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Evaluation of a Combined Raffinate Waste Stream for Mo-99 Production

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EXECUTIVE SUMMARY

Niowave, Inc., based in Lansing, Michigan, intends to produce Mo-99 from the fission of low enriched uranium (LEU) targets. In FY20, SRNL was tasked to provide technical assistance in identifying the primary waste raffinate present in Niowave's commercial scale system and evaluating methods for disposal. Due to limited information on Niowave's complete flowsheet and isotope recovery plans, a combined raffinate stream including the entire radionuclide inventory from the irradiated fuel was used for this evaluation.

Results of the evaluation indicated the majority of the waste generated can be expected to be Class A; however radioisotopes such as Pu-239, Cs-137, Sr-90, and some of the shorter lived (< 5 year half-life) may challenge Niowave's ability to meet the waste acceptance criteria for land burial. With appropriate waste management strategies, it is probable that Niowave's waste could meet Class C requirements for all constituents, with the possible exception of Pu-239. More detailed information of Niowave's processes are needed to form a more accurate understanding required to execute and effective, economic, and feasible waste management strategy.

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LIST OF ABBREVIATIONS

CFR	Code of Federal Regulations
DOE	Department of Energy
HEU	highly enriched uranium
LEU	low enriched uranium
MoLLE	molybdenum liquid liquid extraction
NNSA	National Nuclear Security Administration
PPE	personal protective equipment
SRNL	Savannah River National Laboratory
TRU	transuranic
UREX	Uranium extraction

1.0 Introduction

The Department of Energy's National Nuclear Security Administration (DOE/NNSA) supports the commercial-scale domestic production of molybdenum-99 (Mo-99) without the use of highly enriched uranium (HEU). DOE/NNSA provides financial assistance to accelerate the establishment of non-HEU-based production capabilities in the United States. U.S. national laboratory assistance has been provided to potential U.S. producers also receiving direct financial assistance from DOE/NNSA through cost-sharing cooperative agreements. The national laboratory resources – scientific staff, engineering staff, experimental equipment, laboratories and support staff – are intended to help these emerging producers overcome technical challenges in order to accelerate technology development towards realizing production of Mo-99 without the use of HEU.

Niowave, Inc. (Niowave), based in Lansing, Michigan, intends to produce Mo-99 from the fission of low enriched uranium (LEU) targets by the $^{238}U(\gamma,f)^{99}Mo$ and $^{235}U(n,f)^{99}Mo$ reactions. Niowave will use a two-pass 20 MeV superconducting electron linear accelerator to drive an electron beam at nearly 40 MeV into a liquid metal target. The Bremsstrahlung radiation (x-rays) from the electrons impinging on the liquid metal target drives the photo-fission reaction, $^{238}U(\gamma,f)^{99}Mo$, with the neutrons produced from this reaction driving the U-235 fission reaction, $^{235}U(n,f)^{99}Mo$. The LEU targets used by Niowave will consist of a water-cooled and moderated array of pressed uranium oxide pellets in a subcritical configuration. Irradiated LEU pellets are then dissolved, forming a solution of LEU uranyl nitrate salt in nitric acid. Mo-99 is extracted from the uranyl nitrate solution, the raffinate is purified, the purified uranyl nitrate is calcined and the resulting uranium oxide is pressed into pellets for use in future irradiation cycles. The Mo-99 produced at Niowave will be shipped to Tc-99m generator manufacturers utilizing the existing supply chain.

In fiscal year 2020 (FY20), Savannah River National Laboratory (SRNL) was tasked to provide technical assistance in identifying the primary waste raffinate present in Niowave's commercial scale system and evaluating methods for disposal as part of the Work Package *23.1.2.1.19 - LEU Target Technology - Niowave - SRNL - FY20*. This report discusses the results from those task activities. A brief summary of nuclear waste disposition and treatment practices in the United States is provided as reference in Appendix B.

2.0 Experimental Procedure

The approach to this task was to first identify likely waste streams based on Niowave's anticipated operations and process flowsheets, from which waste disposition options would be assessed. However, the combination of Niowave's interrelated processing steps and restricted access to some technical information, prevented a more comprehensive evaluation. Niowave intends to recover isotopes and chemicals from the fuel, in addition to Mo-99, and carry the actinides through with the fuel. The entirety of these processes and operations were not sufficiently developed or identified to definitively identify waste streams from processing the irradiated LEU cores. Therefore, a combined raffinate stream, to include the entire radionuclide inventory from the irradiated fuel, was used to project potential waste volumes resulting from Niowave's primary uranium extraction (UREX) and molybdenum liquid liquid extraction (MoLLE) processes. This task focused on evaluating a fixed volume of raffinate arising from the combined UREX and MoLLE radiochemical processes.

