would also like to thank the Analytical Development staff that aided in the measurement of the radionuclides in the samples.

EXECUTIVE SUMMARY

This report documents analyses and calculations performed by the Savannah River National Laboratory (SRNL) of Tank 40 sludge as part of the Waste Acceptance Product Specifications (WAPS) requirements for Sludge Batch 9 (SB9) for the Defense Waste Processing Facility (DWPF).

Tank Farm sample HTF-40-17-5 was received by SRNL Shielded Cells Operations (SCO) and was prepared for radionuclide analyses in addition to various other physical and chemical characterizations. Radionuclide analyses were performed by SRNL Analytical Development (AD). Based on criteria set forth in the Department of Energy (DOE) WAPS and DWPF's Waste Form Compliance Plan (WCP), as well as, historical lessons from previous sludge batch analyses, a list of radionuclides was developed for which the sample was analyzed.

The results of these analyses were then used as input into commercially available software, RadDecay version (v) 5.01. The software was used to calculate the activity of the measured analytes in index years 2017 through 3115 in 100-year increments. Radionuclides with half-lives greater than 10 years and activities that comprised more than 0.01% of the total sludge batch activity are reportable.

The following isotopes were identified as being reportable per the DOE WAPS and concurrent with the DWPF WCP:

Cl-36	**Zr-93**	**Sm-151**	**Np-237**	**Pu-241**
Ni-59	**Tc-99**	**Ac-227**	**Pu-238**	**Pu-242**
Ni-63	**Sn-126**	**Th-229**	**U-238**	**Am-243**
Se-79	**I-129**	**Pa-231**	**Pu-239**	**Cm-244**
Sr-90	**Cs-135**	**U-233**	**Pu-240**	**Cm-246**
Nb-93m	**Cs-137**	**U-234**	**Am-241**	

In addition, U-235 and U-236 activities are reportable as set forth by International Atomic Energy Agency (IAEA) safeguards.

The total activity of Sludge Batch 9 was analyzed to be approximately 1.73E+04 μCi/g (dried solids basis) at year 2017 based on the radionuclides that were analyzed in the sample. This activity is equivalent to approximately 71.3 Ci/gal of slurry of Tank 40 Sludge Batch 9. In 3115, the total activity of the Sludge Batch radionuclide inventory will be 1.80E+01 μCi/g.

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LIST OF ABBREVIATIONS

AD	Analytical Development
AMP	Ammonium-molybdophosphate
CST	Crystalline Silicotitanate
DOE	Department of Energy
DWPF	Defense Waste Processing Facility
HLW	High Level Waste
IAEA	International Atomic Energy Agency
ICP-AES	Inductively-coupled Plasma – Atomic Emission Spectroscopy
ICP-MS	Inductively-coupled Plasma – Mass Spectroscopy
IRCP	International Commission on Radiological Protection
MST	Monosodium Titanate
PIPS	Passivated, Implanted, Planar Silicon
SB	Sludge Batch
SCO	Shielded Cells Operations
SRNL	Savannah River National Laboratory
SRR	Savannah River Remediation
$T_{1/2}$	Half-life
TFO	Tank Farm Operations
TTQAP	Task Technical and Quality Assurance Plan
TTR	Technical Task Request
WAPS	Waste Acceptance Product Specifications
WCP	Waste Form Compliance Plan
WQR	Waste Form Qualification Report

1.0 Introduction

In accordance with the Department of Energy (DOE) Waste Acceptance Product Specifications (WAPS) [1], the Defense Waste Processing Facility (DWPF) is required to report all radionuclides with half-lives greater than ten years which comprise greater 0.05% of the total activity inventory for a given waste form at certain specified "index years." DWPF complies with these requirements by considering the half-life requirement ($T_{1/2}$ > 10 years) and radionuclides with concentrations greater than 0.01% of the total inventory from the approximate time of production through 1100 years [2]. In past WAPS analyses the index years were set at 2015 and 3115; however, Savannah River National Laboratory (SRNL) has been directed to set the initial index year at 2017 (year of radionuclide analysis) for Sludge Batch (SB) 9 Macrobatch 11 (SB9)[3]. Future macrobatch analyses will use the year the radionuclide analysis was performed as the initial index year and the final index year will remain at 3115 [3]. An initial set of radionuclides to be listed was based on a design-basis glass described in the Waste Form Compliance Plan (WCP)[4] and the Waste Form Qualification Report (WQR) [2] and is expanded upon when additional radionuclides meet the reportability criterion for a given index year.

As documented in previous WAPS radionuclide reports, "Specification 1.6 of the WAPS, International Atomic Energy Agency (IAEA) Safeguards Reporting for High Level Waste (HLW), requires that the ratio by weights of the following uranium and plutonium isotopes be reported: U-233, U-234, U-235, U-236, U-238, Pu-238, Pu-239, Pu-240, Pu-241, and Pu-242 [5, 6]." As such, a complete list of the Pu and U radionuclides measured during the SB9 radionuclide analysis is provided in this report.

This work is initiated through a Technical Task Request (TTR) [7] and performed with a Task Technical and Quality Assurance Plan (TTQAP) [8].

A Tank 40 sample (HTF-40-17-5) representative of the Sludge Batch 9 composite waste was acquired by Savanah River Remediation (SRR) Tank Farm Operations (TFO) and transferred to the SRNL Shielded Cells Operations (SCO) for preparation. The analyses of the Tank 40 WAPS sample was conducted by the Analytical Development Laboratory (AD) at SRNL. An additional Tank 40 sample (HTF-40-18-9) was collected in 2018 for supplementary physical and chemical characterization. The Tank 40 2017 and 2018 sample results for physical and chemical characterization demonstrated no significant statistical difference - establishing any sample-to-sample variation would require more than two samples [9, 10]. Consequently, further radionuclide analyses of the Tank 40 2018 sample would likely not have yielded statistically different results from the 2017 analysis; therefore, no radionuclide analyses of the 2018 sample were performed.

1.1 Radionuclides Considered

A list of radionuclides that may be reportable is given based on what is known about the various Savannah River Site (SRS) processes that generated the waste. Tank Farm history was developed and reported in the documentation of the analyses of Sludge Batch 7a [11]. No new radionuclides have been added to this list for the SB9 analyses. Further development of potentially reportable radionuclides was presented in a previous report [6]. The preparation of the material used in the radionuclide analysis is described in a previous document [10].

2.0 Experimental Procedure

2.1 Separation Methods

These analytical methods involved separation techniques that enabled radionuclides that were at low concentrations to be measured more accurately and to determine more reliable and lower detection limits. The techniques and methodology for these separations are maintained by SRNL AD and will only be

summarized here. Aliquots of the alkali fusions or the aqua regia dissolutions were analyzed along with blanks. In all cases, the activity in the blanks did not contribute any significant activity to the radionuclides being analyzed. For the special cases involving Se-79, I-129 and Am/Cm aliquots of the sludge slurry were initially treated in the shielded cells for various separation steps (via the methodology detailed below) and then submitted to AD for further separation and/or counting.

2.1.1 *Cl-36 Method*

Aliquots of Sludge Batch 9 aqua regia dissolution were initially rendered caustic and subjected to two Monosodium Titanate (MST) and Crystalline Silico-Titanate (CST) based decontamination steps. The resins and insoluble elements (i.e. actinides, lanthanides, strontium and yttrium) were filtered off, decontaminating the solution. The solutions were then acidified with nitric acid and further decontaminated with Bio-Rad AMP-1 (ammonium molybdophosphate) and Eichrom Diphonix resins. The Cl in the samples was subsequently precipitated as AgCl. The AgCl precipitate was counted using gas flow proportional counter analysis. The AgCl precipitate was then activated by neutron activation analysis to determine Cl losses during the processes. The HCl used to digest the samples initially was used to trace Cl-36 throughout the processes. The chlorine yields were used to correct Cl-36 results for any losses.

2.1.2 *Ni-59/-63 Method*

This separation is based on isolation of Ni from the dissolved sludge using a column containing dimethylglyoxime as an extractant that is specific for Ni. Each of the solutions resulting from the aqua regia digestions of the four samples of dried sludge slurry was spiked with a stable Ni carrier to trace the Ni separation and was then passed through a column containing the above extractant. The absorbed Ni was then eluted from each column. The Ni-59 was measured in the eluted solutions by its characteristic X- rays and Ni-63 by its beta particles. Total Ni in each eluted solution was measured by inductively coupled plasma atomic emission spectroscopy (ICP-AES). The radiochemical Ni analyses were corrected for the Ni carrier recoveries as measured by ICP-AES.

2.1.3 *Se-79 Method*

Four aliquots of wet sludge slurry were spiked with a known amount of stable Se as a carrier. The samples were digested with concentrated nitric acid. The Fe in the dissolutions was reduced to Fe(II) using ascorbic acid to ensure it would not interfere with subsequent decontamination steps designed to extract Y-90, the lanthanides and the actinides from the Se traced dissolutions. The dissolutions were then treated with resins (Bio-Rad AMP-1, Eichrom Sr, RE, and Actinide resins) to reduce levels of Sr-90, Cs-137, Y-90, the lanthanides and the actinides to levels low enough to allow for their removal from the Shielded Cells and submission to AD. The Se traced decontaminated dissolutions were then further decontaminated with Bio-Rad AMP-1, Eichrom Sr and RE resin treatments. The total Se was reduced to Se metal using titanium (III) chloride, hydroxylamine hydrochloride, and ascorbic acid. The precipitated Se metal was then washed repeatedly with deionized water and dilute nitric acid. The Se metal was then dissolved with concentrated HBr, and the resulting SeBr4 was extracted by solvent-solvent extraction using a tri-butyl phosphate/n-paraffin solvent extraction system. The Se was back extracted from the solvent. Aliquots of the purified Se fraction were then analyzed. A portion was neutron activated in a Cf- 252 neutron source at SRNL to determine the total amount of Se present in order to calculate the recovery of Se from the radiochemical separation. A second portion was counted by liquid scintillation to determine the Se-79 beta activity. The yields of the stable Se carrier were applied to the Se-79 beta activity result to determine Se-79 activities in the sample aliquots initially treated.

2.1.4 *Sr-90 Method*

Aliquots of each sample from the alkali fusions were spiked with a stable Sr carrier and a stable Ce carrier. The Sr carrier was used for separation yielding purposes and the Ce carrier was used to enhance the separation rates of undesirable isotopes such as Y-90, the lanthanides or the actinides. The spiked sample aliquots were initially oxidized using nitric acid. The Sr in the samples was extracted using commercially

available Sr extraction resin. This resin also extracts some of the Pu under the conditions used to extract the Sr. The Pu was washed from the resin using an oxalic acid/nitric acid mixture. The Sr was eluted from the resin, and the resulting solution concentrated. A portion of the purified Sr solution was neutron activated in a Cf-252 neutron activation facility at SRNL to determine the total Sr and to calculate the fraction of Sr isolated by the procedure. A second portion of each of the Sr fractions was stored for five to seven days to allow Y-90 to grow in. Each fraction was then counted by liquid scintillation analysis to determine the Y-90 activity. The Sr-90 beta activity in each case was calculated from the Y-90 activity. The yields of the stable Sr carriers were applied to the Sr-90 beta activity results to determine Sr-90 activities in the original aliquots of the solutions resulting from the dissolution of the dried sludge slurry samples.

2.1.5 *Gamma Counting Following Cs-137 Removal*

This method was used to determine Co-60, Ru-106, Sb-125, Sn-126, Ba-133, Ce-144, Eu-152, Eu-154, Eu-155, and Am-241. These gamma emitters could not be determined directly because of the high Cs- 137 activity in the samples. Consequently, the Cs-137 was removed. Aliquots of each of the four alkali fusions of the dried sludge slurry samples were treated with two batch additions of an ammonium phosphomolybdate resin to selectively remove the Cs-137 from the aliquots. This allowed gamma photons for isotopes at low concentrations to be detected or allowed lower detection limits to be determined for those isotopes that were not detected. A high purity coaxial germanium detector was utilized to detect the gamma rays from Co-60, Ru-106, Sb-125, Sn-126, Ba-133, Ce-144, Eu-152, Eu-154, Eu-155, and Am-241. Only Co-60, Eu-152, Eu-154, Eu-155, and Am-241 were detected. Because of their low concentrations the other isotopes were not detected. To obtain reliable and lower detection limits for these radionuclides, each of the solutions was counted for four hours or more. The detection limits were used to calculate the maximum activity of each for input to the projection calculations. Of this group of radionuclides, only Sn-126 and Ba-133 have half-lives greater than 10 years. Even though the others have half-lives less than 10 years, their activities were included to calculate the total Curies present in SB8 at the selected decay times except for Ru-106 and Ce-144 which are discussed in Section 3.1.

2.1.6 *Sn-121m Method*

Aliquots of alkali fusions were spiked with Sn-113. The aliquots were converted to a chloride matrix with hydrochloric acid, and elemental tin was extracted from the matrix using anion exchange. Tin was eluted with dilute nitric acid, and the tin extract was analyzed by low energy gamma-ray spectrometry for Sn-121m and for the Sn-113 tracer. The Sn-121m results were then yielded with the results from the Sn- 113 recovery

2.1.7 *I-129 Method*

The radionuclide I-129 is a long-lived beta emitting fission product ($T_{1/2}$ = 1.6E+07 years) that is in SRS wastes. Aliquots of wet sludge slurry were spiked with a known amount of stable KI to act as an iodine tracer/carrier. The samples were digested with 8M nitric acid. The traced samples were then rendered caustic, precipitating out the actinides, lanthanides, Sr-90 and Y-90, among some other radioactive species. MST was added to further decontaminate the caustic dissolutions from Sr-90, Y-90, and select actinides and lanthanides. CST was added to reduce levels of Cs-137. The treated solutions were filtered, and the decontaminated filtrate was then removed from the Shielded Cells for submission to AD. The samples were decontaminated a final time with a resin treatment to remove Cs-137 and the actinide elements. The solution was then treated with AgNO3 to precipitate the iodide ion as AgI. The precipitate was analyzed by low energy photon spectrometry to determine the amount of I-129 present. I-129 is detected by its characteristic gamma and x-ray emissions. The precipitate was then neutron activated in a Cf-252 neutron source at SRNL to determine the total amount of iodine present to calculate the recovery of I-129 in the radiochemical separation.

2.1.8 *Sm-151/Pm-147 Method*

Aliquots of each sample from the alkali fusions were spiked with a stable Sm carrier. The Sm carrier was used for separation yielding purposes. The spiked sample aliquots were initially oxidized using nitric acid.

The Sm and Pm along with other trivalent species in the samples were extracted using Eichrom RE resin. The Sm and Pm where then extracted from the other radionuclides present using Eichrom Ln resin. A portion of the purified Pm/Sm solution was neutron activated in a Cf-252 neutron activation facility at SRNL to determine the total Sm and to calculate the fraction of Sm isolated by the procedure. A second portion of each of the Pm/Sm fractions was then counted by liquid scintillation analysis to determine the Pm-147 and Sm-151 activity. The Pm-147 measurement was conducted using a higher energy beta window which was free of any interference from the low energy Sm-151 beta. The Sm-151 beta result is corrected for any Pm-147 events occurring in its beta counting window when necessary. The yields of the stable Sm carriers were applied to the Sm-151 and the Pm-147 beta activity results to determine Sm-151 and Pm-147 activities in the original aliquots of the solutions resulting from the dissolution of the dried sludge slurry samples. A Pm-147 spiked sample was analyzed through the process to monitor and correct for any slight differences in the chemical recoveries of Sm and Pm.

2.1.9 *Th-229/-230, Ac-227 Method*

Aliquots of each sample from the alkali fusions were processed through a thorium separation procedure. The Th species were extracted from the matrix using two stages of a quaternary amine based solid phase extraction and purified further via co-precipitation with cerium. Th-229 and Th-230 concentrations were measured using passivated, implanted, planar silicon (PIPS) alpha spectrometers. The Th separation was yielded by measuring the Th-232 activities in the separated fractions, and comparing those activities to the Th-232 concentrations measured directly off aliquots of dissolution by Inductively-coupled plasma – mass spectroscopy (ICP-MS.) The Th-232 yields were used to correct the various analytes for any Th losses from the radiochemical separations.

2.1.10 *Pa-231 Method*

Aliquots of each sample from the alkali fusions were analyzed through a Pa separation procedure in duplicate with the duplicate containing a Pa-233 tracer. The dissolutions were decontaminated with AMP and quaternary amine-based resins. Protactinium species were then extracted from the matrix using a CMPO/TBP based extractant. Pa-233 tracer concentrations were measured using high purity germanium spectrometers to determine separation yields. Pa-231 was measured using the ICP-MS. The Pa-233 tracer yields were decay corrected and then used to correct the Pa-231 analyses for any losses from the radiochemical separations.

2.1.11 *U Separation Method*

To lower detection limits for U-234 from the ICP-MS analyses on alkali fusion dissolution, aliquots of dissolution were purified with a DAAP based solid phase extraction. The purified aliquots were analyzed by the ICP-MS to measure U-234/U-238 mass ratios. Those ratios were applied to U-238 concentrations measured by the ICP-MS directly on aliquots of dissolution to quantify the U-234 concentration.

2.1.12 *Pu-238/-241 Method*

Pu-241 is a beta-emitting Pu isotope that cannot be measured directly in the dissolved dried sludge slurry solutions because of its low concentration. Pu-241 has a relatively short half-life (t1/2 =15 years). Its concentration, along with that for Pu-238, was determined via alkali fusion by isolating the Pu from each solution by a 2- thenoyltrifluoroacetone extraction procedure. The extracted Pu was then analyzed by beta and alpha counting to determine the ratio of beta activity from Pu-241 to the alpha activity from the other isotopes of Pu (Pu-238, Pu-239, Pu-240, and Pu-242). In the original dissolution solutions, the total alpha activity from the Pu isotopes was determined by alpha counting and ICP-MS. Knowing the total alpha activity from Pu in the solutions resulting from the extraction allows the concentration of Pu-241 in the original dissolution solutions to be calculated using the beta/alpha ratio determined in the extracted solution. In the extracted solution, the alpha counting technique also gives the alpha counts due specifically to Pu-238 so that the total amount of Pu-238 can be determined. The activities of these two radionuclides were then used in the calculations to determine the reportable radionuclides.

2.1.13 *Am/Cm Method*

This method was used for Am-241, Am-242m, Cm-242, Am-243, Cm-243, Cm-244, Cm-245, Cm-246, Cm-247, Cm-248, Bk-247, Cf-249, Cf-250, Cf-251, and Cf-252. These radionuclides are neutron activation products produced in the SRS reactors. These isotopes are difficult to measure because of their low concentrations in the sludge slurry and the dilutions necessary to get the dissolved slurry samples out of the Shielded Cells. Of these isotopes, the Am-241 can be easily and accurately analyzed directly by extended gamma counting of the dissolved sludge (see Section 2.1.5). For the other radionuclides listed above, a separation method has been developed by AD for isolating Am, Cm, Bk and Cf from a wet sludge slurry solution. The slurry is digested in the Shielded Cells with an alkali fusion. The trivalent actinides are then extracted from the dissolution filtrate using a commercially available ion exchange resin (Eichrom DGA). As Y-90 coextracts with the trivalent actinides on DGA resin, the treated samples were held in the Shielded Cells for nine days to allow the Y-90 to decay before they were removed and submitted to AD. The solutions were purified further with a second RE resin extraction followed by an Eichrom Ln resin extraction. The Am, Cm, Bk, and Cf extracts were then analyzed by alpha and low energy gamma counting techniques as well as by ICP-MS. The radionuclides Cm-242, Am-242m, Cm-244, and Cf-252 were measured by alpha spectroscopy, Am- 241, Am-243, Cm-243, Cm-245, Cf-249, and Cf-251 were measured by low energy gamma spectroscopy, and Cm-245, Cm-246, Cm-247, Bk-247, Cm-248 and Cf-250 were measured by ICP-MS. The fraction of each actinide element isolated by this ion exchange technique was determined by comparing the measured concentrations of Am-241 in the eluted solutions with their respective concentration in the original dissolved slurry that was measured by direct gamma counting of Cs-137 removed aliquots of the dissolved slurry.