2.1 Combined raffinate

The raffinate radionuclide concentration was based on the projected fission spectrum of one, 25 kg LEU core from Niowave's commercial scale facility after a one-week irradiation followed by 1 day cooling. The combined raffinate stream used for this activity assumed 121 L of liquid waste produced per core. A liquid density of 1000 g/L was used to calculate waste classification limits on a mass basis. The initial radionuclide inventory in the raffinate was provided by Niowave and was based on modeling projections using the ORIGEN code.[1] A subset of the initial radionuclide inventory encompassing radioisotopes with activities greater than 10^{-9} Ci were computationally decayed using the RadDecay® software.[2] These isotopes were computationally decayed for 30, 180, and 365 days to capture ingrowth and decay changes to the raffinate radionuclide inventory that would be representative of a realistic period of time from production to disposition. An initial 234 isotopes were identified as having activity greater than 10^{-9} Ci after 1 week of irradiation and 1 day of cooling.

The following isotopes – Ba-136m, Ga-72m, Ge-73m, I-133m, Nb-97m, Pd-111m, and Rh-105m – were present at $>10^{-9}$ Ci in the original LEU fuel activity provided by Niowave, but were not listed in the ICRP Publication 107 database[3] and not included in the inventory decay calculations. Excepting Nb-97m, all of these have short half-lives and will not contribute significant activity from decay. Nb-97m, will increase the activity of Nb-97 at one day, by about 10 Ci, but at 30 days, the Nb-97 is below 10^{-9} Ci (7E-10 Ci).

A total of 287 isotopes were subsequently identified in the raffinate after 1 day, with 137, 101, and 98, isotopes having greater than 10^{-9} Ci after 30, 180, and 365 days, respectively. These isotopes were used to generate the raffinate radionuclide concentration and compared against the waste classification tables and rules for land disposal according to Waste Classification, 10 CFR § 61.55 (2001).[4]

2.2 <u>Quality Assurance</u>

Requirements for performing reviews of technical reports and the extent of review are established in manual E7 2.60. SRNL documents the extent and type of review using the SRNL Technical Report Design Checklist contained in WSRC-IM-2002-00011, Rev. 2.

3.0 Results and Discussion

3.1 <u>Radionuclide Inventory Assessment</u>

A list of the calculated radionuclide inventory used to evaluate the raffinate is provided in Appendix A. That list includes all the radionuclides with an activity $>10^{-9}$ Ci before decay (time = 0 days) for 1 complete LEU core. Although the waste classification limits are normalized, in order to estimate the total activity and volumes of waste, multipliers can be applied to account for the actual number of cores processed and volume of effluent. Niowave intends to recover several isotopes, in addition to Mo-99, all of which are included the radionuclide inventory calculations. As such, the projected radionuclide inventory can be considered conservative with respect to waste classification calculations.

A summary of the projected waste classification based on the 10 CFR Part 61 for near surface land burial is provided in Table 1. Appendix B provides more detailed information on how to use the 10 CFR Part 61 guidelines for waste disposal classification. The vast majority of the radionuclide constituents described in the classification guidelines can be expected to be produced in Class A quantities. However, Cs-137, Sr-90, Pu-239, and several radionuclides with a <5 year half-life are in concentrations that, when combined in a single waste stream, are projected to be Class C or greater than Class C. These select radionuclides can be expected to have the greatest impact on waste classification.

3.1.1 Cs-137 / Sr-90

Cs-137 and Sr-90 are medium-lived radioisotopes that are produced in sufficient quantity to contribute enough activity to be nominally Class B, but more likely to be Class C, when combined together or with other radionuclides because of the sum of fractions rule for mixed radionuclides. There will be no significant reduction in activity after 1 year of decay from either of these radioisotopes.

3.1.2 Radionuclides with half-life less than 5 years

246 of the 299 select radionuclides (82%) have a half-life less than 5 years. Significant reduction in activity from these radioisotopes will result after 1 year of decay. For example, excluding Mo-99 and Tc-99m, the combined radionuclide inventory with half-life <5 years has ~$1x10^5$ Ci of original activity, which after 1 year of decay, has ~250 Ci of activity. In this scenario, ~0.1% of the radionuclide inventory with half-life <5 years would meet Class A disposal guidelines when produced, compared to ~32% meeting Class A disposal guidelines after 1 year of decay. When radioisotopes such as Pr-144, Ce-144, Nb-95, and Zr-95 are excluded, the remaining inventory after 1 year of decay is calculated to meet Class A disposal guidelines.