By using this technique, the radionuclides Am-242m, Am-243, Cm-242, Cm-244, Cm-245, and Cm-246 were detected and measured along with the Am-241. All the other radionuclides (Cm-243, Cm-247, Bk-247, Cm-248, Cf-249, Cf-250, Cf-251 and Cf-252) had concentrations below the detection limit of the analytical methods. For the later series of radionuclides, the detection limits were then used as the maximum concentrations or activities that could be present.

2.1.14 *Pd-107 Method*

Aliquots of each sample from the alkali fusions were spiked with elemental Pd. Pd was then extracted from the samples using a DMG based extractant. Pd-107 levels were measured using the ICP-MS, and the results were yielded from sample stable Pd recoveries as measured by the ICP-MS.

2.1.15 *Ra-226 Method*

Aliquots of each sample from the alkali fusions were decontaminated with a number of resin treatments. Radium was extracted from the matrix using an Empore-Radium-Disk-based extraction. Sample aliquots matrix spiked with Ra-226 were also run through the procedure for chemical yielding purposes. The disks containing extracted radium were then analyzed three days following the extraction and 14 days following the extraction to allow for daughter ingrowth. Sample Ra-226 results were corrected with matrix spike recoveries.

2.1.16 *Cd-113m Method*

The indium-113 isobaric interference was chemically extracted from aliquots of aliquots of sample alkali fusions. The purified Cd solution was analyzed by ICP-MS. Both Cd-113 and a bounding limit for Cd-113m were calculated from the ICP-MS analysis.

2.2 Cs-134,137 Method

Aliquots of peroxide fusion dissolution and aqua regia dissolution were analyzed by coaxial high purity germanium gamma-ray spectrophotometers to measure Cs-134 and Cs-137. Cell reagent blanks were run as controls.

2.3 Assumptions

The following assumptions were used in determining the radionuclide inventory inputs for the RadDecay® v 5.01 calculations:

1. When a radionuclide analysis yielded results that were below the detection limits for the measurement technique, the detection limit was used as the initial activity in the RadDecay® v 5.01 input.
2. Yttrium-90 was assumed to be in secular equilibrium with Sr-90.
3. Californium-252 was assumed to have the same activity as Cm-242. The primary alpha radiation from both radionuclides have nearly identical emission energies and could not be resolved by the detection method. The analysis of Cm-242 was below the detection limit for the method – the detection limit for Cm-242 was used as the initial activity for both Cm-242 and Cf-252.
4. The ratio of Cs-135 to Cs-137 in the supernate, measured via ICPMS, was used to determine the amount of Cs-135 activity to account for in the RadDecay® v 5.01 input. As opposed to the solids analysis, the supernate analysis was used because of Ba-135 interferes with the detection of Cs-135 in the solid. Ba-135 is a stable isotope that is insoluble; therefore, no Ba-135 would interfere with the Cs-135 signal from the supernate.
5. The amount of Ba-137m was calculated from the decay of Cs-137 wherein the Cs-137 radionuclide decays to the metastable Ba-137m approximately 94% of the time. Thus, the amount of Ba-137m was assumed to be 0.946*A_o^{Cs-137} where A_o^{Cs-137} is the initial amount of Cs-137.
6. The amounts of Nb-93m, Pb-210, and Ra-226 were calculated based on methodology given in Appendix B.
7. While Cd-113m was measured, the concentration was determined as an upper bound only. Therefore, the concentration of Cd-113m used in the RadDecay v. 5.01 input deck was calculated from the fission yield.

The assumptions were made to provide a conservative estimate of the radionuclide inventory for the Tank 40 Sludge Batch 9 WAPS sample.

2.4 Quality Assurance

Requirements for performing reviews of technical reports and the extent of review are established in manual E7 2.60 [12]. SRNL documents the extent and type of review using the SRNL Technical Report Design Checklist contained in WSRC-IM-2002-00011, Rev. 2 [13]. Calculations performed using the RadDecay v. 5.01 software are performed in accordance with a software quality assurance plan [14].

3.0 Results and Discussion

Per the Task Technical Request (TTR), the radionuclide composition of the 2017 Tank 40 WAPS sample (HTF-40-17-5) is reported for waste acceptance purposes. The TTR requests data regarding "radionuclides which have half-lives greater than 10 years and those that will be present in greater than 0.01% of the total activity at any time up to 1100 years after production (per WSRC-IM-91-116-4 and WSRC-TR-94-0505)". The TTR also requests data on: "Co-60, Sr-90, Ru-106, Rh-106, Sb-125, Ba-137m, Cs-134, Cs-137, Ce-144, Pr-144, Pm-147, Eu-154, Eu-155, U-233, U-234, U-235, U-236, U-238, Pu-238, Pu-239, Pu-240, Pu-241, Am-241, Am-242m, Cm-244, and Cm-245[7]." The results of the radionuclide analyses were tabulated and are given in Table 3-1 in terms of various parameters. These results form the basis for the determination of reportable radionuclides at the index years as defined by the WAPS [1] and subsequent follow-on memo [2].

Each of the radionuclides shown in Table 3-1 has an associated specific activity [6, 15], weight percent of the total solids [9], activity in terms of dried solids, an activity per gallon of slurry, and the associated relative standard deviation of the replicate analyses. The analytical method for each of the radionuclides is

also shown. The assay date for the radionuclides in Table 3-1, which is also the start date for the index decay calculations, was April 27th, 2017. Activity measurements that were below the detection limit of a given technique do not have an associated relative standard deviation and are marked as N/A in Table 3-1.

Two analyses were performed for Pd-107 because of an unexpected variation in the replicate values reported for the first analysis. The second analysis was conducted in the same fashion as the first, and two of the four replicate samples provided adequate material recovery to complete a Pd-107 measurement. The average of these two measurements was used in the radioactive decay calculations.

The concentrations of Nb-93m and Pb-210 were not directly measured. Therefore, estimated concentrations obtained using decay calculations with an assumption that the waste is 45 years old. Similarly, Cd-113m and Ra-226 were not detected analytically, but the measured detection limits were very high, at levels within the WAPS reportable range. Therefore, in addition to the laboratory upper bounds, calculated upper bounds were provided, which were obtained from fission yield considerations (Cd-113m) and uranium series decay with an assumption that the waste is 45 years old (Ra-226).

The total measured alpha activity of the digested samples was less than 188 μCi/g and the total beta activity was 1.67E+04 μCi/g. The total activity of the sample on a dried solids basis as input into the RadDecay® 5.01 calculations was 1.73E+04 μCi/g (or 71.3 Ci/gal of slurry of Tank 40 Sludge Batch 9).

The two radionuclides in Table 3-2, Rh-106 and Pr-144, were requested to be reported [7] but were not directly measured in the submitted WAPS samples. They are being reported in Table 3-2 as these radionuclides would be in secular equilibrium with their parent nuclides. The activity of the parent nuclides was below the detection limit of the respective methods used in the analysis. These two radionuclides, Rh-106 and Pr-144, were not included in the input deck for the RadDecay v. 5.01 calculations.

Table 3-1: Results of the radionuclide analyses performed by SRNL. The activities on a dried solids basis were used as inputs to the RadDecay 5.01 software. Four replicates were used in each analysis except where otherwise noted.

Nuclide	Specific Activity (Ci/g) [6, 15]	wt% Total Solids [9]	Activity (µCi/g dried solids)	Ci/gal-Slurry	%RSD	Analytical Method
Cl-36	3.30E-02	< 1.20E-04	< 3.97E-02	< 2.31E-05	NA	Cl36
Ni-59	8.08E-02	6.88E-04	5.56E-01	3.23E-04	8.02	Ni59/63
Co-60	1.13E+03	4.39E-08	4.96E-01	2.88E-04	0.62	Cs-removed gamma counting
Ni-63	6.17E+01	1.02E-04	6.29E+01	3.65E-02	6.62	Ni59/63
Se-79	6.97E-02	6.03E-05	4.20E-02	2.44E-05	99.90	Se79
Sr-90	1.36E+02	5.52E-03	7.51E+03	4.36E+00	3.28	Sr90
Y-90	5.44E+05	1.38E-06	7.51E+03	4.36E+00	3.30	Secular equilibrium w/ Sr90
Zr-93	2.51E-03	1.02E-02	2.57E-01	1.49E-04	42.10	ICPMS
Nb-93m	2.83E+02	7.77E-08	2.20E-01	1.28E-04	NA	obtained from Zr93 & est. waste age
Tc-99	1.70E-02	1.64E-03	2.78E-01	1.62E-04	1.25	ICPMS
Ru-106	3.35E+03	< 5.44E-09	< 1.82E-01	< 1.06E-04	NA	Cs-removed gamma counting
Pd-107[1]	5.14E-04	2.52E-04	1.29E-03	7.52E-07	19.6	Pd107
Cd-113m	2.17E+02	< 1.70E-03	< 3.68E+03	< 2.14E+00	NA	LSC/Cd113m
Cd-113m (calc)	2.17E+02	6.77E-07	1.47E+00	8.54E-04	NA	estimated based on fission yield
Sn-121m	5.91E+01	4.90E-07	2.89E-01	1.68E-04	14.80	Sn126/121m
Sb-125	1.03E+03	< 1.31E-08	< 1.35E-01	< 7.82E-05	NA	Cs-removed gamma counting
Te-125m	1.80E+04	< 7.47E-10	< 1.34E-01	< 7.81E-05	NA	Secular equilibrium w/ Sb125
Sn-126	2.84E-02	< 1.42E-04	< 4.04E-02	< 2.35E-05	NA	Cs-removed gamma counting
I-129[2]	1.77E-04	2.46E-03	4.35E-03	2.53E-06	9.39	I-129
Ba-133	2.50E+02	< 2.79E-08	< 6.99E-02	< 4.06E-05	NA	Cs-removed gamma counting
Cs-134	1.29E+03	< 3.40E-08	< 4.39E-01	< 2.55E-04	NA	gamma
Cs-135	1.15E-03	4.19E-04	4.82E-03	2.80E-06	NA	ratio of Cs135/Cs137 supernate applied
Cs-137	8.70E+01	1.03E-03	8.96E+02	5.20E-01	2.56	gamma
Ba-137m	5.38E+08	1.57E-10	8.47E+02	4.92E-01	NA	= 0.946 x Cs137 activity
Ce-144	3.19E+03	< 1.99E-08	< 6.34E-01	< 3.69E-04	NA	Cs-removed gamma counting
Pm-147	9.27E+02	< 1.04E-05	< 9.64E+01	< 5.60E-02	NA	Pm147/Sm151
Sm-151	2.63E+01	5.03E-04	1.32E+02	7.69E-02	5.86	Pm147/Sm151
Eu-154	2.70E+02	2.07E-06	5.58E+00	3.24E-03	5.33	Cs-removed gamma counting
Eu-155	4.65E+02	2.10E-07	9.78E-01	5.68E-04	26.90	Cs-removed gamma counting
Pb-210	7.63E+01	< 7.55E-13	5.76E-07	< 2.38E-09	NA	calculated from uranium series & est. waste age
Ra-226	9.89E-01	< 1.81E-07	< 1.79E-03	< 1.04E-06	NA	Ra226
Ra-226 (calc)	9.89E-01	< 1.29E-10	1.28E-06	< 5.29E-09	NA	calculated from uranium series & est. waste age
Ac-227	7.23E+01	1.55E-09	1.12E-03	6.53E-07	30.80	Th229/230
Th-229	2.13E-01	< 1.11E-07	< 2.36E-04	< 1.37E-07	NA	Th229/230
Th-230	2.11E-02	< 3.57E-07	< 7.53E-05	< 4.38E-08	NA	Th229/230
Pa-231	4.72E-02	< 5.35E-05	< 2.52E-02	< 1.47E-05	NA	Pa231
Th-232	1.10E-07	7.56E-01	8.31E-04	4.83E-07	0.90	ICPMS
U-233	9.68E-03	6.88E-04	6.66E-02	3.87E-05	1.49	ICPMS
U-234	6.25E-03	7.64E-04	4.77E-02	2.77E-05	1.10	U-ICPMS
U-235	2.16E-06	3.07E-02	6.62E-04	3.85E-07	0.63	ICPMS
U-236	6.47E-05	1.83E-03	1.19E-03	6.90E-07	1.57	U-ICPMS
Np-237	7.05E-04	2.74E-03	1.93E-02	1.12E-05	1.56	ICPMS
U-238	3.36E-07	2.97E+00	9.97E-03	5.79E-06	1.15	U-ICPMS
Pu-238	1.71E+01	7.62E-04	1.30E+02	7.57E-02	9.61	Pu238/241
Pu-239	6.22E-02	8.86E-03	5.51E+00	3.20E-03	1.04	ICPMS
Pu-240	2.28E-01	8.59E-04	1.96E+00	1.14E-03	2.98	ICPMS
Pu-241	1.03E+02	2.62E-05	2.69E+01	1.57E-02	8.82	Pu238/241
Am-241	3.43E+00	5.00E-04	1.72E+01	9.97E-03	2.72	Cs-removed gamma counting
Pu-242	3.82E-03	< 1.13E-04	< 4.32E-03	< 2.51E-06	NA	ICPMS
Am-242m[2]	9.72E+00	2.43E-07	2.36E-02	1.37E-05	19.90	AmCm
Cm-242[2]	3.31E+03	5.90E-10	1.95E-02	1.14E-05	19.80	AmCm
Am-243	1.99E-01	8.95E-05	1.78E-01	1.03E-04	16.00	AmCm
Cm-243	5.16E+01	< 2.14E-07	< 1.10E-01	< 6.40E-05	NA	AmCm
Cm-244	8.09E+01	7.23E-06	5.85E+00	3.40E-03	14.60	AmCm
Cm-245	1.72E-01	5.66E-07	9.74E-04	5.66E-07	15.70	AmCm-ICPMS
Cm-246	3.07E-01	9.24E-07	2.84E-03	1.65E-06	16.00	AmCm-ICPMS
Cm-247	9.28E-05	1.50E-08	1.39E-08	8.06E-12	16.30	AmCm-ICPMS
Bk-247	1.03E+00	< 1.24E-08	< 1.28E-04	< 7.43E-08	NA	AmCm-ICPMS
Cm-248	4.25E-03	< 2.04E-08	< 8.65E-07	< 5.03E-10	NA	AmCm-ICPMS
Cf-249	4.38E+00	< 8.78E-09	< 3.85E-04	< 2.23E-07	NA	AmCm
Cf-250	1.09E+02	< 2.35E-13	< 2.56E-07	< 1.49E-10	NA	AmCm-ICPMS
Cf-251	1.86E+00	< 5.32E-08	< 9.90E-04	< 5.75E-07	NA	AmCm
Cf-252	5.38E+02	< 3.62E-09	< 1.95E-02	< 1.14E-05	NA	AmCm

[1] Only two of the four replicates yielded sufficient material recovery to perform an analysis for Pd-107.
[2] Three replicate samples were averaged for I-129, Cm-242, and Am-242m.

Table 3-2: Concentrations of Rh-106 and Pr-144.

Nuclide	Specific Activity (Ci/g)	wt% Total Solids	Activity (µCi/g dried solids)	Ci/gal-Slurry	Analytical Method
Rh-106	3.54E+09	< 5.14E-15	< 1.82E-01	< 1.06E-04	secular equilibrium w/ Ru-106
Pr-144	7.56E+07	< 8.39E-13	< 6.34E-01	< 3.69E-4	secular equilibrium w/ Ce-144

3.1 Determination of Reportable Radionuclides

The commercially available software RadDecay® version 5.01 [16-18]was used to identify reportable radionuclides through calendar year 3115 at the specified index years. The initial activities were entered into RadDecay based on the analytical results of the Tank 40 SB9 WAPS samples as given in Table 3-1. The assay date for the radionuclide analysis was April 27th, 2017 – this day was used as the initial date in the decay calculations as directed by DWPF [3]. Calculations were performed in 100-year intervals except for the initial interval, which was 98 years per the aforementioned directive. The concentrations of all radionuclides present at the various index years are given in Appendix C. The ICRP-107 library [19] was used for half-life data for the decay calculations.

The RadDecay® v 5.01 software was benchmarked against Scale 6.1 [17, 18, 20], which is a modeling and simulation suite for nuclear safety analysis and design[3]. The RadDecay® v 5.01 software proved acceptable for WAPS compliance use [18].

The total activity of the dried sludge as input into the RadDecay calculations at year 2017 was 1.73E+04 µCi/g. The activity of only the radionuclides that were reportable at year 2017 was 8.79E+03 µCi/g. The total activity of the sludge in 3115 is 1.80E+01 µCi/g of which 1.22E+01 µCi/g is coming from reportable radionuclides. The discrepancies between the total activity of the sludge batch and the activity attributable to reportable radionuclides is caused by radionuclides with half-lives shorter than 10 years contributions to the total activity. The total activity and reportable radionuclide activity of SB9 is shown in Figure 3-1.

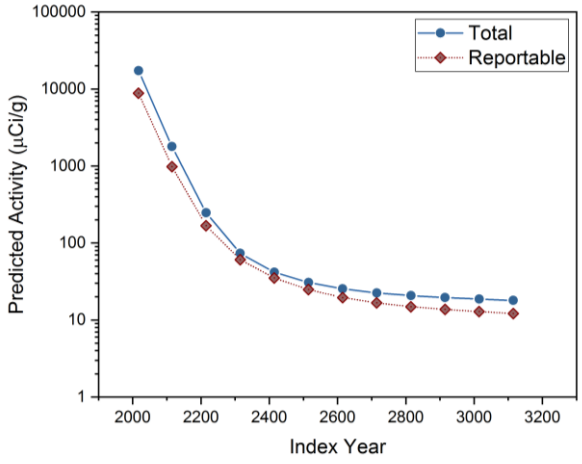

Figure 3-1: The total and reportable radioactivity of Tank 40 SB9 as measured for 2017 and predicted for the index years through 3115 by RadDecay v. 5.01. At each index year including 2017, the discrepancy between the total and reportable activity is attributable to radionuclides with half-lives of less than 10 years.

[3] A newer version of Scale was released prior to the writing of this document; however, it was assumed that the results of the decay calculations between the newest version and version 6.1 did not change.

Twenty-nine radionuclides were identified as being reportable at some point throughout the 1100-year duration. These nuclides are shown in Table 3-3.

Table 3-3: Reportable radionuclides in SB9 as identified by radionuclide analysis and predicted by the RadDecay v 5.01 software for the 1100-year duration outline in the WAPS

Cl-36	**Zr-93**	**Sm-151**	**Np-237**	**Pu-241**
Ni-59	**Tc-99**	**Ac-227**	**Pu-238**	**Pu-242**
Ni-63	**Sn-126**	**Th-229**	**U-238**	**Am-243**
Se-79	**I-129**	**Pa-231**	**Pu-239**	**Cm-244**
Sr-90	**Cs-135**	**U-233**	**Pu-240**	**Cm-246**
Nb-93m	**Cs-137**	**U-234**	**Am-241**	

Figure 3-2 is a matrix of the reportable elements denoting which index years a specific radionuclide is reportable.

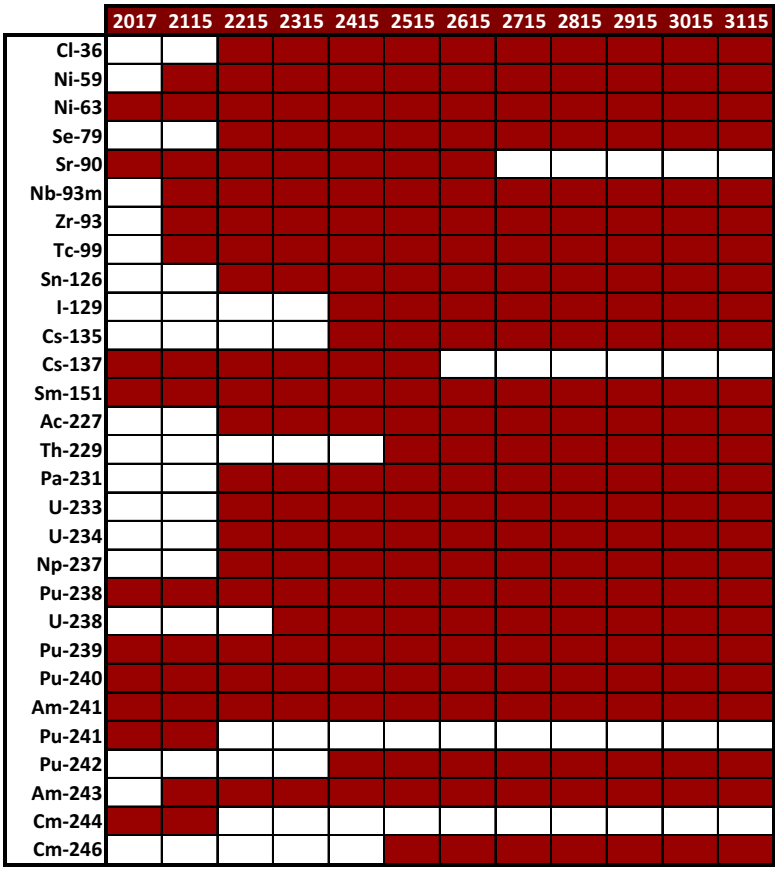

Figure 3-2: The reportability matrix for SB9 index years 2017 through 3115 – cells highlighted in red indicate that a radionuclide is reportable at that year.

The activities of individual reportable radionuclides as well as their activities' contribution to the total activity of the sludge batch at each index year are given in Appendix A.

3.2 IAEA Safeguards Reportable Radionuclides

In accordance with criteria set forth in the Waste Form Qualification Report, Revision 4, "Reporting the Radionuclide Inventory of the DWPF Product [2]":

DWPF must also report the inventories of plutonium and uranium to comply with International Atomic Energy Agency (IAEA) requirements. The following information must be provided for each canister produced by DWPF:

- *The total content of uranium and plutonium, in grams, and the concentration of plutonium per cubic meter. Canisters with more than 2500 g Pu/m^3 may be subject to additional safeguards.*
- *The mass ratios of U-233, U-234, U-235, U-236, and U-238 to the total uranium content.*
- *The mass ratios of Pu-238, Pu-239, Pu-240, Pu-241, and Pu-242 to total plutonium content.*

As such, these uranium and plutonium radionuclides are presented in this section. Tables 3-4 and 3-5 show the distribution of uranium and plutonium isotopes and determined for SB9 from the 2017 Tank 40 WAPS Sample.

Table 3-4: Distribution of uranium isotopes as measured for SB9.

Isotope	wt.% Total Solids	Percent Distribution (%) of Total U
U-233	6.88E-04	0.02
U-234	7.64E-04	0.03
U-235	3.07E-02	1.02
U-236	1.83E-03	0.06
U-238	2.97E+00	98.9
Total	3.00E+00	

Table 3-5: Distribution of plutonium isotopes as measured for SB9.

Isotope	wt.% Total Solids	Percent Distribution (%) of Total Pu
Pu-238	7.62E-04	7.18
Pu-239	8.86E-03	83.4
Pu-240	8.59E-04	8.09
Pu-241	2.62E-05	0.25
Pu-242	1.13E-04	1.07
Total	1.06E-02	

All of the Pu isotopes as well as U-233, U-234, and U-238 were identified as reportable with respect to the criteria set forth in the WAPS in terms of half-life and concentration. In addition, U-235 and U-236 are reportable for compliance with IAEA safeguards.

4.0 Conclusions

Twenty-nine radionuclides were identified as reportable using the criteria set forth by WAPS 1.2[1] and WQR [2]. In addition, two uranium isotopes are also reportable according to IAEA safeguards [5, 6]. The reportable radionuclides meeting the criteria are presented in Table 4-1.

Table 4-1: Radionuclides identified as reportable in DWPF SB9.

WAPS/WQR Criteria ($T_{1/2}$ > 10 years, Activity > 0.01%)	**Cl-36**	**Zr-93**	**Sm-151**	**Np-237**	**Pu-241**
	Ni-59	**Tc-99**	**Ac-227**	**Pu-238**	**Pu-242**
	Ni-63	**Sn-126**	**Th-229**	**U-238**	**Am-243**
	Se-79	**I-129**	**Pa-231**	**Pu-239**	**Cm-244**
	Sr-90	**Cs-135**	**U-233**	**Pu-240**	**Cm-246**
	Nb-93m	**Cs-137**	**U-234**	**Am-241**	
IAEA	**U-235**			**U-236**	

5.0 References

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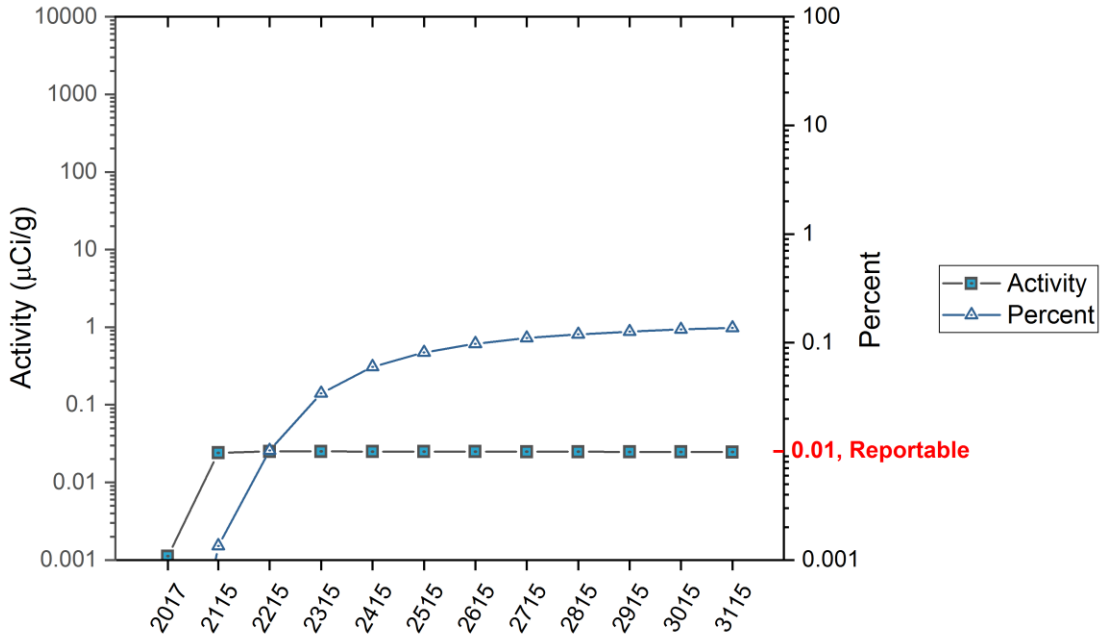
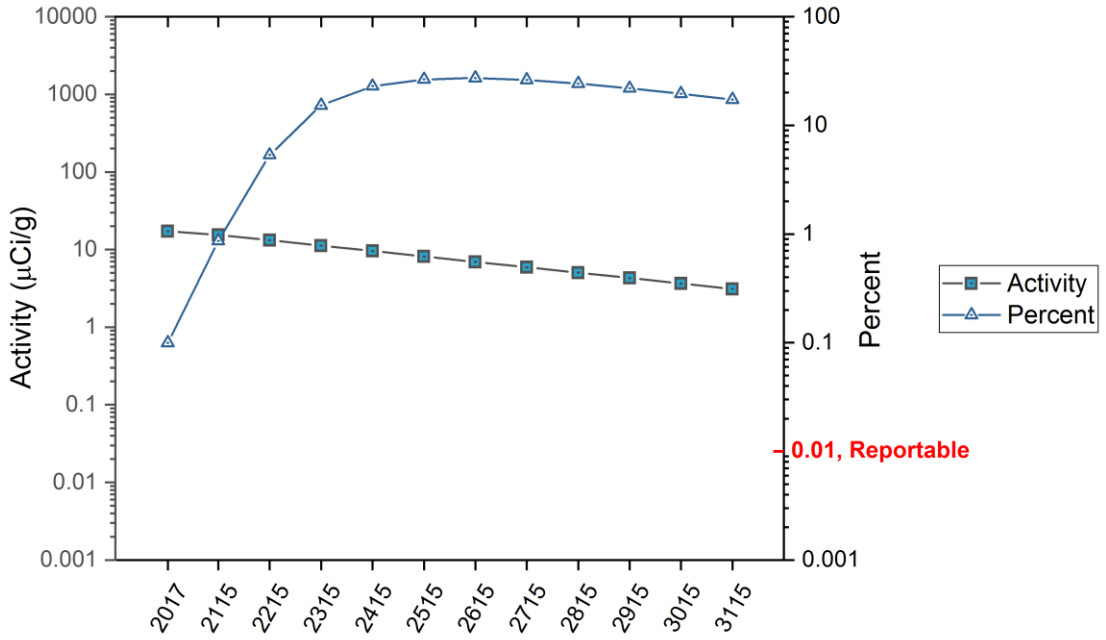
Appendix A**: Individual radionuclide concentrations.**

Ac-227



Am-241



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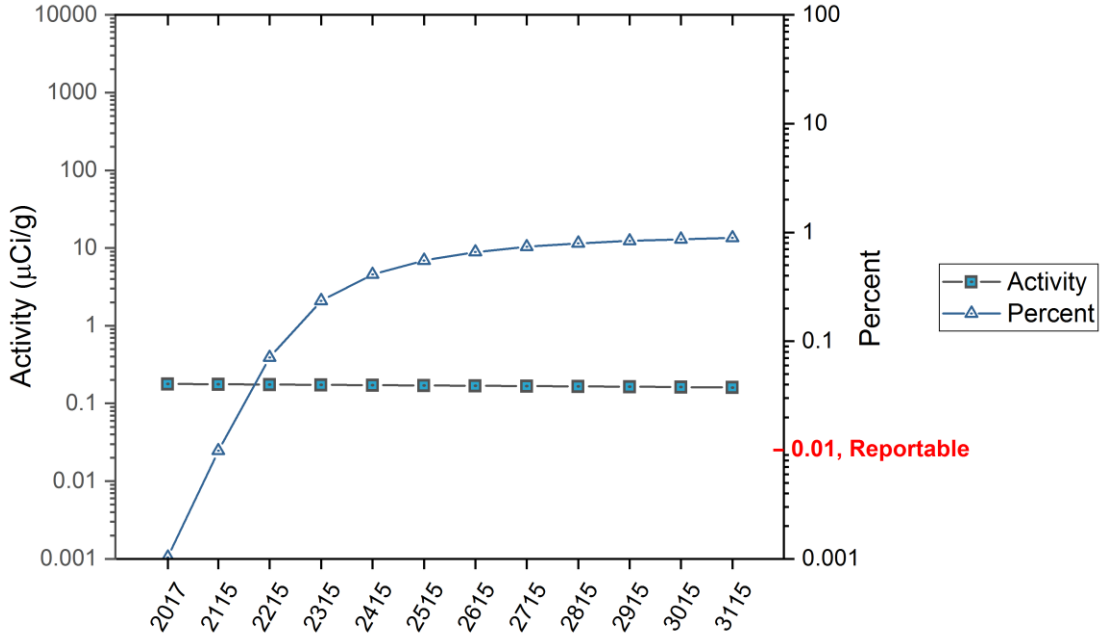
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Percent
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1000
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0.1
0.01
0.001
100
10
1
0.1
0.01, Reportable
0.001
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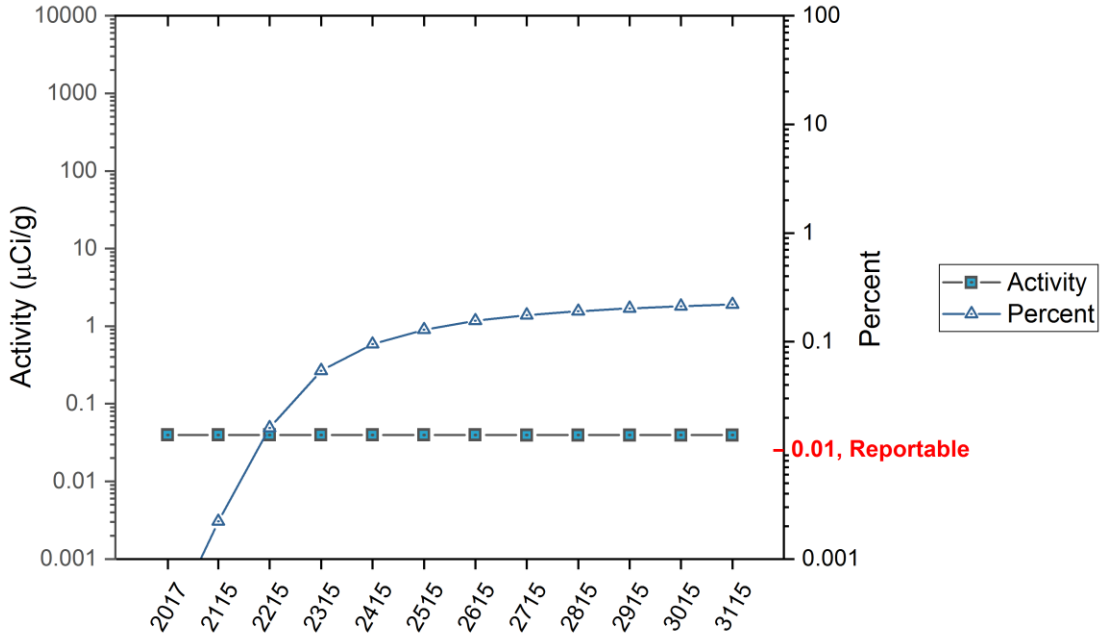
2315
2415
2515
2615
2715
2815
2915
3015
3115
Activity
Percent

Cl-36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0.01
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100
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0.001
2017
2115
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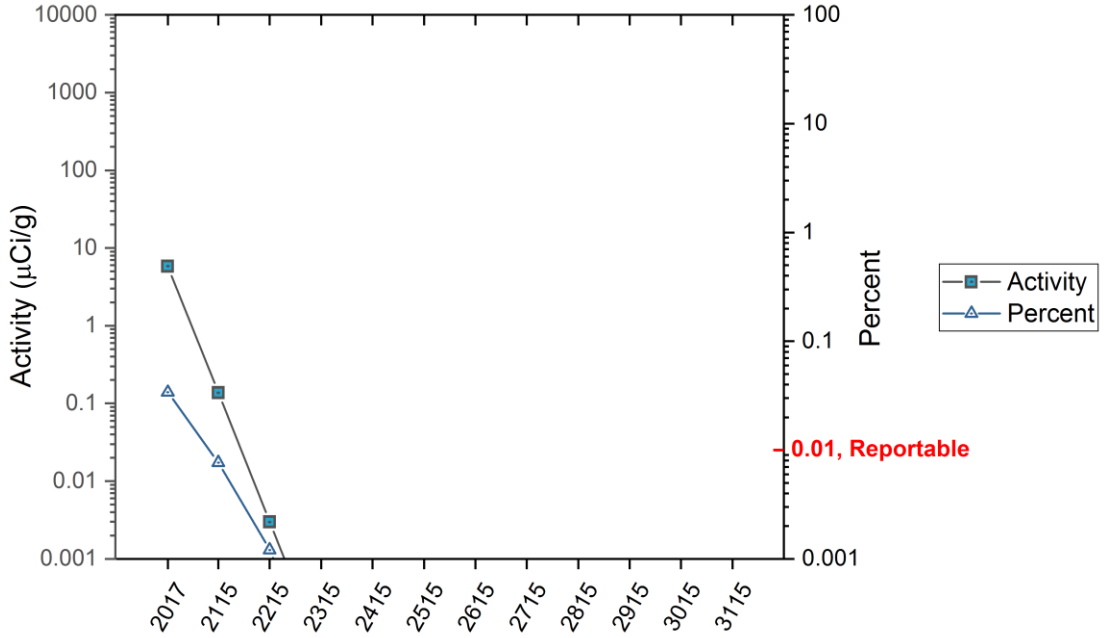
2315
2415
2515
2615
2715
2815
2915
3015
3115
Activity
Percent

Cm-244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0.01, Reportable
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Percent
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2415
2515
2615
2715
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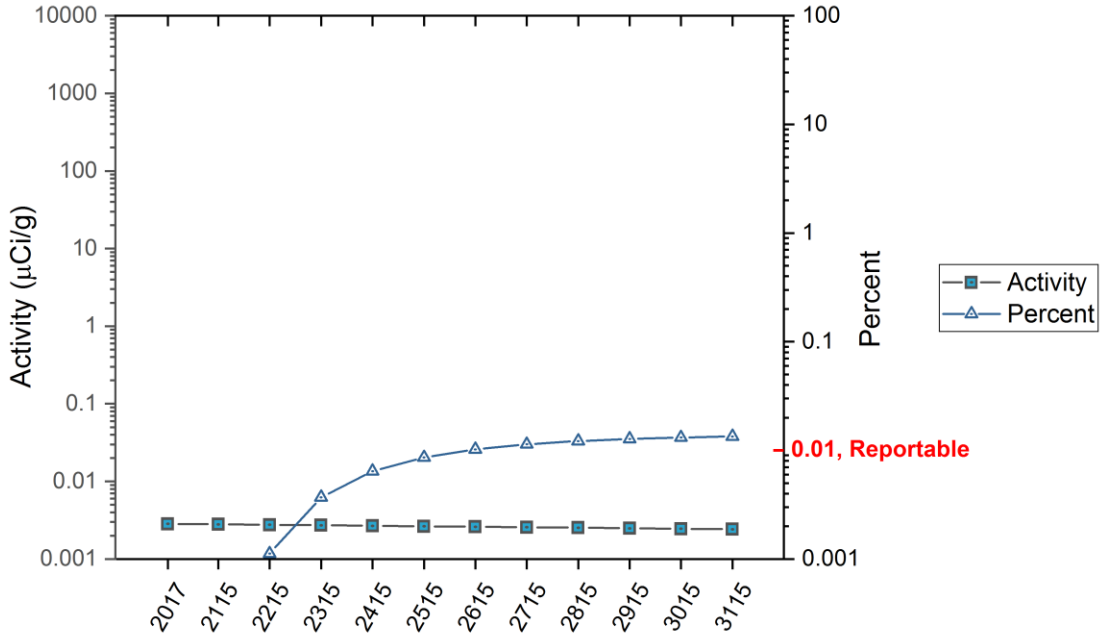
2915
3015
3115