There is no Class B or Class C limit specification for this list of radionuclides. If the classification is greater than Class A, then practical considerations like thermal loading, handling, and transportation are considered.

3.1.3 Pu-239

Pu-239 is an alpha emitting transuranic element with half-life >5 years. This radioisotope accounts for more than 99% of the total activity from alpha emitting transuranic elements with half-life >5 years. When Pu-239 is removed from the waste stream, the remaining inventory is calculated to meet Class A disposal guidelines. Regardless of the fate of Pu-239 – whether it is recycled with the U or otherwise – the estimated quantities of Pu-239 produced will be greater than can be expected to maintain a less than Class C waste. The analysis indicates that ~40-50% of the Pu-239 can be combined with the process raffinate and still maintain a Class C waste.

3.2 Waste Disposal Considerations

3.2.1 Radionuclide inventory from the LEU cores

The nominal waste classifications for the radionuclide inventory in the raffinate was based on chemical processing volumes taken at the point of generation. Any processing steps that were not considered in this analysis of the baseline UREX and MoLLE process will affect the total volume of the waste at point of generation, and hence, the classification. Figure 1 describes how a process that generated more or less raffinate will affect a given radionuclide's waste classification. Although not explicitly shown, it can be understood that stockpiling radionuclides that are troublesome to meet classification limits, may have significant impact on the future ability to dispose of them as the activity may increase in concentration relative to volume or mass.

The waste classifications calculated for this task are based on untreated waste. Waste treatment, which requires specific permitting, is not to be used a method to affect the waste classification at the point of generation. If Niowave were to consider treating the raffinate waste, the final volume of waste would depend upon the density of final treated waste package or waste form material, but the bulk density of many cementitious materials is less than 2 times that of the process raffinate. A more detailed discussion of waste treatment, including the advantages and disadvantages, is provided in Appendix B.

3.2.2 Additional waste streams

The described radionuclide inventory calculated to result from the irradiation and decay of Niowave's LEU cores, represents but one, combined waste stream. In practice, Niowave's operations will result in multiple waste streams, each with varying amounts of the radionuclide inventory. For example, contaminated and spent process equipment, raffinate fractionation, end-of-life reactor components, PPE, etc. will contribute to the aggregate waste volumes and categories that are generated. These will need to be identified in order to evaluate and develop a comprehensive waste management strategy. Furthermore, a greater understanding of the complete waste generation outlook would be valuable to develop the most economic and efficient disposition of the more troublesome waste constituents like Pu-239 and Cs-137.

Table 1. Waste classification projection for combined UREX/MoLLE process raffinate based on Niowave UTA-3 facility.

	Original Fuel		Decayed – 30 days		Decayed – 180 days		Decayed – 365 days		Class Limits[3]			
	Activity (Ci, unless noted)	Concentration (units equal class)	Activity (Ci, unless noted)	Concentration (units equal class)	Activity (Ci, unless noted)	Concentration (units equal class)	Activity (Ci, unless noted)	Concentration (units equal class)	A	B	C	Class Units
Table 1 Isotopes[1]												
Tc-99	4.56E-04	3.77E-03	7.56E-04	6.25E-03	7.56E-04	6.25E-03	7.56E-04	6.25E-03	0.3	n/a	3	Ci/m^3
I-129	8.00E-07	6.61E-06	8.67E-07	7.17E-06	9.41E-07	7.78E-06	9.45E-07	7.81E-06	0.008	n/a	0.08	Ci/m^3
Alpha emitting TRU with half-life > 5 y (**in nCi**)	1.78E+07	1.47E+02	2.61E+07	2.16E+02	2.61E+07	2.16E+02	2.61E+07	2.16E+02	10	n/a	100	nCi/g
Pu-241 (**in nCi**)	2.26E+04	1.87E-01	2.25E+04	1.86E-01	2.21E+04	1.82E-01	2.15E+04	1.78E-01	350	n/a	3500	nCi/g
Cm-242 (**in nCi**)	0.00E+00	0.00E+00	7.46E-03	6.17E-08	3.94E-03	3.26E-08	1.79E-03	1.48E-08	2000	n/a	20000	nCi/g
Table 2 Isotopes[2]												
Total of all nuclides <5 year half-life	1.23E+05	1.02E+06	7.28E+03	6.01E+04	9.22E+02	7.62E+03	2.66E+02	2.20E+03	700	NLE[4]	NLE	Ci/m^3
H-3	2.14E-02	1.77E-01	2.13E-02	1.76E-01	2.08E-02	1.72E-01	2.02E-02	1.67E-01	40	NLE	NLE	Ci/m^3
Sr-90	5.18E+00	4.28E+01	5.17E+00	4.27E+01	5.12E+00	4.23E+01	5.06E+00	4.18E+01	0.04	150	7000	Ci/m^3
Cs-137	5.38E+00	4.45E+01	5.37E+00	4.44E+01	5.32E+00	4.40E+01	5.26E+00	4.35E+01	1	44	4600	Ci/m^3
Total Curies	**1.23E+05**		**7.29E+03**		**9.32E+02**		**2.77E+02**					