Cm-246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0.01, Reportable
Activity
Percent
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2415
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2615
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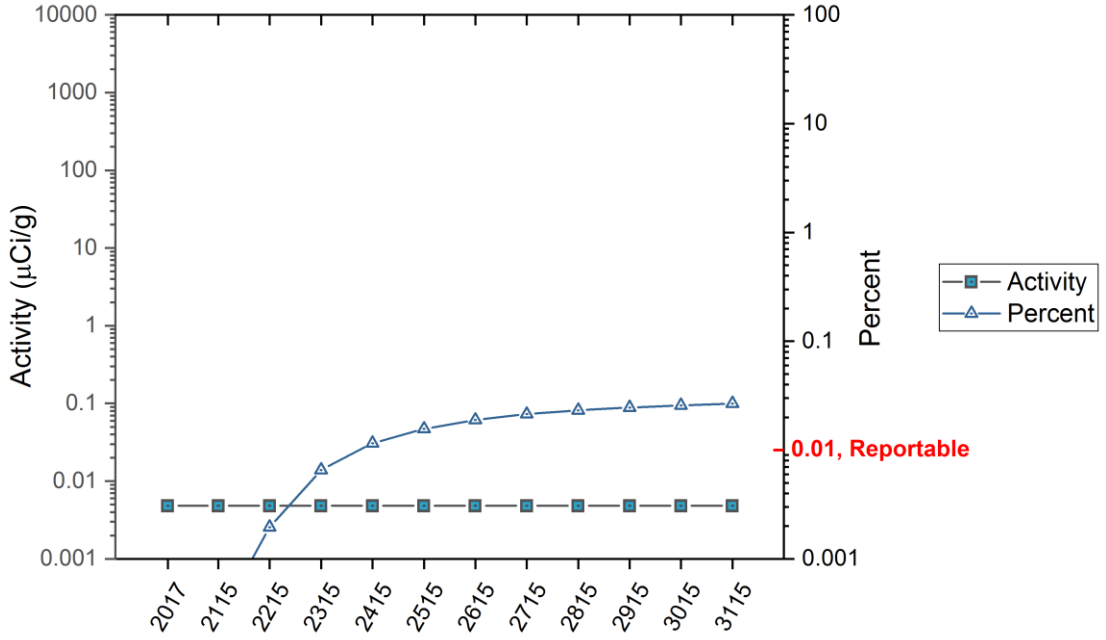
2915
3015
3115

Cs-135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Percent
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2715
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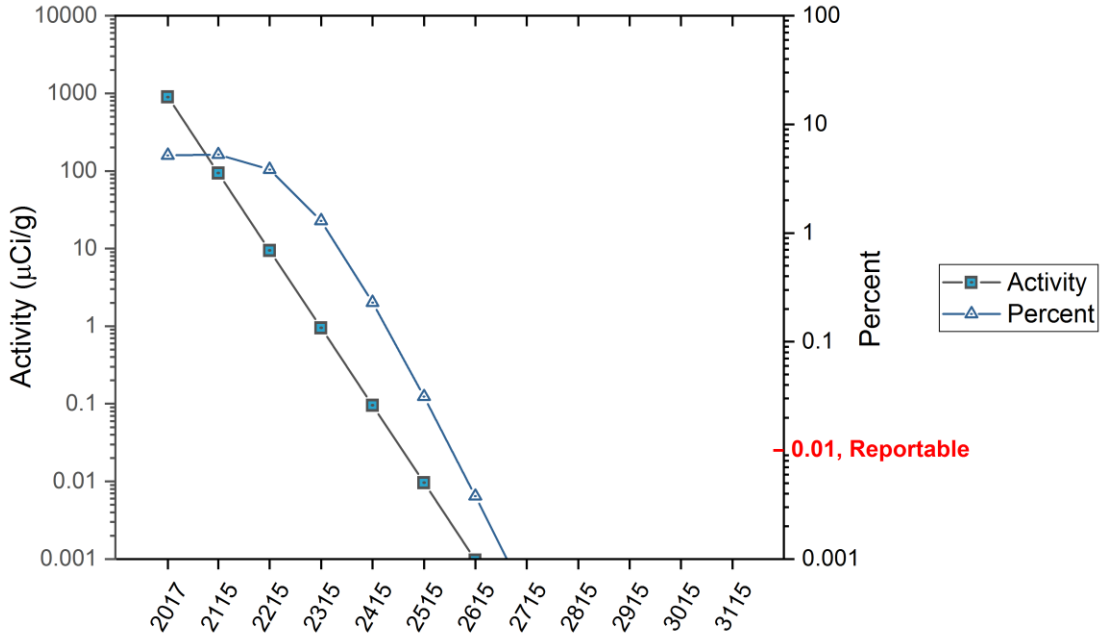
2915
3015
3115

Cs-137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Percent
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Percent
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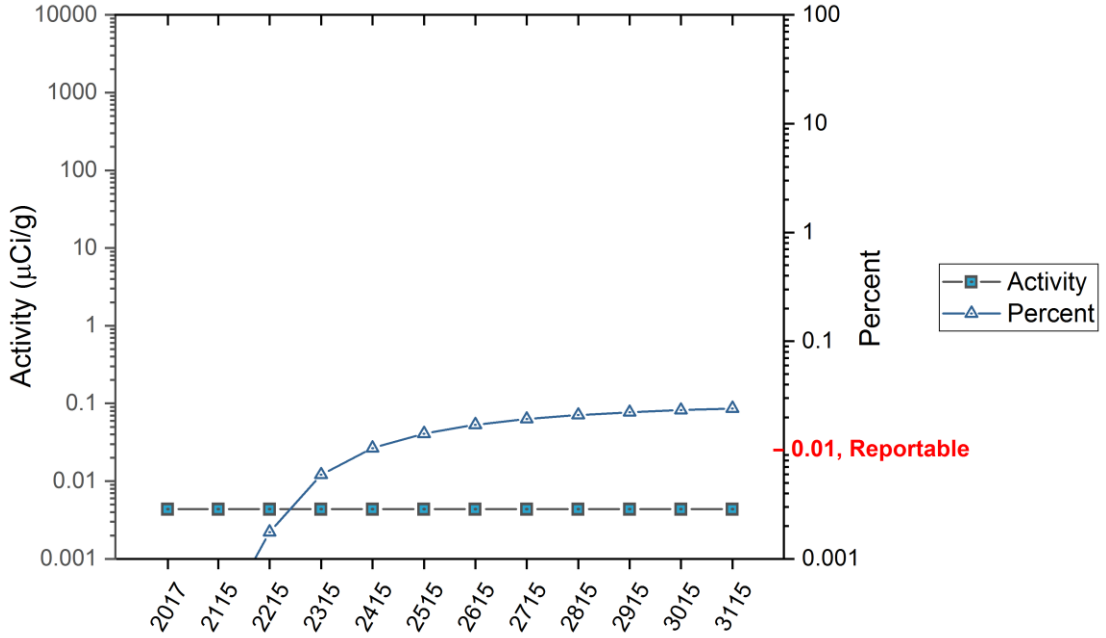
2915
3015
3115

I-129


Activity (µCi/g)
Percent
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1000
100
10
1
0.1
0.01
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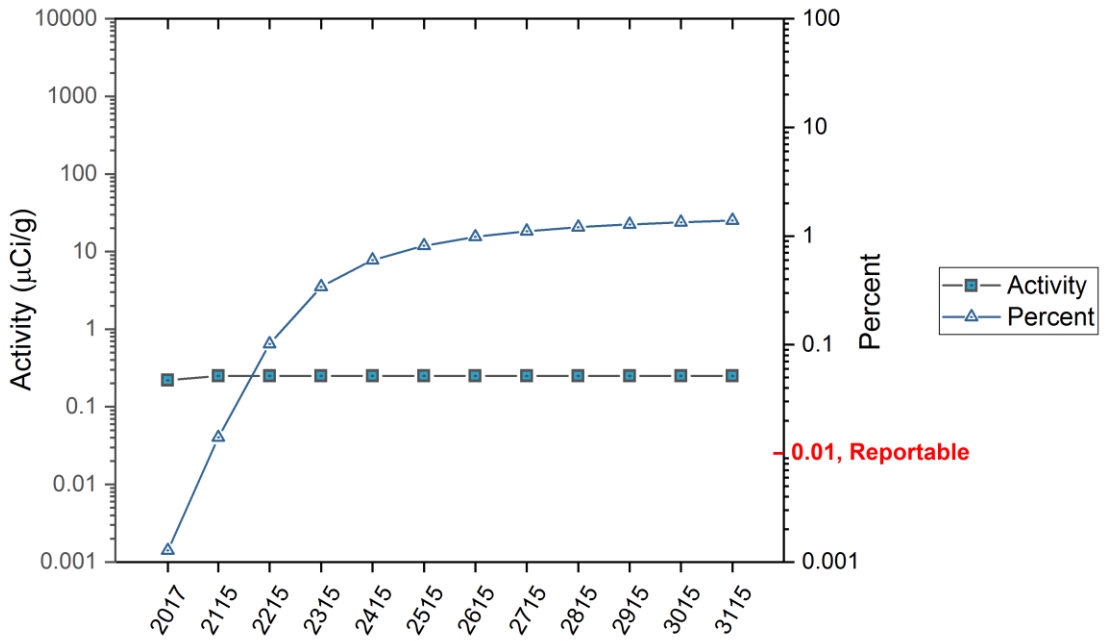
100
10
1
0.1
0.001
0.01, Reportable
Activity
Percent
2017
2115
2215
2315
2415
2515
2615
2715
2815
2915
3015
3115

Nb-93m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1
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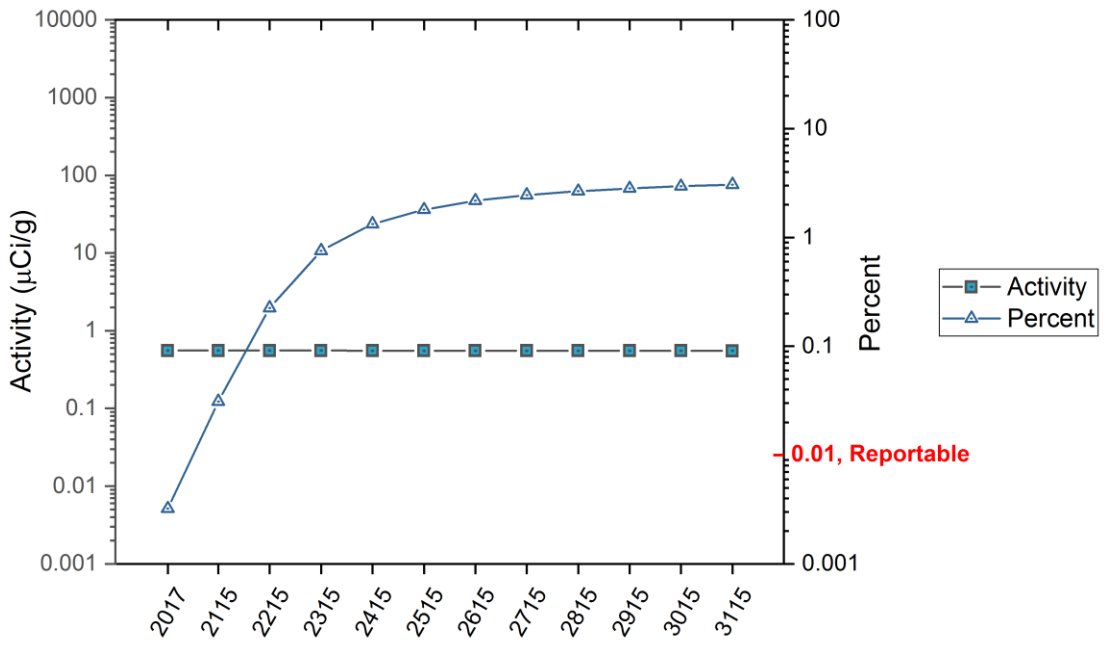
0.001
0.01, Reportable
Activity
Percent
2017
2115
2215
2315
2415
2515
2615
2715
2815
2915
3015
3115

Ni-59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Activity (µCi/g)
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Percent
0.01, Reportable
Activity
Percent
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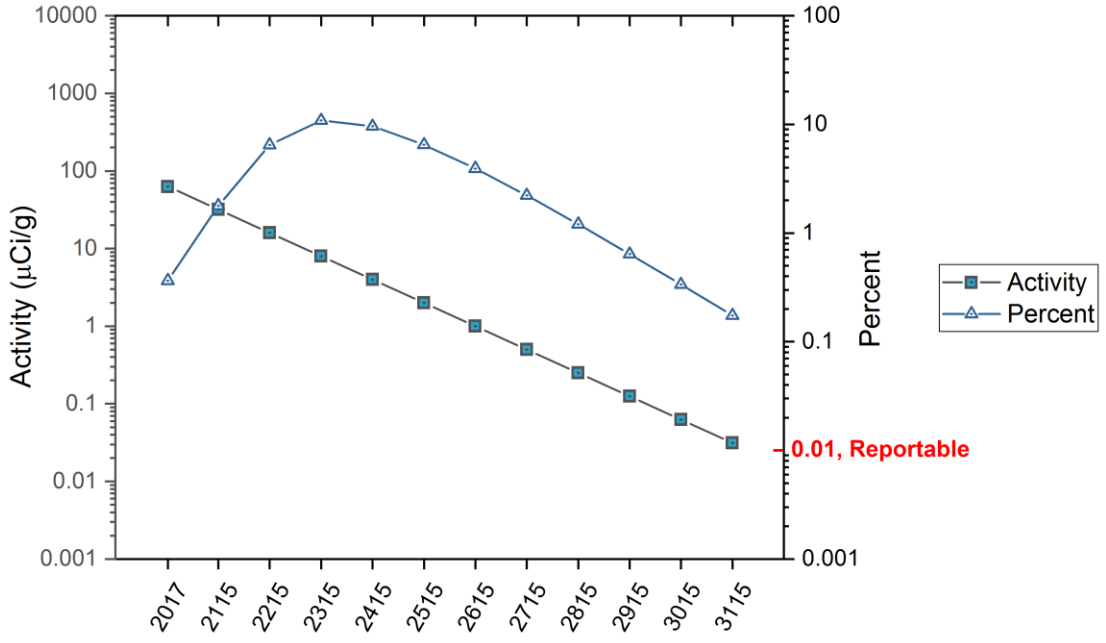
2215
2315
2415
2515
2615
2715
2815
2915
3015
3115

Ni-63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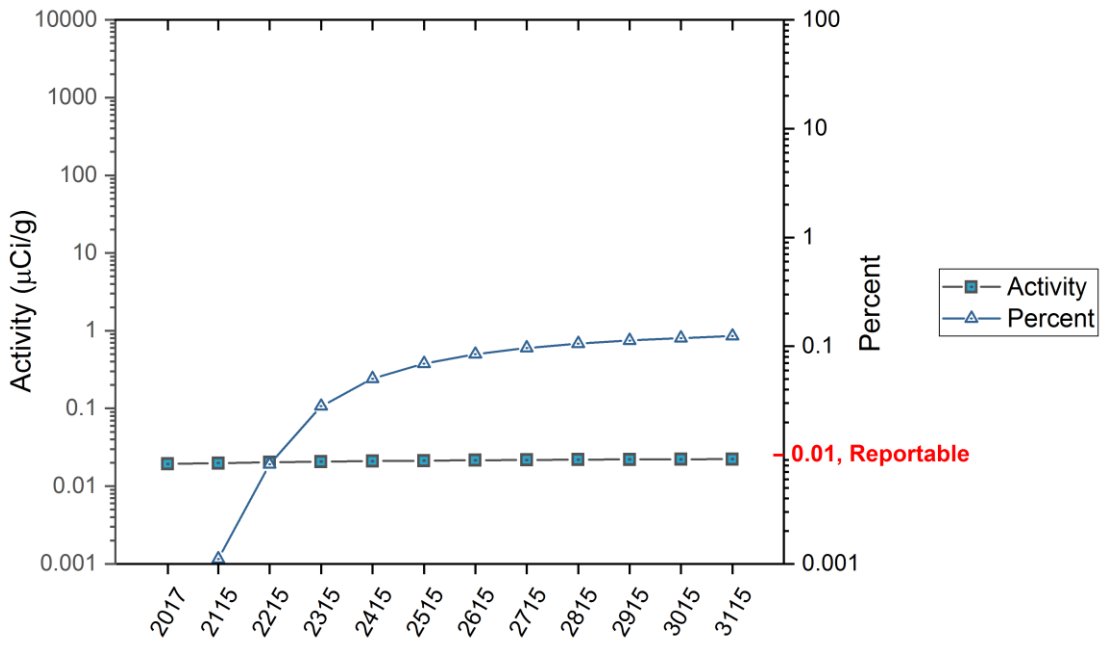
0.001
Percent
0.01, Reportable
Activity
Percent
2017
2115
2215
2315
2415
2515
2615
2715
2815
2915
3015
3115

Np-237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1
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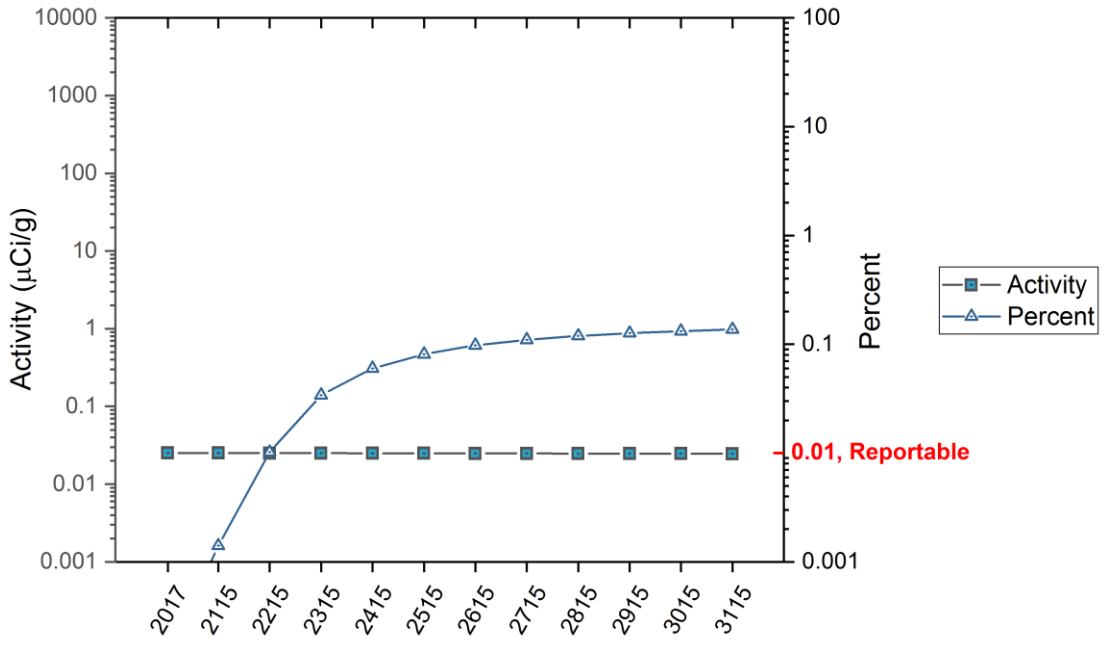
0.01
0.001
Activity
Percent
0.01, Reportable
2017
2115
2215
2315
2415
2515
2615
2715
2815
2915
3015
3115

Pa-231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0.1
0.01
0.001
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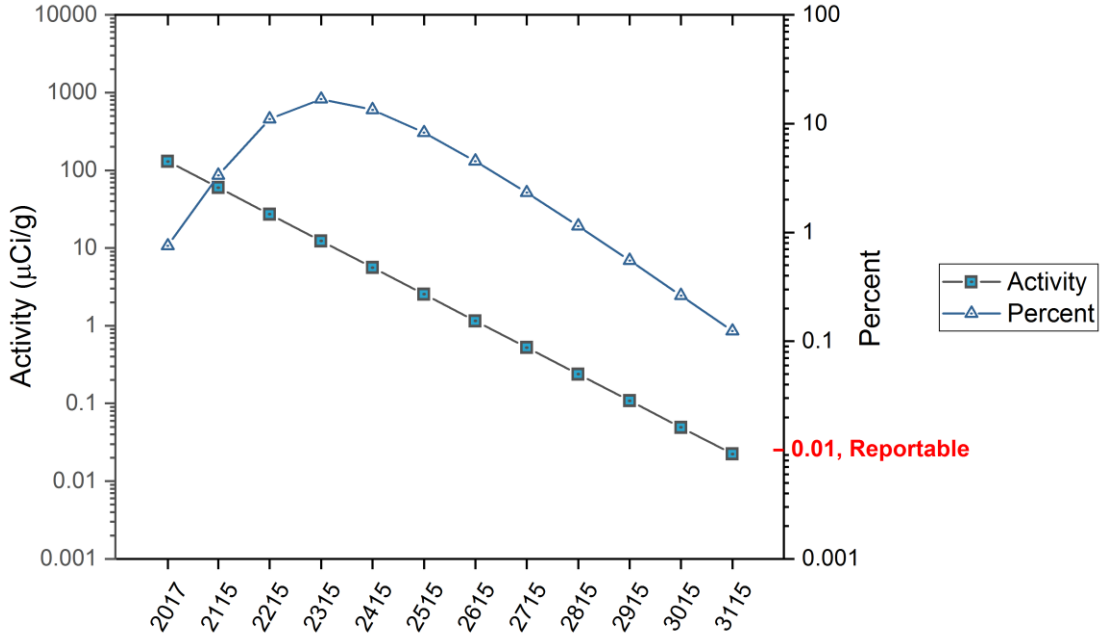
10
1
0.1
0.01
0.001
Activity
Percent
0.01, Reportable
2017
2115
2215
2315
2415
2515
2615
2715
2815
2915
3015
3115

Pu-238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0.01
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Activity (µCi/g)
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10
1
0.1
0.001
Percent
0.01, Reportable
Activity
Percent
2017
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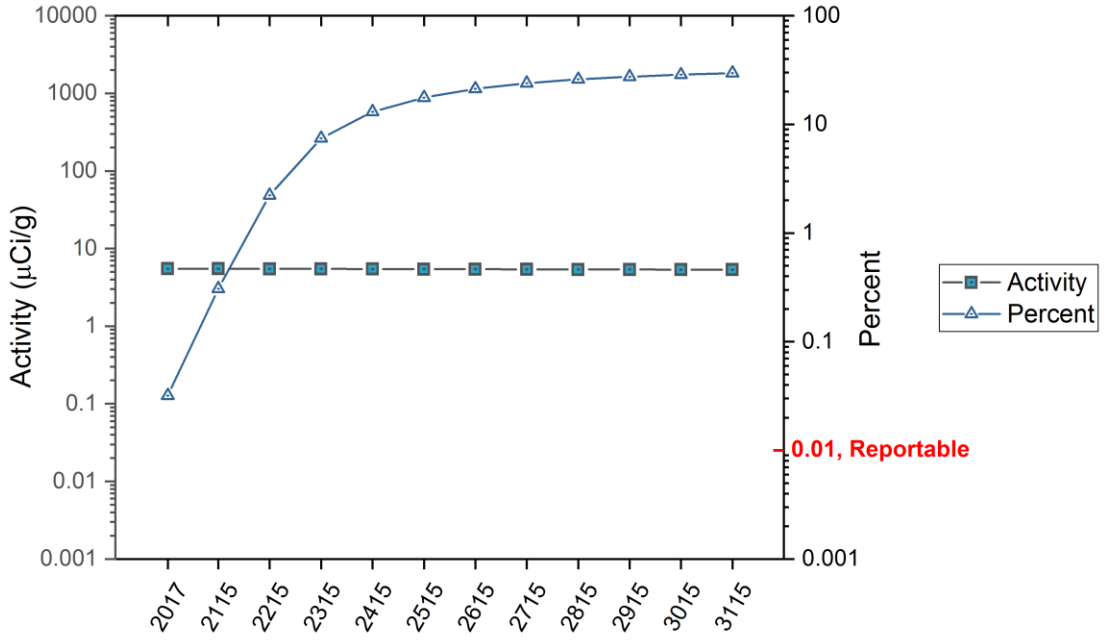
2215
2315
2415
2515
2615
2715
2815
2915
3015
3115

Pu-239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Activity (µCi/g)
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10
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0.1
0.001
Percent
0.01, Reportable
Activity
Percent
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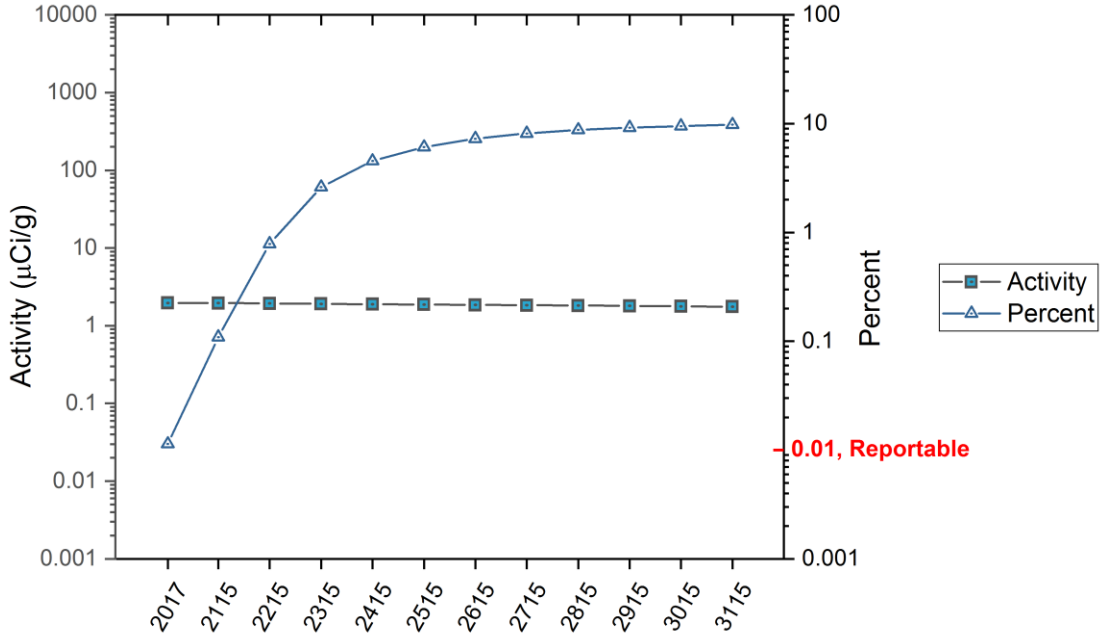
2115
2215
2315
2415
2515
2615
2715
2815
2915
3015
3115

Pu-240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Activity (µCi/g)
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10
1
0.1
0.001
Percent
0.01, Reportable
Activity
Percent
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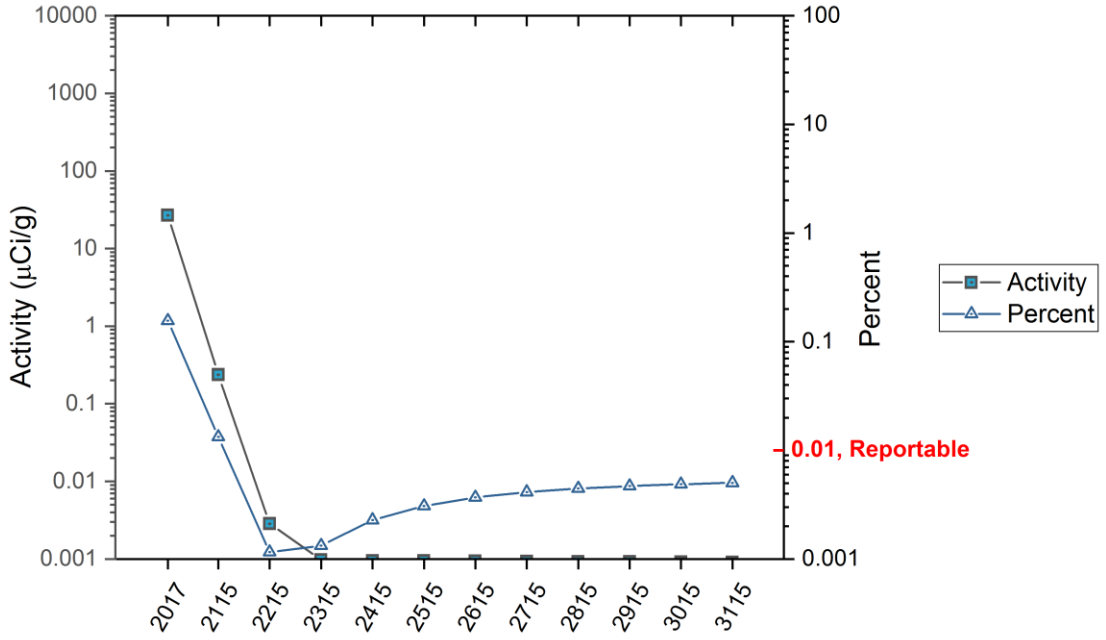
2315
2415
2515
2615
2715
2815
2915
3015
3115

Pu-241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10
1
0.1
0.01
0.001
Activity (µCi/g)
100
10
1
0.1
0.001
Percent
0.01, Reportable
Activity
Percent
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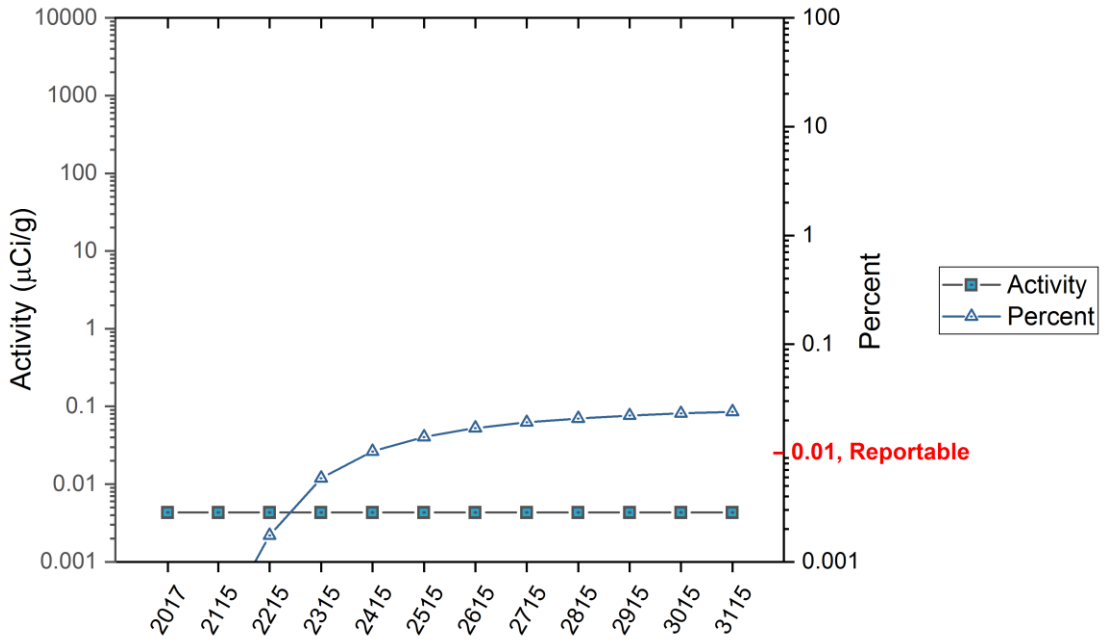
2115
2215
2315
2415
2515
2615
2715
2815
2915
3015
3115

Pu-242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Activity (µCi/g)
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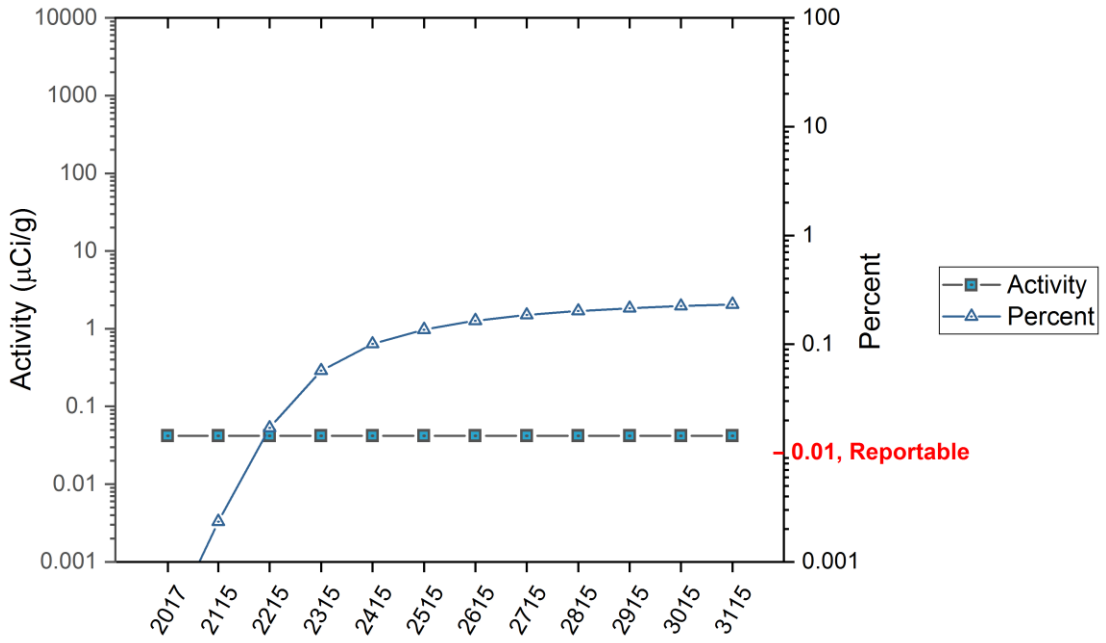
0.1
0.001
Percent
0.01, Reportable
Activity
Percent
2017
2115
2215
2315
2415
2515
2615
2715
2815
2915
3015
3115

Se-79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Activity (µCi/g)
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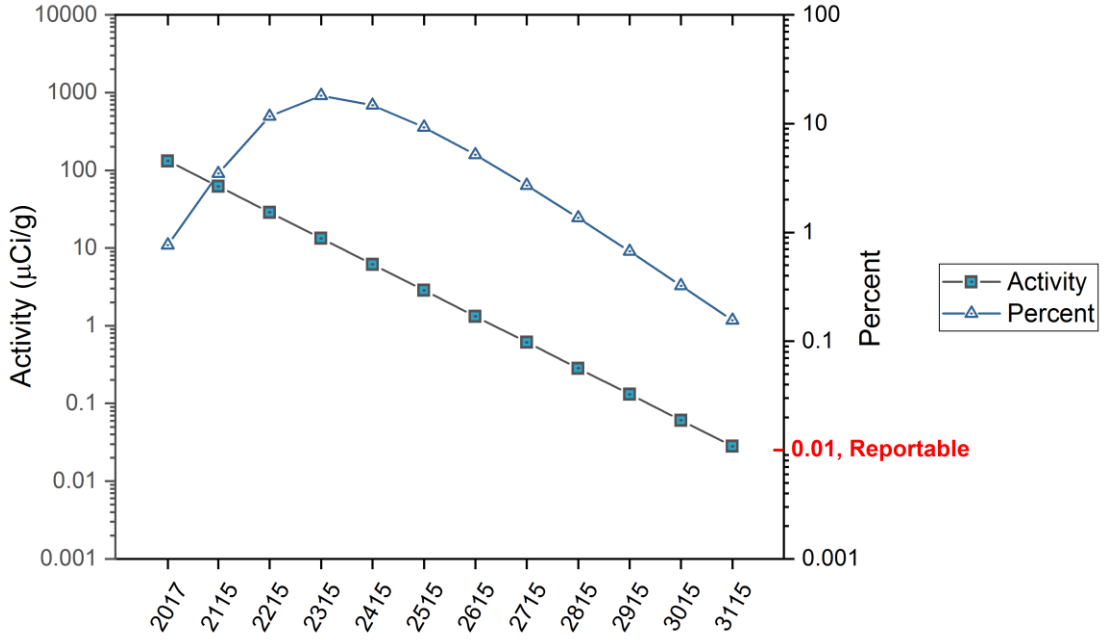
Percent
0.01, Reportable
Activity
Percent
2017
2115
2215
2315
2415
2515
2615
2715
2815
2915
3015
3115

Sm-151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Activity (µCi/g)
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Percent
0.01, Reportable
Activity
Percent
2017
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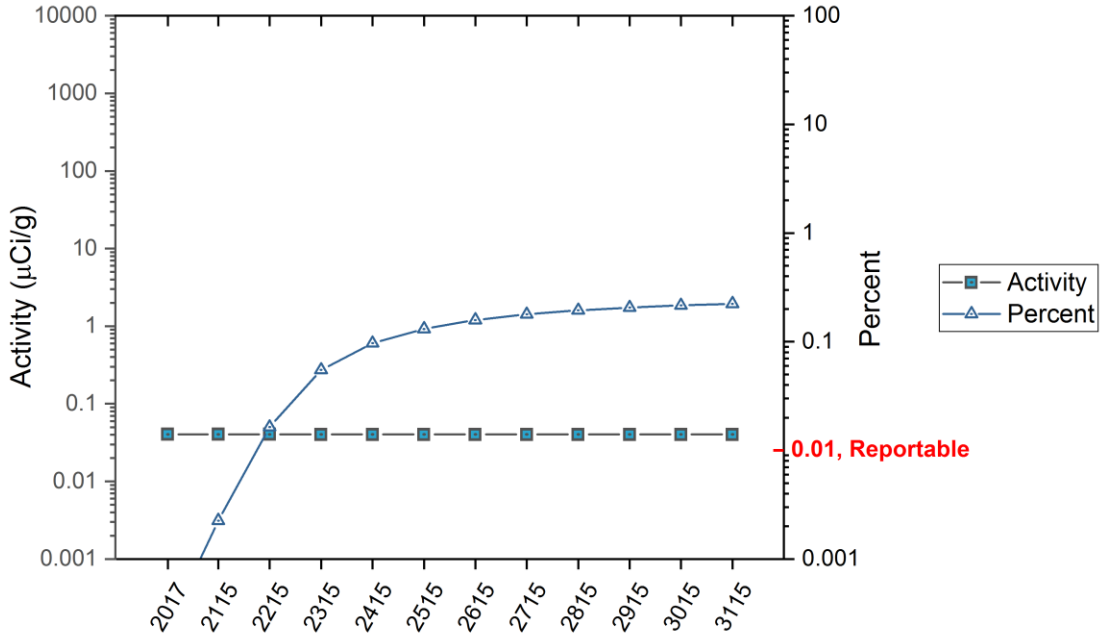
2215
2315
2415
2515
2615
2715
2815
2915
3015
3115