Class A
Class B
Class C
> Class A, no established limit
> Class C

[1]C-14, C-14 in activated metal, Ni-59 in activated metal, and Nb-94 in activated metal are listed in Waste Classification, 10 CFR § 61.55 (2001), but are not considered in the process raffinate.
[2]Co-60, Ni-63, and Ni-63 in activated metal are listed in Waste Classification, 10 CFR § 61.55 (2001)., but not considered in the process raffinate.
[3]Values from Waste Classification, 10 CFR § 61.55 (2001).
[4]There are no limits established for these radionuclides in Class B or C wastes. Practical considerations such as the effects of external radiation and internal heat generation on transportation, handling, and disposal will limit the concentrations for these wastes.

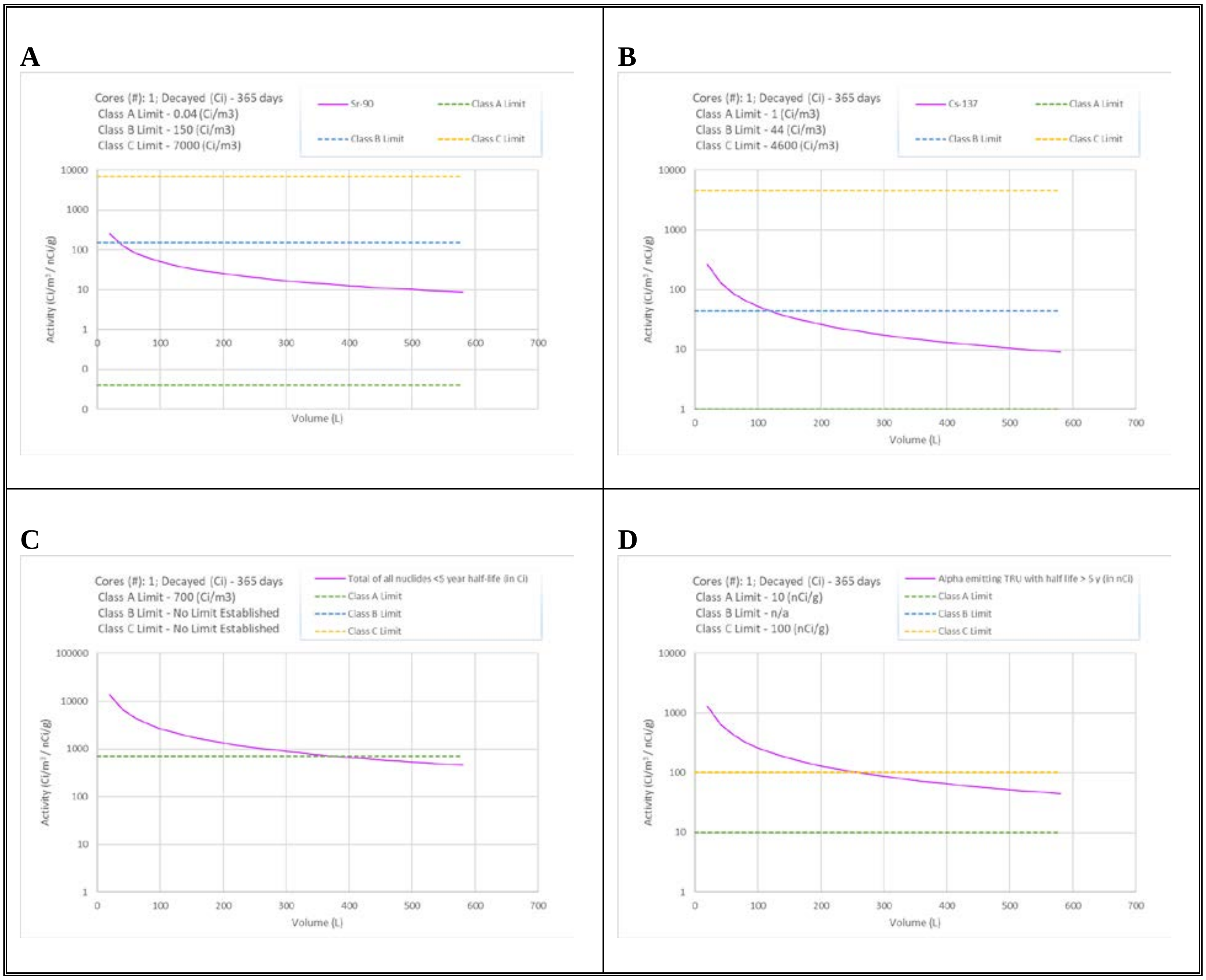

Figure 1. Normalized activity of (A) Sr-90, (B) Cs-137, (C) total of radionuclides half-life <5 years, and (D) alpha emitting TRU with half-life >5 years as a function of concentration in the combined UREX and MoLLE raffinate. Baseline volume is 121 L. 10 CFR Part 61 waste classification limits are shown for reference.

4.0 Conclusions

This report describes the chemical processing raffinate waste Niowave will generate, assuming no recovery. The evaluation of the radionuclide inventory from irradiation and decay from Niowave's UTA-3 commercial-scale process indicated that the majority of waste generated can be expected to be Class A, according to 10 CFR Part 61 for land burial in near surface facilities. However, radioisotopes such as Pu-239, Cs-137, Sr-90, and some of the shorter lived (<5 year half-life) will challenge Niowave's ability to meet waste acceptance criteria for land burial. Nevertheless, with appropriate waste management strategies, it is highly probable that Niowave's waste could meet Class C requirements for all constituents, with the exception of possibly Pu-239.

The estimated radionuclide inventory describes, in general terms, the projected waste classification outlook. However, more detailed information of Niowave's processes are needed to form a more accurate understanding required to execute an effective, economic, and feasible waste management strategy.

5.0 Recommendations

The data presented in this report is intended to serve as a guide from which to identify an effective path to waste disposition for Niowave. Successful waste management requires a robust and sensible strategy. Niowave is in a favorable operational phase to develop a waste management plan in tandem with commercialization of their radionuclide production. The nature of radioactive materials and the regulatory aspects to dispose of their associated waste necessitate effective waste management as part of a greater business strategy. A successful waste management strategy will result in reduced life-cycle operational costs and will demonstrate a commensurate level of safeguards and security that will strengthen stakeholder support now and into the future. An integrated approach that seeks to optimize the radionuclide production in concert with waste disposition considerations may have profound impacts. The following recommendations are suggested to support Niowave's successful waste management strategy:

1) A waste treatment plan is needed as it can have a significant impact on the business operations. Appendix B provides a brief overview of waste treatment options.

2) A more complete waste outlook should be developed to facilitate blending options that will support resource-intensive infrastructure builds and process considerations, many of which will likely be irreversible.

6.0 References

1. *B. T. Rearden, M. A. Jessee, Eds., SCALE Code System, ORNL/TM-2005/39, Oak Ridge National Laboratory , Oak Ridge, Tennessee (2016). .*
2. *RadDecay version 5.02*. Grove Software: https://radiationsoftware.com/raddecay.
3. *ICRP, 2008. Nuclear Decay Data for Dosimetric Calculations. ICRP Publication 107. Ann. ICRP 38 (3).*
4. *Waste Classification, 10 CFR § 61.55 (2001).*

Appendix A. Radionuclide inventory calculated for a single LEU fuel core after 0, 30, 180, and 360 days following irradiation and 1 day of cooling.