Sn-126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0.001
Activity (µCi/g)
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10
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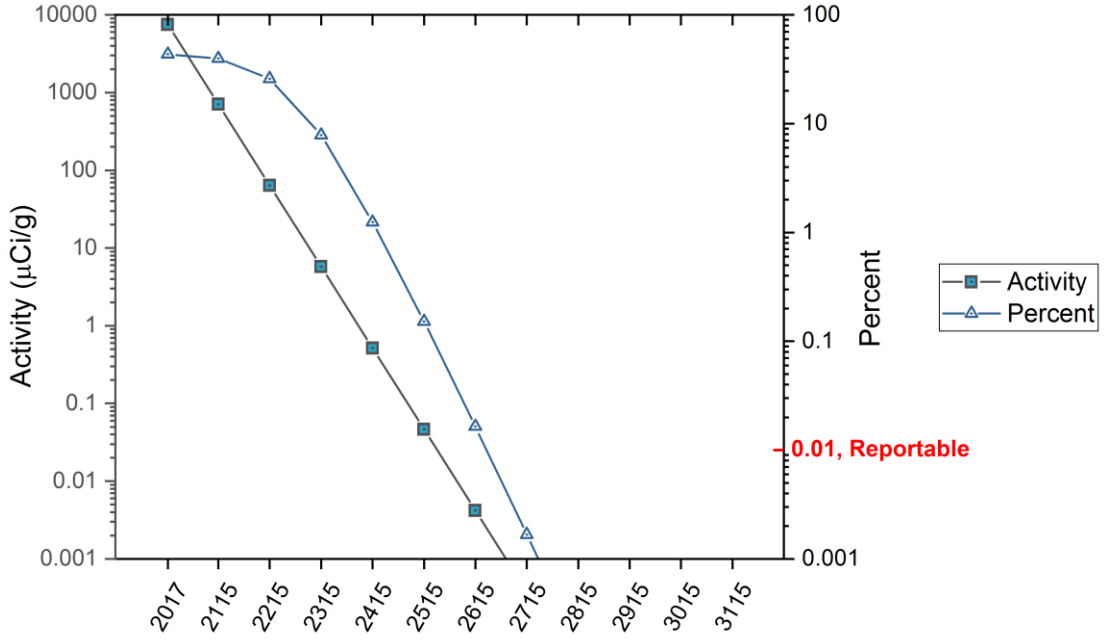
0.1
0.001
Percent
0.01, Reportable
Activity
Percent
2017
2115
2215
2315
2415
2515
2615
2715
2815
2915
3015
3115

Sr-90


10000
1000
100
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1
0.1
0.01
0.001
Activity (µCi/g)
100
10
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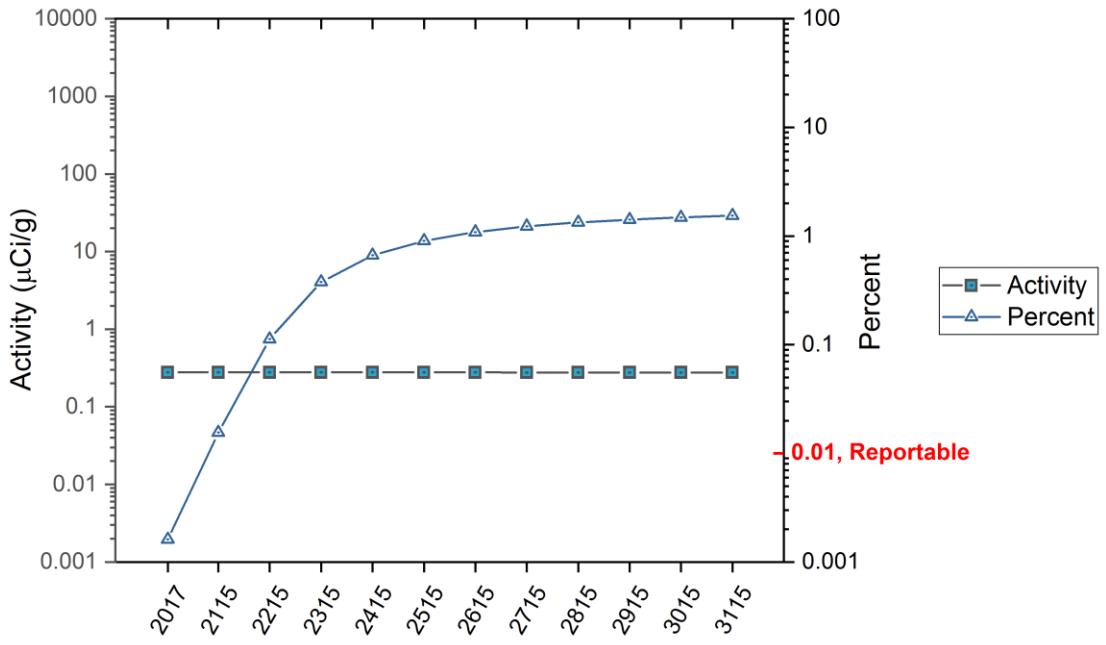
0.1
0.001
Percent
0.01, Reportable
Activity
Percent
2017
2115
2215
2315
2415
2515
2615
2715
2815
2915
3015
3115

Tc-99


10000
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100
10
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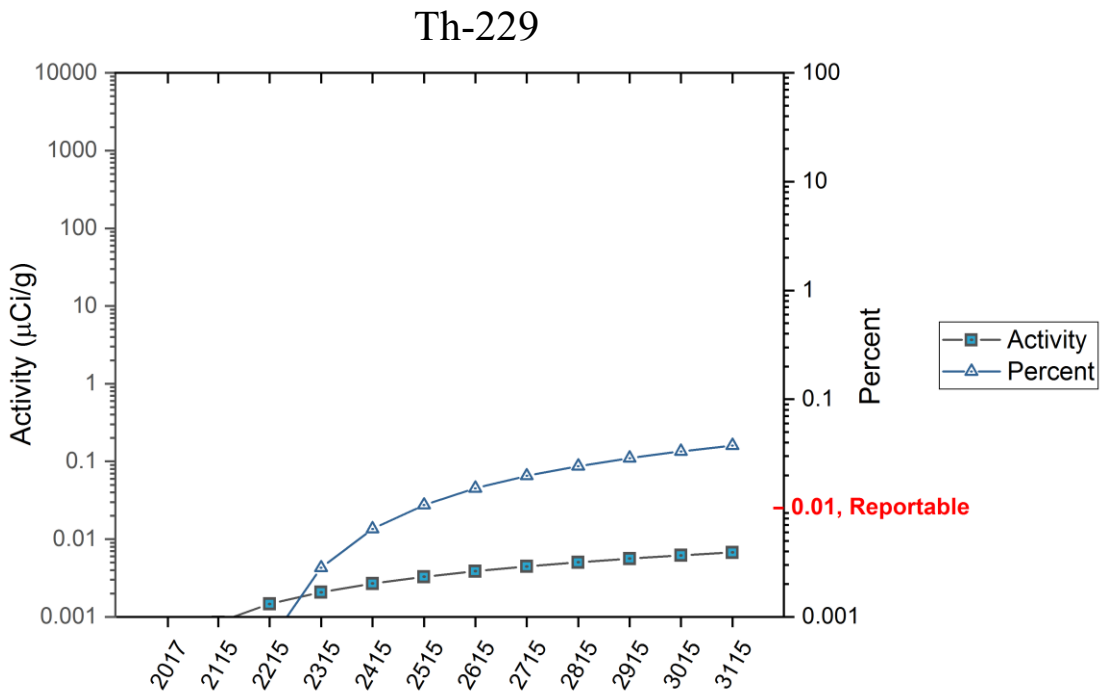
0.01
0.001
Activity (µCi/g)
100
10
1
0.1
0.001
Percent
0.01, Reportable
Activity
Percent
2017
2115
2215
2315
2415
2515
2615
2715
2815
2915
3015
3115


Th-229
Activity (µCi/g)
Percent
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1000
100
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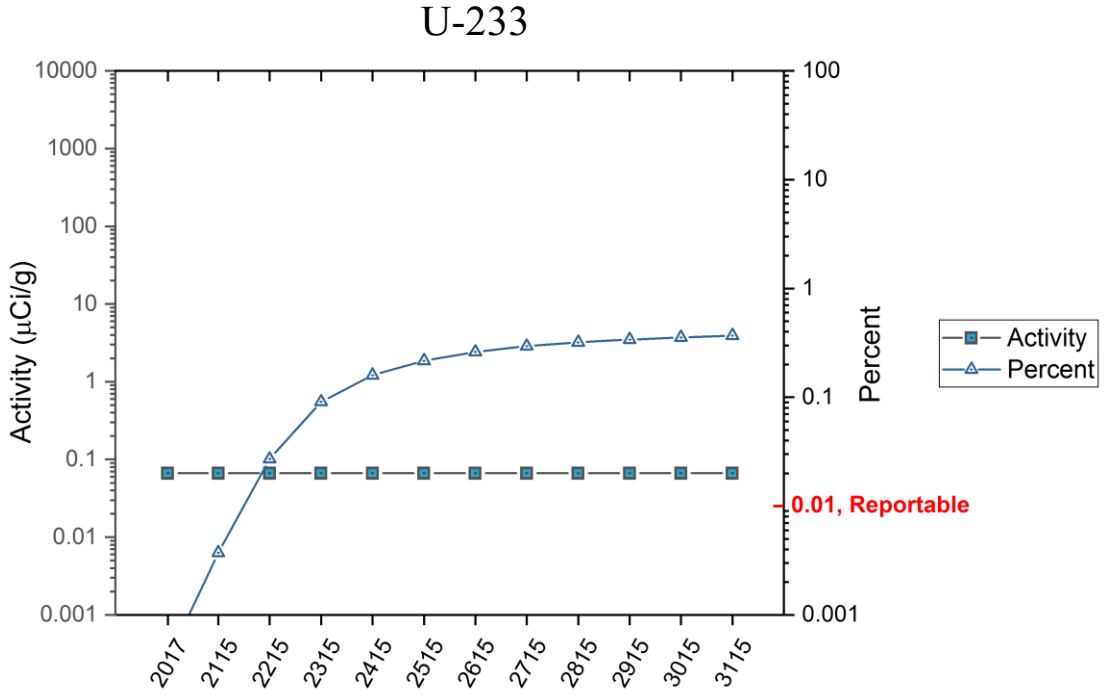
0.1
0.01
0.001
100
10
1
0.1
0.001
0.01, Reportable
Activity
Percent
2017
2115
2215
2315
2415
2515
2615
2715
2815
2915
3015
3115


U-233
Activity (µCi/g)
Percent
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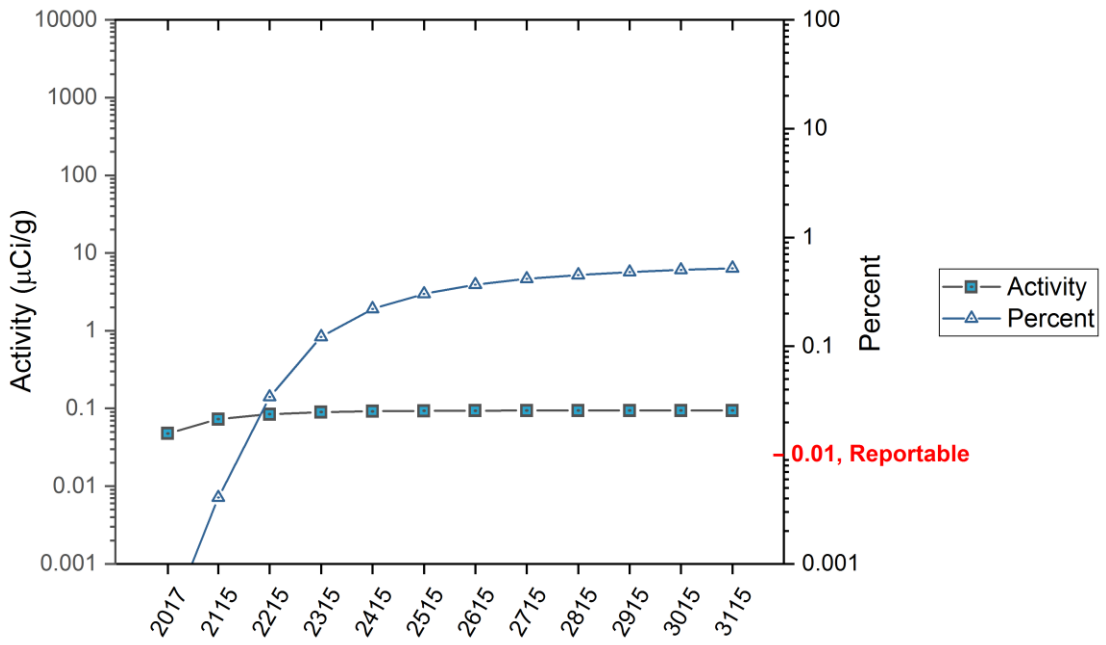
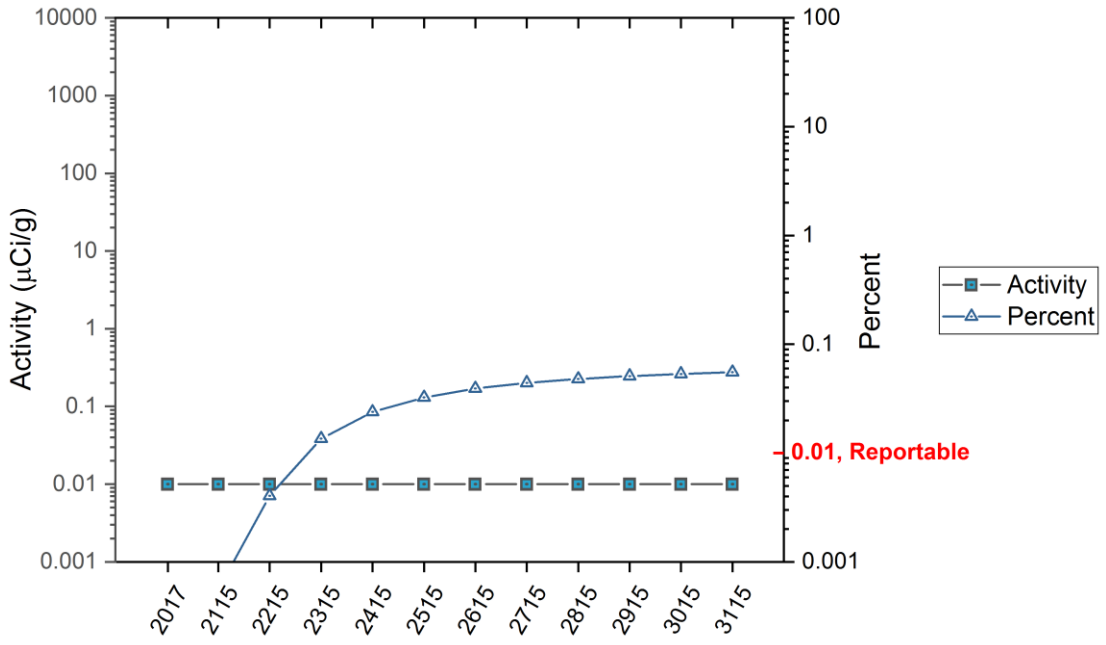
0.001
100
10
1
0.1
0.001
0.01, Reportable
Activity
Percent
2017
2115
2215
2315
2415
2515
2615
2715
2815
2915
3015
3115

U-234


Activity (µCi/g)
Percent
10000
1000
100
10
1
0.1
0.01
0.001
100
10
1
0.1
0.001
0.01, Reportable
Activity
Percent
2017
2115
2215
2315
2415
2515
2615
2715
2815
2915
3015
3115

U-238


Activity (µCi/g)
Percent
10000
1000
100
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0.01
0.001
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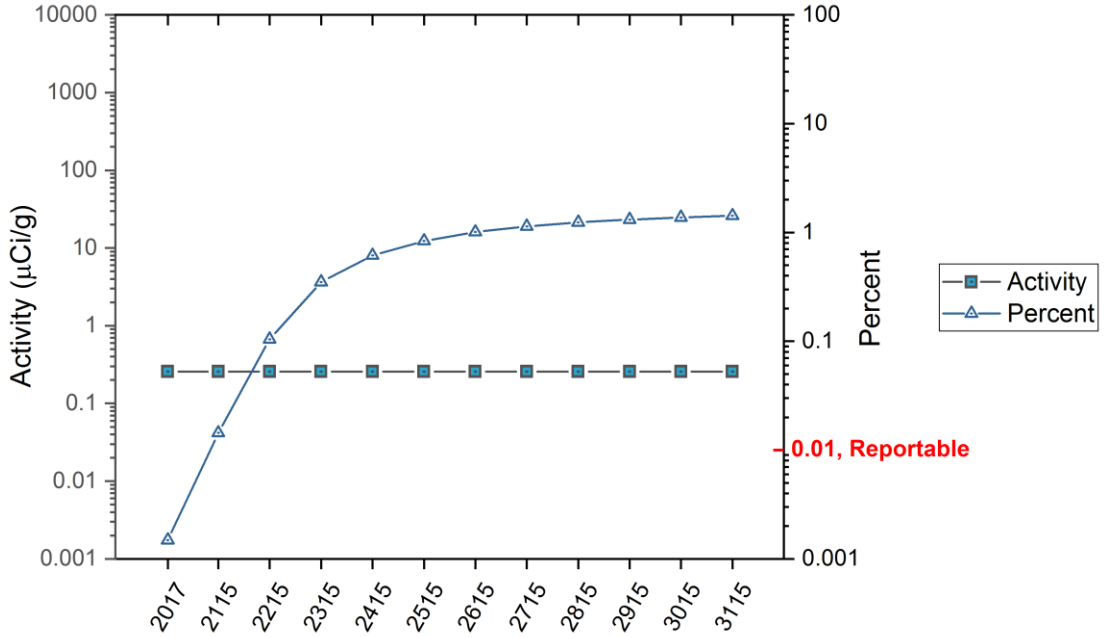
10
1
0.1
0.001
0.01, Reportable
Activity
Percent
2017
2115
2215
2315
2415
2515
2615
2715
2815
2915
3015
3115