Nuclide	half-life (yrs)	Original (Ci)*	Decayed (Ci) - 30 days	Decayed (Ci) - 180 days	Decayed (Ci) - 365 days
Ac-225	2.74E-02		4.92E-15	1.08E-13	2.46E-13
Ac-227	2.18E+01		1.72E-11	4.61E-10	1.82E-09
Ac-228	7.02E-04		5.13E-19	1.85E-17	7.49E-17
Ag-109m	1.26E-06	2.43E+01	0.00E+00	0.00E+00	0.00E+00
Ag-110	7.80E-07	3.19E-07	2.93E-07	1.93E-07	1.16E-07
Ag-110m	6.84E-01	2.34E-05	2.15E-05	1.42E-05	8.50E-06
Ag-111	2.04E-02	1.90E+01	1.17E+00	1.01E-06	3.39E-14
Ag-111m	2.05E-06	8.12E-04	0.00E+00	0.00E+00	0.00E+00
Ag-112	3.57E-04	1.84E+01	9.11E-10	2.68E-61	7.46E-125
Ag-113	6.13E-04	1.06E+00	4.61E-41	7.18E-243	0.00E+00
Am-241	4.32E+02		2.97E-09	1.76E-08	3.53E-08
Am-242	1.83E-03	2.49E-09	7.36E-23	1.66E-90	6.14E-174
As-74	4.87E-02	1.87E-08	5.80E-09	1.67E-11	1.23E-14
As-76	2.95E-03	2.32E-04	9.69E-13	1.23E-54	2.64E-106
As-77	4.43E-03	1.25E+01	3.67E-05	4.52E-33	1.71E-67
As-78	1.73E-04	7.16E-03	9.71E-146	0.00E+00	0.00E+00
At-217	1.02E-09		4.92E-15	1.08E-13	2.46E-13
At-218	4.76E-08		3.47E-16	1.13E-14	4.59E-14
At-219	1.78E-06		1.42E-17	3.81E-16	1.51E-15
Ba-135m	3.28E-03	4.44E-05	1.25E-12	2.17E-50	5.82E-97
Ba-137m	4.86E-06	5.09E+00	5.07E+00	5.02E+00	4.96E+00
Ba-139	1.58E-04	8.60E-02	2.33E-158	0.00E+00	0.00E+00
Ba-140	3.49E-02	3.66E+03	7.17E+02	2.06E-01	8.85E-06
Bi-210	1.37E-02		8.18E-16	2.60E-13	2.25E-12
Bi-211	4.07E-06		2.14E-12	2.86E-10	1.44E-09
Bi-212	1.15E-04		2.26E-12	1.64E-11	3.12E-11
Bi-213	8.67E-05		4.90E-15	1.08E-13	2.46E-13
Bi-214	3.79E-05		1.73E-12	5.66E-11	2.30E-10
Bi-215	1.45E-05		1.38E-17	3.70E-16	1.46E-15
Br-80	3.36E-05	5.63E-06	5.24E-55	3.66E-300	0.00E+00
Br-80m	5.05E-04	5.25E-06	4.89E-55	3.42E-300	0.00E+00
Br-82	4.03E-03	7.26E-02	5.26E-08	1.05E-38	1.44E-76
Br-83	2.74E-04	1.19E+00	5.84E-91	0.00E+00	0.00E+00
Cd-113	7.70E+15		8.29E-20	8.29E-20	8.29E-20
Cd-113m	1.41E+01	3.69E-04	3.68E-04	3.61E-04	3.52E-04
Cd-115	6.10E-03	1.95E+01	1.72E-03	9.21E-24	9.18E-49

Nuclide	half-life (yrs)	Original (Ci)	Decayed (Ci) - 30 days	Decayed (Ci) - 180 days	Decayed (Ci) - 365 days
Cd-115m	1.22E-01	1.76E-01	1.10E-01	1.07E-02	6.05E-04
Cd-117	2.84E-04	3.11E-02	2.81E-89	0.00E+00	0.00E+00
Cd-117m	3.84E-04	4.25E-02	1.32E-66	0.00E+00	0.00E+00
Cd-118	9.57E-05	7.12E-08	2.06E-266	0.00E+00	0.00E+00
Ce-139	3.77E-01	1.76E-07	1.51E-07	7.11E-08	2.80E-08
Ce-141	8.90E-02	1.56E+03	8.23E+02	3.36E+01	6.51E-01
Ce-143	3.77E-03	6.87E+03	1.89E-03	2.99E-36	1.05E-76
Ce-144	7.80E-01	1.81E+02	1.68E+02	1.17E+02	7.45E+01
Cm-242	4.46E-01		7.46E-12	3.94E-12	1.79E-12
Cs-131	2.65E-02	7.53E-09	8.80E-10	1.92E-14	3.44E-20
Cs-132	1.78E-02	7.55E-05	3.05E-06	3.27E-13	8.30E-22
Cs-134	2.06E+00	1.62E-03	1.58E-03	1.37E-03	1.16E-03
Cs-134m	3.31E-04	2.60E-04	5.67E-79	0.00E+00	0.00E+00
Cs-135	2.30E+06	6.04E-05	6.27E-05	6.27E-05	6.27E-05
Cs-135m	1.01E-04	3.30E-09	1.41E-254	0.00E+00	0.00E+00
Cs-136	3.61E-02	2.49E+00	5.13E-01	1.90E-04	1.11E-08
Cs-137	3.02E+01	5.38E+00	5.37E+00	5.32E+00	5.26E+00
Cs-138	6.36E-05	2.36E-09	0.00E+00	0.00E+00	0.00E+00
Cu-66	9.74E-06	5.33E-04	5.71E-08	8.11E-28	2.69E-52
Cu-67	7.06E-03	1.77E-03	5.53E-07	1.64E-24	3.97E-46
Dy-165	2.66E-04	1.03E-05	1.41E-98	0.00E+00	0.00E+00
Dy-166	9.32E-03	4.69E-03	1.04E-05	5.42E-19	2.26E-35
Er-167m	7.19E-08	2.86E-06	0.00E+00	0.00E+00	0.00E+00
Er-169	2.58E-02	6.54E-04	7.16E-05	1.13E-09	1.34E-15
Er-171	8.58E-04	5.63E-05	8.19E-34	5.33E-178	0.00E+00
Er-172	5.63E-03	4.61E-04	1.85E-08	1.93E-30	1.49E-57
Eu-152	1.35E+01	8.54E-08	8.50E-08	8.33E-08	8.11E-08
Eu-152m	1.06E-03	2.20E-05	1.16E-28	4.82E-145	1.40E-288
Eu-154	8.59E+00	1.43E-04	1.42E-04	1.37E-04	1.32E-04
Eu-155	4.76E+00	1.95E-01	1.93E-01	1.82E-01	1.69E-01
Eu-156	4.16E-02	8.93E+00	2.31E+00	2.46E-03	5.30E-07
Eu-157	1.73E-03	4.92E+00	2.59E-14	1.06E-85	9.44E-174
Eu-158	8.73E-05	3.10E-09	1.48E-292	0.00E+00	0.00E+00
Fr-221	9.32E-06		4.92E-15	1.08E-13	2.46E-13
Fr-223	4.19E-05		2.37E-13	6.36E-12	2.51E-11
Ga-72	1.61E-03	5.78E-02	1.48E-06	7.30E-30	1.32E-58
Ga-73	5.55E-04	8.09E-03	2.05E-47	2.12E-270	0.00E+00
Gd-152	1.08E+14		1.68E-22	2.30E-22	3.05E-22
Gd-159	2.11E-03	1.07E+00	2.00E-12	4.52E-71	2.12E-143
Ge-71	3.13E-02	1.29E-09	2.09E-10	2.34E-14	3.15E-19