Zr-93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Activity (µCi/g)
100
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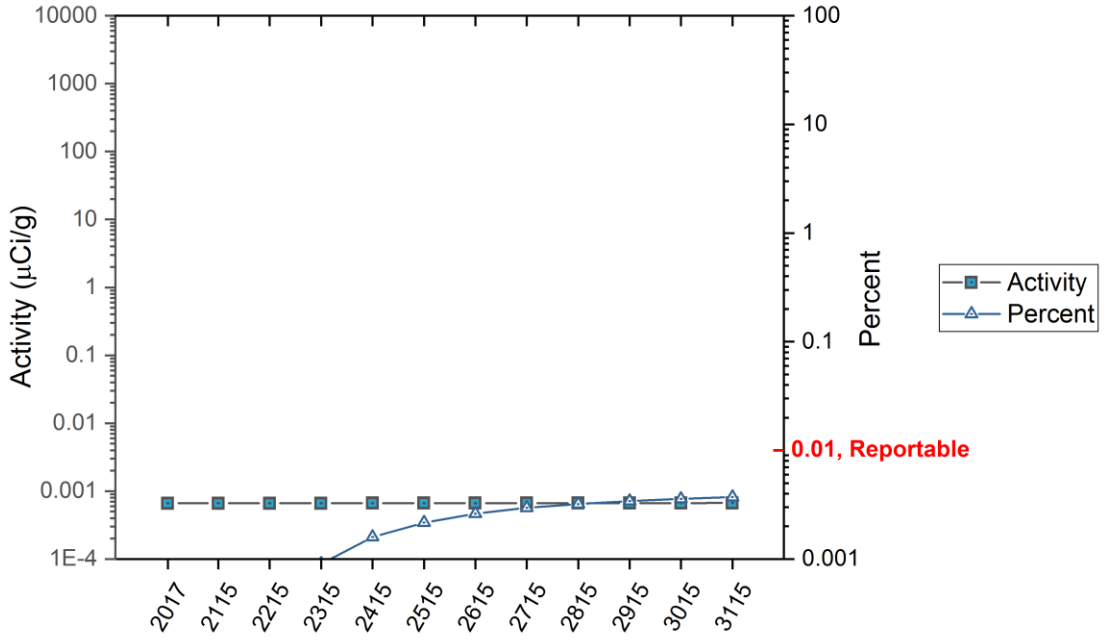
0.001
Percent
0.01, Reportable
Activity
Percent
2017
2115
2215
2315
2415
2515
2615
2715
2815
2915
3015
3115

U-235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Activity (µCi/g)
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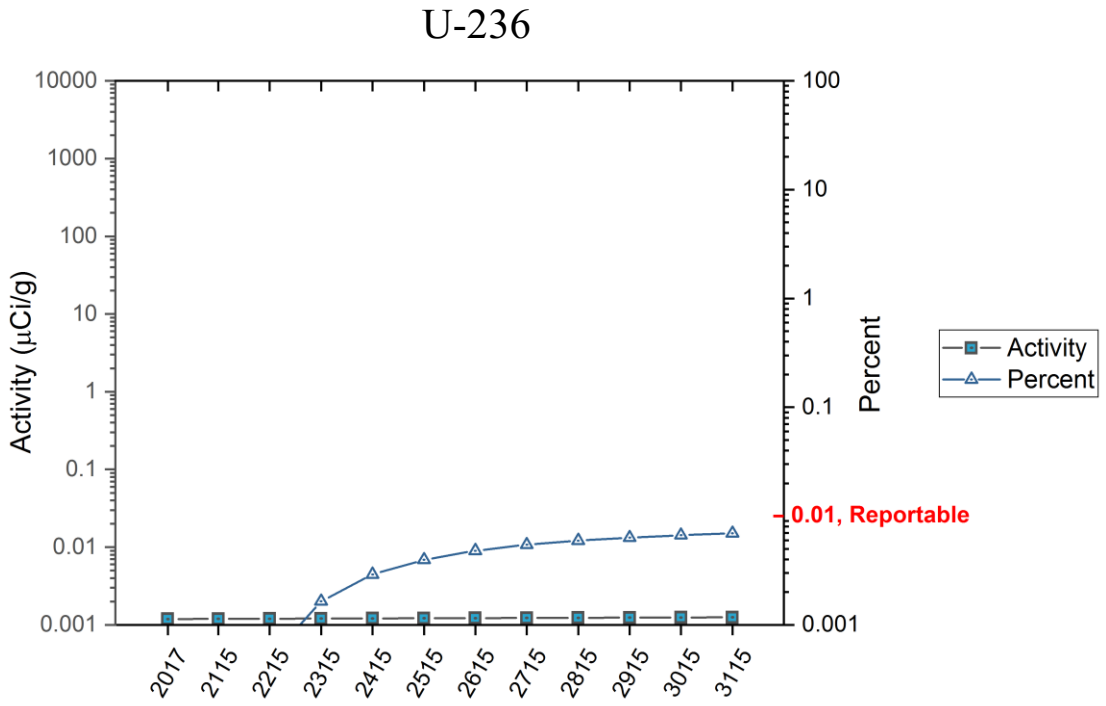
0.001
Percent
0.01, Reportable
Activity
Percent
2017
2115
2215
2315
2415
2515
2615
2715
2815
2915
3015
3115


U-236
Activity (µCi/g)
Percent
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0.001
100
10
1
0.1
0.001
0.01, Reportable
Activity
Percent
2017
2115
2215
2315
2415
2515
2615
2715
2815
2915
3015
3115

Appendix B: **Calculation of Pb-210, Ra-226, and Nb-93m**

OBJECTIVE: Calculate concentrations of Pb210 and Ra226 in SB9 Tank 40 slurry, using measured concentrations of Pu238, U238, U234, Th230, and Th232. Assumptions:

(1) waste is 45 years old (1972),

(2) there was no Pb210 or Ra226 in the waste in 1972.

	2017 conc. (µCi/g solids)	Wt% of total solids
Pu238	1.30E+02	
U238	9.97E-03	
U234	4.77E-02	
Th230	<7.53E-05	
Th232	8.31E-04	7.56E-01

APPROACH: Obtain, by calculation or estimation, 1972 concentrations of Pu238, U238, U234, and Th230 in the slurry. Decay all four nuclides and their progeny for 45 years to estimate 2017 concentrations of Ra226 and Pb210.

STEP 1. Find the concentration of Pu238 in 1972, by back-decaying from the 2017 concentration.

$Pu238_{1972}$ = **1.855E+02** µCi/g

STEP 2. Find the concentration of U238 in 1972. Since the half-life is very long, the amount decayed in 45 years is assumed to be negligible.

$U238_{1972}$ = **9.97E-03** µCi/g

STEP 3. Decay $Pu238_{1972}$ and $U238_{1972}$ for 45 years to find ingrown $U234_{2017}$.

Ingrown $U234_{2017}$ = 1.98E-02 µCi/g from Pu238 + 1.27E-06 µCi/g from U238 = 1.98E-02 total.

STEP 4. $U234_{1972} = U234_{2017} - U234_{ingrown}$ = 4.77E-02 – 1.98E-02 = **2.79E-02** µCi/g.
(assumes negligible U234 decay between 1972 and 2017 due to long half-life).

STEP 5. Decay $Pu238_{1972}$, $U238_{1972}$, and $U234_{1972}$ for 45 years to find ingrown $Th230_{2017}$.

- Pu238(45y) makes 4.35E-06 µCi/g ingrown $Th230_{2017}$
- U238 (45y) makes 2.61E-10 µCi/g ingrown $Th230_{2017}$
- U234 (45y) makes 1.15E-05 µCi/g ingrown $Th230_{2017}$

STEP 6. Subtract the three ingrown $Th230_{2017}$ terms from total $Th230_{2017}$ (<7.53E-05) to find $Th230_{1972}$ =
<5.94E-05 µCi/g (assumes negligible Th230 decay between 1972 and 2017 due to long half-life).

	1972 conc. (µCi/g solids)	Wt% of total solids
Pu238	1.86E+02	
U238	9.97E-03	
U234	2.79E-02	
Th230	<5.94E-05	
Th232	8.31E-04	7.56E-01

STEP 7. Decay $Pu238_{1972}$, $U238_{1972}$, $U234_{1972}$, and $Th230_{1972}$ for 45 years to find ingrown Ra226 and Pb210.

	2017 conc. (µCi/g solids)
Ra226	1.28E-06
Pb210	5.76E-07

CALCULATION OF Nb-93m

The amount of Nb-93m was calculated by assuming that it is in secular equilibrium with its parent isotope, Zr-93. Consequently, the ingrown concentration of Nb-93m was calculated using the following equation:

$$N_2^t = \frac{\lambda_1}{\lambda_2 - \lambda_1} N_1^o \left(e^{-\lambda_1 t} - e^{-\lambda_2 t} \right)$$

where:

N_2^t = is the number of atoms of Nb-93m at time "t".

λ_1 = is the decay constant for Zr-93 (sec^{-1}).

λ_2 = is the decay constant for Nb-93m (sec^{-1}).

N_1^o = is the initial concentration of Zr-93 atoms (45 years ago).

t = is time (sec).

Appendix C**: RadDecay output for the specified index years.**

	Index Year:	2017	2115	2215	2315	2415	2515	2615	2715	2815	2915	3015	3115
Name	Half-life (y)	Activity (µCi/g)	Activity (µCi/g)	Activity (µCi/g)	Activity (µCi/g)	Activity (µCi/g)	Activity (µCi/g)	Activity (µCi/g)	Activity (µCi/g)	Activity (µCi/g)	Activity (µCi/g)	Activity (µCi/g)	Activity (µCi/g)
Ac-225	2.74E-02	0.00E+00	8.47E-04	1.46E-03	2.08E-03	2.68E-03	3.28E-03	3.88E-03	4.46E-03	5.05E-03	5.62E-03	6.20E-03	6.76E-03
Ac-227	2.18E+01	1.12E-03	2.41E-02	2.51E-02	2.51E-02	2.50E-02	2.50E-02	2.49E-02	2.49E-02	2.48E-02	2.48E-02	2.47E-02	2.47E-02
Ac-228	7.02E-04	0.00E+00	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04
Am-241	4.32E+02	1.72E+01	1.55E+01	1.32E+01	1.12E+01	9.57E+00	8.15E+00	6.95E+00	5.92E+00	5.04E+00	4.29E+00	3.66E+00	3.12E+00
Am-242	1.83E-03	0.00E+00	1.45E-02	8.88E-03	5.43E-03	3.32E-03	2.03E-03	1.24E-03	7.60E-04	4.65E-04	2.84E-04	1.74E-04	1.06E-04
Am-242m	1.41E+02	2.36E-02	1.46E-02	8.92E-03	5.45E-03	3.34E-03	2.04E-03	1.25E-03	7.63E-04	4.67E-04	2.86E-04	1.75E-04	1.07E-04
Am-243	7.37E+03	1.78E-01	1.76E-01	1.75E-01	1.73E-01	1.71E-01	1.70E-01	1.68E-01	1.67E-01	1.65E-01	1.64E-01	1.62E-01	1.61E-01
At-217	9.51E-10	0.00E+00	8.47E-04	1.46E-03	2.08E-03	2.68E-03	3.28E-03	3.88E-03	4.46E-03	5.05E-03	5.62E-03	6.20E-03	6.76E-03
At-218	4.76E-08	0.00E+00	1.09E-09	2.46E-09	4.42E-09	6.99E-09	1.02E-08	1.39E-08	1.83E-08	2.31E-08	2.85E-08	3.44E-08	4.08E-08
At-219	1.78E-06	0.00E+00	2.00E-08	2.08E-08	2.08E-08	2.07E-08	2.07E-08	2.06E-08	2.06E-08	2.05E-08	2.05E-08	2.05E-08	2.04E-08
Ba-133	1.05E+01	6.99E-02	1.10E-04	1.51E-07	2.08E-10	2.86E-13	3.93E-16	5.40E-19	7.43E-22	1.02E-24	1.41E-27	1.94E-30	2.66E-33
Ba-137m	4.85E-06	8.47E+02	8.90E+01	8.94E+00	8.99E-01	9.03E-02	9.08E-03	9.12E-04	9.16E-05	9.21E-06	9.25E-07	9.30E-08	9.35E-09
Bi-210	1.37E-02	0.00E+00	3.96E-06	9.92E-06	1.88E-05	3.07E-05	4.56E-05	6.35E-05	8.42E-05	1.08E-04	1.34E-04	1.63E-04	1.94E-04
Bi-211	4.07E-06	0.00E+00	2.41E-02	2.51E-02	2.51E-02	2.50E-02	2.50E-02	2.49E-02	2.49E-02	2.48E-02	2.48E-02	2.47E-02	2.47E-02
Bi-212	1.15E-04	0.00E+00	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04
Bi-213	8.68E-05	0.00E+00	8.47E-04	1.46E-03	2.08E-03	2.68E-03	3.28E-03	3.88E-03	4.46E-03	5.05E-03	5.62E-03	6.19E-03	6.76E-03
Bi-214	3.79E-05	0.00E+00	5.44E-06	1.23E-05	2.21E-05	3.50E-05	5.09E-05	6.97E-05	9.13E-05	1.16E-04	1.43E-04	1.72E-04	2.04E-04
Bi-215	1.45E-05	0.00E+00	1.94E-08	2.01E-08	2.01E-08	2.01E-08	2.00E-08	2.00E-08	2.00E-08	1.99E-08	1.99E-08	1.98E-08	1.98E-08
Bk-247	1.38E+03	1.28E-04	1.22E-04	1.16E-04	1.10E-04	1.05E-04	9.97E-05	9.48E-05	9.01E-05	8.57E-05	8.15E-05	7.75E-05	7.37E-05
Cd-113	7.70E+15	0.00E+00	3.74E-18	3.77E-18	3.77E-18	3.77E-18	3.77E-18	3.77E-18	3.77E-18	3.77E-18	3.77E-18	3.77E-18	3.77E-18
Cd-113m	1.41E+01	1.47E+00	1.19E-02	8.71E-05	6.38E-07	4.68E-09	3.43E-11	2.51E-13	1.84E-15	1.35E-17	9.89E-20	7.25E-22	5.31E-24

	Index Year:	2017	2115	2215	2315	2415	2515	2615	2715	2815	2915	3015	3115
Name	**Half-life (y)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**
Ce-144	**7.80E-01**	6.34E-01	9.60E-39	2.46E-77	6.30E-116	1.61E-154	4.13E-193	1.06E-231	2.71E-270	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cf-249	**3.51E+02**	3.85E-04	3.17E-04	2.60E-04	2.14E-04	1.75E-04	1.44E-04	1.18E-04	9.70E-05	7.96E-05	6.54E-05	5.36E-05	4.40E-05
Cf-250	**1.31E+01**	2.56E-07	1.42E-09	7.10E-12	3.55E-14	1.77E-16	8.85E-19	4.42E-21	2.21E-23	1.10E-25	5.51E-28	2.75E-30	1.38E-32
Cf-251	**9.00E+02**	9.90E-04	9.18E-04	8.50E-04	7.87E-04	7.29E-04	6.75E-04	6.25E-04	5.78E-04	5.35E-04	4.96E-04	4.59E-04	4.25E-04
Cf-252	**2.65E+00**	1.95E-02	1.37E-13	5.69E-25	2.37E-36	9.85E-48	4.09E-59	1.70E-70	7.08E-82	2.94E-93	1.22E-104	5.09E-116	2.12E-127
Cl-36	**3.01E+05**	3.97E-02	3.97E-02	3.97E-02	3.97E-02	3.97E-02	3.97E-02	3.96E-02	3.96E-02	3.96E-02	3.96E-02	3.96E-02	3.96E-02
Cm-242	**4.47E-01**	1.95E-02	1.20E-02	7.36E-03	4.50E-03	2.76E-03	1.69E-03	1.03E-03	6.30E-04	3.86E-04	2.36E-04	1.44E-04	8.82E-05
Cm-243	**2.91E+01**	1.10E-01	1.07E-02	9.84E-04	9.09E-05	8.40E-06	7.76E-07	7.17E-08	6.62E-09	6.11E-10	5.65E-11	5.22E-12	4.82E-13
Cm-244	**1.81E+01**	5.85E+00	1.37E-01	2.98E-03	6.47E-05	1.41E-06	3.05E-08	6.63E-10	1.44E-11	3.13E-13	6.79E-15	1.48E-16	3.20E-18
Cm-245	**8.50E+03**	9.74E-04	9.69E-04	9.64E-04	9.58E-04	9.51E-04	9.45E-04	9.38E-04	9.32E-04	9.25E-04	9.18E-04	9.11E-04	9.04E-04
Cm-246	**4.76E+03**	2.84E-03	2.80E-03	2.76E-03	2.72E-03	2.68E-03	2.64E-03	2.60E-03	2.57E-03	2.53E-03	2.49E-03	2.46E-03	2.42E-03
Cm-247	**1.56E+07**	1.39E-08	1.81E-08	2.20E-08	2.56E-08	2.90E-08	3.21E-08	3.50E-08	3.77E-08	4.01E-08	4.24E-08	4.45E-08	4.65E-08
Cm-248	**3.48E+05**	8.65E-07	1.01E-06	1.01E-06	1.01E-06	1.01E-06	1.01E-06	1.01E-06	1.01E-06	1.01E-06	1.01E-06	1.01E-06	1.01E-06
Co-60	**5.27E+00**	4.96E-01	1.26E-06	2.44E-12	4.76E-18	9.26E-24	1.80E-29	3.51E-35	6.83E-41	1.33E-46	2.59E-52	5.04E-58	9.81E-64
Cs-134	**2.06E+00**	4.39E-01	2.26E-15	5.97E-30	1.57E-44	4.14E-59	1.09E-73	2.88E-88	7.59E-103	2.00E-117	5.27E-132	1.39E-146	3.66E-161
Cs-135	**2.30E+06**	4.82E-03	4.82E-03	4.82E-03	4.82E-03	4.82E-03	4.82E-03	4.82E-03	4.82E-03	4.82E-03	4.82E-03	4.82E-03	4.82E-03
Cs-137	**3.02E+01**	8.96E+02	9.43E+01	9.47E+00	9.52E-01	9.57E-02	9.61E-03	9.66E-04	9.71E-05	9.76E-06	9.80E-07	9.85E-08	9.90E-09
Eu-154	**8.59E+00**	5.58E+00	2.06E-03	6.46E-07	2.03E-10	6.37E-14	2.00E-17	6.27E-21	1.97E-24	6.18E-28	1.94E-31	6.09E-35	1.91E-38
Eu-155	**4.76E+00**	9.78E-01	6.22E-07	2.96E-13	1.41E-19	6.70E-26	3.19E-32	1.52E-38	7.21E-45	3.43E-51	1.63E-57	7.76E-64	3.69E-70
Fr-221	**9.32E-06**	0.00E+00	8.47E-04	1.46E-03	2.08E-03	2.68E-03	3.28E-03	3.88E-03	4.46E-03	5.05E-03	5.62E-03	6.20E-03	6.76E-03
Fr-223	**4.19E-05**	0.00E+00	3.33E-04	3.46E-04	3.46E-04	3.45E-04	3.44E-04	3.44E-04	3.43E-04	3.42E-04	3.42E-04	3.41E-04	3.40E-04
Hg-206	**1.55E-05**	0.00E+00	7.52E-14	1.89E-13	3.57E-13	5.83E-13	8.66E-13	1.21E-12	1.60E-12	2.05E-12	2.54E-12	3.09E-12	3.68E-12
I-129	**1.57E+07**	4.35E-03	4.35E-03	4.35E-03	4.35E-03	4.35E-03	4.35E-03	4.35E-03	4.35E-03	4.35E-03	4.35E-03	4.35E-03	4.35E-03

	Index Year:	2017	2115	2215	2315	2415	2515	2615	2715	2815	2915	3015	3115
Name	**Half-life (y)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**
Nb-93m	**1.61E+01**	2.20E-01	2.50E-01	2.51E-01	2.51E-01	2.51E-01	2.51E-01	2.51E-01	2.51E-01	2.50E-01	2.50E-01	2.50E-01	2.50E-01
Nd-144	**2.29E+15**	0.00E+00	2.16E-16	2.16E-16	2.16E-16	2.16E-16	2.16E-16	2.16E-16	2.16E-16	2.16E-16	2.16E-16	2.16E-16	2.16E-16
Ni-59	**1.01E+05**	5.56E-01	5.56E-01	5.55E-01	5.55E-01	5.54E-01	5.54E-01	5.54E-01	5.53E-01	5.53E-01	5.53E-01	5.52E-01	5.52E-01
Ni-63	**1.00E+02**	6.29E+01	3.19E+01	1.60E+01	7.99E+00	4.00E+00	2.00E+00	1.00E+00	5.01E-01	2.51E-01	1.25E-01	6.27E-02	3.14E-02
Np-237	**2.14E+06**	1.93E-02	1.98E-02	2.03E-02	2.07E-02	2.10E-02	2.13E-02	2.15E-02	2.18E-02	2.19E-02	2.21E-02	2.22E-02	2.23E-02
Np-238	**5.81E-03**	0.00E+00	6.56E-05	4.01E-05	2.45E-05	1.50E-05	9.18E-06	5.62E-06	3.44E-06	2.10E-06	1.29E-06	7.86E-07	4.81E-07
Np-239	**6.47E-03**	0.00E+00	1.76E-01	1.75E-01	1.73E-01	1.71E-01	1.70E-01	1.68E-01	1.67E-01	1.65E-01	1.64E-01	1.62E-01	1.61E-01
Np-240	**1.18E-04**	0.00E+00	8.57E-16	1.74E-15	2.62E-15	3.49E-15	4.37E-15	5.25E-15	6.13E-15	7.01E-15	7.89E-15	8.76E-15	9.64E-15
Np-240m	**1.37E-05**	0.00E+00	7.79E-13	1.58E-12	2.38E-12	3.18E-12	3.98E-12	4.77E-12	5.57E-12	6.37E-12	7.17E-12	7.97E-12	8.77E-12
Pa-231	**3.28E+04**	2.52E-02	2.51E-02	2.51E-02	2.50E-02	2.50E-02	2.49E-02	2.49E-02	2.48E-02	2.48E-02	2.47E-02	2.47E-02	2.46E-02
Pa-233	**7.40E-02**	0.00E+00	1.98E-02	2.03E-02	2.07E-02	2.10E-02	2.13E-02	2.15E-02	2.18E-02	2.19E-02	2.21E-02	2.22E-02	2.23E-02
Pa-234	**7.65E-04**	0.00E+00	1.60E-05	1.60E-05	1.60E-05	1.60E-05	1.60E-05	1.60E-05	1.60E-05	1.60E-05	1.60E-05	1.60E-05	1.60E-05
Pa-234m	**2.23E-06**	0.00E+00	9.97E-03	9.97E-03	9.97E-03	9.97E-03	9.97E-03	9.97E-03	9.97E-03	9.97E-03	9.97E-03	9.97E-03	9.97E-03
Pb-209	**3.71E-04**	0.00E+00	8.47E-04	1.46E-03	2.08E-03	2.68E-03	3.28E-03	3.88E-03	4.46E-03	5.05E-03	5.62E-03	6.19E-03	6.76E-03
Pb-210	**2.22E+01**	5.76E-07	3.96E-06	9.92E-06	1.88E-05	3.07E-05	4.56E-05	6.35E-05	8.43E-05	1.08E-04	1.34E-04	1.63E-04	1.94E-04
Pb-211	**6.87E-05**	0.00E+00	2.41E-02	2.51E-02	2.51E-02	2.50E-02	2.50E-02	2.49E-02	2.49E-02	2.48E-02	2.48E-02	2.47E-02	2.47E-02
Pb-212	**1.21E-03**	0.00E+00	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04
Pb-214	**5.10E-05**	0.00E+00	5.44E-06	1.23E-05	2.21E-05	3.50E-05	5.08E-05	6.97E-05	9.13E-05	1.16E-04	1.43E-04	1.72E-04	2.04E-04
Pd-107	**6.50E+06**	1.29E-03	1.29E-03	1.29E-03	1.29E-03	1.29E-03	1.29E-03	1.29E-03	1.29E-03	1.29E-03	1.29E-03	1.29E-03	1.29E-03
Pm-147	**2.62E+00**	9.64E+01	5.48E-10	1.84E-21	6.15E-33	2.06E-44	6.91E-56	2.32E-67	7.76E-79	2.60E-90	8.72E-102	2.92E-113	9.79E-125
Po-210	**3.78E-01**	0.00E+00	3.93E-06	9.88E-06	1.87E-05	3.06E-05	4.55E-05	6.34E-05	8.41E-05	1.08E-04	1.34E-04	1.62E-04	1.93E-04
Po-211	**1.65E-08**	0.00E+00	6.65E-05	6.92E-05	6.92E-05	6.90E-05	6.89E-05	6.87E-05	6.86E-05	6.85E-05	6.83E-05	6.82E-05	6.80E-05
Po-212	**0.00E+00**	0.00E+00	5.32E-04	5.32E-04	5.32E-04	5.32E-04	5.32E-04	5.32E-04	5.32E-04	5.32E-04	5.32E-04	5.32E-04	5.32E-04

Name	Index Year:	2017	2115	2215	2315	2415	2515	2615	2715	2815	2915	3015	3115
	Half-life (y)	Activity (µCi/g)	Activity (µCi/g)	Activity (µCi/g)	Activity (µCi/g)	Activity (µCi/g)	Activity (µCi/g)	Activity (µCi/g)	Activity (µCi/g)	Activity (µCi/g)	Activity (µCi/g)	Activity (µCi/g)	Activity (µCi/g)
Po-213	**0.00E+00**	0.00E+00	8.29E-04	1.43E-03	2.03E-03	2.63E-03	3.21E-03	3.79E-03	4.37E-03	4.94E-03	5.51E-03	6.06E-03	6.62E-03
Po-214	**0.00E+00**	0.00E+00	5.44E-06	1.23E-05	2.21E-05	3.50E-05	5.08E-05	6.97E-05	9.13E-05	1.16E-04	1.43E-04	1.72E-04	2.04E-04
Po-215	**0.00E+00**	0.00E+00	2.41E-02	2.51E-02	2.51E-02	2.50E-02	2.50E-02	2.49E-02	2.49E-02	2.48E-02	2.48E-02	2.47E-02	2.47E-02
Po-216	**4.76E-09**	0.00E+00	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04
Po-218	**5.90E-06**	0.00E+00	5.44E-06	1.23E-05	2.21E-05	3.50E-05	5.09E-05	6.97E-05	9.13E-05	1.16E-04	1.43E-04	1.72E-04	2.04E-04
Pr-144	**3.29E-05**	0.00E+00	9.60E-39	2.46E-77	6.30E-116	1.61E-154	4.13E-193	1.06E-231	2.71E-270	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pr-144m	**1.37E-05**	0.00E+00	9.38E-41	2.40E-79	6.15E-118	1.58E-156	4.04E-195	1.03E-233	2.65E-272	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pu-238	**8.77E+01**	1.30E+02	5.99E+01	2.72E+01	1.23E+01	5.60E+00	2.54E+00	1.15E+00	5.24E-01	2.38E-01	1.08E-01	4.92E-02	2.24E-02
Pu-239	**2.41E+04**	5.51E+00	5.50E+00	5.48E+00	5.46E+00	5.45E+00	5.43E+00	5.42E+00	5.40E+00	5.39E+00	5.37E+00	5.36E+00	5.34E+00
Pu-240	**6.56E+03**	1.96E+00	1.96E+00	1.94E+00	1.92E+00	1.89E+00	1.87E+00	1.86E+00	1.84E+00	1.82E+00	1.80E+00	1.78E+00	1.76E+00
Pu-241	**1.44E+01**	2.69E+01	2.38E-01	2.85E-03	9.74E-04	9.53E-04	9.46E-04	9.40E-04	9.33E-04	9.26E-04	9.19E-04	9.12E-04	9.05E-04
Pu-242	**3.75E+05**	4.32E-03	4.32E-03	4.32E-03	4.32E-03	4.32E-03	4.32E-03	4.32E-03	4.32E-03	4.32E-03	4.32E-03	4.32E-03	4.32E-03
Pu-243	**5.67E-04**	0.00E+00	1.81E-08	2.20E-08	2.56E-08	2.90E-08	3.21E-08	3.50E-08	3.77E-08	4.01E-08	4.24E-08	4.45E-08	4.65E-08
Pu-244	**8.00E+07**	0.00E+00	7.80E-13	1.58E-12	2.38E-12	3.18E-12	3.98E-12	4.78E-12	5.58E-12	6.38E-12	7.18E-12	7.98E-12	8.78E-12
Ra-223	**3.12E-02**	0.00E+00	2.41E-02	2.51E-02	2.51E-02	2.50E-02	2.50E-02	2.49E-02	2.49E-02	2.48E-02	2.48E-02	2.47E-02	2.47E-02
Ra-224	**1.00E-02**	0.00E+00	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04
Ra-225	**4.08E-02**	0.00E+00	8.47E-04	1.46E-03	2.08E-03	2.68E-03	3.28E-03	3.88E-03	4.46E-03	5.05E-03	5.62E-03	6.20E-03	6.76E-03
Ra-226	**1.60E+03**	1.28E-06	5.44E-06	1.23E-05	2.21E-05	3.50E-05	5.09E-05	6.97E-05	9.14E-05	1.16E-04	1.43E-04	1.72E-04	2.04E-04
Ra-228	**5.75E+00**	0.00E+00	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04
Rh-106	**9.94E-07**	0.00E+00	2.62E-30	9.70E-60	3.60E-89	1.33E-118	4.94E-148	1.83E-177	6.79E-207	2.52E-236	9.33E-266	3.46E-295	0.00E+00
Rn-218	**1.27E-09**	0.00E+00	1.09E-12	2.46E-12	4.42E-12	6.99E-12	1.02E-11	1.39E-11	1.83E-11	2.31E-11	2.85E-11	3.44E-11	4.08E-11
Rn-219	**1.26E-07**	0.00E+00	2.41E-02	2.51E-02	2.51E-02	2.50E-02	2.50E-02	2.49E-02	2.49E-02	2.48E-02	2.48E-02	2.47E-02	2.47E-02

	Index Year:	2017	2115	2215	2315	2415	2515	2615	2715	2815	2915	3015	3115
Name	**Half-life (y)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**
Rn-220	**1.76E-06**	0.00E+00	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04
Rn-222	**1.05E-02**	0.00E+00	5.44E-06	1.23E-05	2.21E-05	3.50E-05	5.09E-05	6.97E-05	9.13E-05	1.16E-04	1.43E-04	1.72E-04	2.04E-04
Ru-106	**1.02E+00**	1.82E-01	2.62E-30	9.70E-60	3.60E-89	1.33E-118	4.94E-148	1.83E-177	6.79E-207	2.52E-236	9.33E-266	3.46E-295	0.00E+00
Sb-125	**2.76E+00**	1.35E-01	2.73E-12	3.34E-23	4.08E-34	4.99E-45	6.11E-56	7.47E-67	9.13E-78	1.12E-88	1.37E-99	1.67E-110	2.04E-121
Sb-126	**3.40E-02**	0.00E+00	4.04E-02	4.04E-02	4.04E-02	4.04E-02	4.03E-02	4.03E-02	4.03E-02	4.03E-02	4.03E-02	4.03E-02	4.03E-02
Se-79	**2.95E+05**	4.20E-02	4.20E-02	4.20E-02	4.20E-02	4.20E-02	4.20E-02	4.19E-02	4.19E-02	4.19E-02	4.19E-02	4.19E-02	4.19E-02
Sm-147	**1.06E+11**	0.00E+00	2.39E-09	2.39E-09	2.39E-09	2.39E-09	2.39E-09	2.39E-09	2.39E-09	2.39E-09	2.39E-09	2.39E-09	2.39E-09
Sm-151	**9.00E+01**	1.32E+02	6.21E+01	2.87E+01	1.33E+01	6.16E+00	2.85E+00	1.32E+00	6.11E-01	2.83E-01	1.31E-01	6.06E-02	2.81E-02
Sn-121	**3.08E-03**	0.00E+00	4.77E-02	9.84E-03	2.03E-03	4.18E-04	8.63E-05	1.78E-05	3.67E-06	7.56E-07	1.56E-07	3.22E-08	6.63E-09
Sn-121m	**4.39E+01**	2.89E-01	6.15E-02	1.27E-02	2.61E-03	5.39E-04	1.11E-04	2.29E-05	4.73E-06	9.75E-07	2.01E-07	4.14E-08	8.55E-09
Sn-126	**2.30E+05**	4.04E-02	4.04E-02	4.04E-02	4.04E-02	4.04E-02	4.03E-02	4.03E-02	4.03E-02	4.03E-02	4.03E-02	4.03E-02	4.03E-02
Sr-90	**2.88E+01**	7.51E+03	7.09E+02	6.39E+01	5.75E+00	5.18E-01	4.66E-02	4.20E-03	3.78E-04	3.40E-05	3.06E-06	2.76E-07	2.48E-08
Tc-99	**2.11E+05**	2.78E-01	2.78E-01	2.78E-01	2.78E-01	2.78E-01	2.78E-01	2.77E-01	2.77E-01	2.77E-01	2.77E-01	2.77E-01	2.77E-01
Te-125m	**1.57E-01**	1.34E-01	6.70E-13	8.19E-24	1.00E-34	1.22E-45	1.50E-56	1.83E-67	2.24E-78	2.74E-89	3.35E-100	4.10E-111	5.01E-122
Th-227	**5.12E-02**	0.00E+00	2.38E-02	2.47E-02	2.47E-02	2.47E-02	2.46E-02	2.46E-02	2.45E-02	2.45E-02	2.44E-02	2.44E-02	2.43E-02
Th-228	**1.91E+00**	0.00E+00	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04
Th-229	**7.34E+03**	2.36E-04	8.47E-04	1.47E-03	2.08E-03	2.68E-03	3.28E-03	3.88E-03	4.46E-03	5.05E-03	5.62E-03	6.20E-03	6.76E-03
Th-230	**7.54E+04**	7.53E-05	1.31E-04	2.04E-04	2.84E-04	3.67E-04	4.52E-04	5.38E-04	6.23E-04	7.09E-04	7.95E-04	8.80E-04	9.66E-04
Th-231	**2.91E-03**	0.00E+00	6.63E-04	6.63E-04	6.64E-04	6.64E-04	6.65E-04	6.65E-04	6.66E-04	6.66E-04	6.67E-04	6.67E-04	6.68E-04
Th-232	**1.41E+10**	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04	8.31E-04
Th-234	**6.60E-02**	0.00E+00	9.97E-03	9.97E-03	9.97E-03	9.97E-03	9.97E-03	9.97E-03	9.97E-03	9.97E-03	9.97E-03	9.97E-03	9.97E-03
Tl-206	**7.99E-06**	0.00E+00	5.30E-12	1.33E-11	2.51E-11	4.11E-11	6.10E-11	8.50E-11	1.13E-10	1.44E-10	1.79E-10	2.18E-10	2.59E-10
Tl-207	**9.08E-06**	0.00E+00	2.40E-02	2.50E-02	2.50E-02	2.49E-02	2.49E-02	2.48E-02	2.48E-02	2.47E-02	2.47E-02	2.46E-02	2.46E-02

	Index Year:	2017	2115	2215	2315	2415	2515	2615	2715	2815	2915	3015	3115
Name	**Half-life (y)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**	**Activity (µCi/g)**
Tl-208	**5.80E-06**	0.00E+00	2.99E-04	2.99E-04	2.99E-04	2.99E-04	2.99E-04	2.99E-04	2.99E-04	2.99E-04	2.99E-04	2.99E-04	2.99E-04
Tl-209	**4.11E-06**	0.00E+00	1.77E-05	3.06E-05	4.34E-05	5.60E-05	6.86E-05	8.10E-05	9.33E-05	1.05E-04	1.18E-04	1.29E-04	1.41E-04
Tl-210	**2.47E-06**	0.00E+00	1.14E-09	2.58E-09	4.64E-09	7.34E-09	1.07E-08	1.46E-08	1.92E-08	2.43E-08	3.00E-08	3.62E-08	4.28E-08
U-233	**1.59E+05**	6.66E-02	6.66E-02	6.66E-02	6.65E-02	6.65E-02	6.65E-02	6.65E-02	6.65E-02	6.64E-02	6.64E-02	6.64E-02	6.64E-02
U-234	**2.46E+05**	4.77E-02	7.27E-02	8.44E-02	8.97E-02	9.21E-02	9.31E-02	9.36E-02	9.38E-02	9.39E-02	9.39E-02	9.39E-02	9.39E-02
U-235	**7.04E+08**	6.62E-04	6.63E-04	6.63E-04	6.64E-04	6.64E-04	6.65E-04	6.65E-04	6.66E-04	6.66E-04	6.67E-04	6.67E-04	6.68E-04
U-235m	**4.95E-05**	0.00E+00	5.49E+00	5.48E+00	5.46E+00	5.45E+00	5.43E+00	5.42E+00	5.40E+00	5.39E+00	5.37E+00	5.36E+00	5.34E+00
U-236	**2.34E+07**	1.19E-03	1.20E-03	1.20E-03	1.21E-03	1.21E-03	1.22E-03	1.22E-03	1.23E-03	1.23E-03	1.24E-03	1.25E-03	1.25E-03
U-237	**1.85E-02**	0.00E+00	5.83E-06	7.00E-08	2.39E-08	2.33E-08	2.32E-08	2.30E-08	2.29E-08	2.27E-08	2.25E-08	2.24E-08	2.22E-08
U-238	**4.47E+09**	9.97E-03	9.97E-03	9.97E-03	9.97E-03	9.97E-03	9.97E-03	9.97E-03	9.97E-03	9.97E-03	9.97E-03	9.97E-03	9.97E-03
U-240	**1.61E-03**	0.00E+00	7.79E-13	1.58E-12	2.38E-12	3.18E-12	3.98E-12	4.77E-12	5.57E-12	6.37E-12	7.17E-12	7.97E-12	8.77E-12
Y-90	**7.32E-03**	7.51E+03	7.10E+02	6.39E+01	5.75E+00	5.18E-01	4.66E-02	4.20E-03	3.78E-04	3.40E-05	3.06E-06	2.76E-07	2.48E-08
Zr-93	**1.53E+06**	2.57E-01	2.57E-01	2.57E-01	2.57E-01	2.57E-01	2.57E-01	2.57E-01	2.57E-01	2.57E-01	2.57E-01	2.57E-01	2.57E-01