Nuclide	half-life (yrs)	Original (Ci)	Decayed (Ci) - 30 days	Decayed (Ci) - 180 days	Decayed (Ci) - 365 days
Ge-75	1.57E-04	1.32E-05	1.06E-162	0.00E+00	0.00E+00
Ge-77	1.29E-03	3.66E+00	2.41E-19	3.02E-115	1.58E-233
Ge-78	1.67E-04	4.94E-04	8.23E-152	0.00E+00	0.00E+00
H-3	1.23E+01	2.14E-02	2.13E-02	2.08E-02	2.02E-02
Hg-206	1.55E-05		2.86E-23	5.55E-21	4.53E-20
Ho-166	3.06E-03	5.02E-03	1.54E-05	8.08E-19	3.37E-35
Ho-167	3.54E-04	2.39E-05	2.90E-75	0.00E+00	0.00E+00
I-126	3.54E-02	2.02E-07	4.04E-08	1.30E-11	6.42E-16
I-129	1.57E+07	8.00E-07	8.67E-07	9.41E-07	9.45E-07
I-130	1.41E-03	1.15E-01	3.35E-19	7.02E-107	5.12E-215
I-131	2.20E-02	2.36E+03	1.83E+02	4.30E-04	4.90E-11
I-132	2.62E-04	5.52E+03	8.37E+00	6.76E-14	2.81E-31
I-132m	1.58E-04	1.14E-04	6.17E-161	0.00E+00	0.00E+00
I-133	2.37E-03	6.03E+03	2.29E-07	1.81E-59	1.00E-123
I-134	9.98E-05	3.80E-04	7.55E-252	0.00E+00	0.00E+00
I-135	7.49E-04	9.88E+02	1.01E-30	1.14E-195	0.00E+00
In-114	2.28E-06	4.69E-09	3.08E-09	3.78E-10	2.83E-11
In-114m	1.36E-01	4.85E-09	3.19E-09	3.90E-10	2.93E-11
In-115	4.41E+14		2.98E-16	3.25E-16	3.28E-16
In-115m	5.12E-04	2.13E+01	1.89E-03	1.14E-06	6.43E-08
In-117	8.22E-05	1.32E-01	1.69E-66	0.00E+00	0.00E+00
In-117m	2.21E-04	1.14E-01	3.12E-68	0.00E+00	0.00E+00
In-118	1.59E-07	7.13E-08	2.06E-266	0.00E+00	0.00E+00
Kr-83m	2.09E-04	4.53E+00	1.52E-08	4.56E-09	1.03E-09
Kr-85	1.08E+01	6.81E-01	6.78E-01	6.60E-01	6.39E-01
Kr-85m	5.11E-04	6.27E+01	2.61E-47	3.30E-289	0.00E+00
Kr-87	1.45E-04	1.05E-02	3.82E-173	0.00E+00	0.00E+00
Kr-88	3.24E-04	1.97E+01	9.48E-76	0.00E+00	0.00E+00
La-140	4.59E-03	3.06E+03	8.25E+02	2.37E-01	1.02E-05
La-141	4.47E-04	1.79E+02	9.15E-54	0.00E+00	0.00E+00
La-142	1.73E-04	2.25E-01	4.00E-144	0.00E+00	0.00E+00
Mo-99	7.52E-03	7.75E+03	4.00E+00	1.47E-16	7.91E-37
Nb-93m	1.61E+01	4.94E-08	4.20E-07	2.25E-06	4.47E-06
Nb-95	9.58E-02	7.85E+01	3.89E+02	2.33E+02	3.75E+01
Nb-95m	9.88E-03	5.52E+00	7.58E+00	1.50E+00	2.02E-01
Nb-96	2.66E-03	5.08E-01	2.65E-10	1.03E-56	5.91E-114
Nb-97	1.37E-04	4.67E+03	5.33E-10	1.01E-74	1.51E-154
Nb-98m	9.75E-05	2.57E-07	8.15E-261	0.00E+00	0.00E+00
Nd-144	2.29E+15		4.34E-15	2.19E-14	3.63E-14
Nd-147	3.01E-02	1.49E+03	2.24E+02	1.73E-02	1.47E-07

Nuclide	half-life (yrs)	Original (Ci)	Decayed (Ci) - 30 days	Decayed (Ci) - 180 days	Decayed (Ci) - 365 days
Nd-149	1.97E-04	1.46E-01	5.43E-127	0.00E+00	0.00E+00
Ni-65	2.87E-04	3.57E-09	2.81E-95	0.00E+00	0.00E+00
Ni-66	6.23E-03	5.32E-04	5.71E-08	8.09E-28	2.68E-52
Np-236m	2.57E-03	4.28E-07	9.97E-17	6.82E-65	2.69E-124
Np-237	2.14E+06	6.61E-07	1.80E-06	1.86E-06	1.86E-06
Np-238	5.80E-03	2.07E-02	1.12E-06	5.26E-28	2.60E-54
Np-239	6.46E-03	3.08E+04	4.53E+00	3.12E-19	7.27E-43
Np-240	1.18E-04	2.77E-07	2.26E-217	0.00E+00	0.00E+00
Pa-231	3.28E+04	1.99E-09	1.12E-08	5.70E-08	1.14E-07
Pa-232	3.59E-03	2.00E-06	2.55E-13	8.67E-48	2.67E-90
Pa-233	7.39E-02	2.84E-07	9.64E-07	1.84E-06	1.86E-06
Pa-234	7.65E-04	3.37E-06	8.03E-06	1.21E-05	1.22E-05
Pa-234m	2.23E-06	1.56E-03	5.05E-03	7.57E-03	7.60E-03
Pb-209	3.71E-04		4.83E-15	1.08E-13	2.46E-13
Pb-210	2.22E+01		1.49E-15	2.92E-13	2.38E-12
Pb-211	6.87E-05		2.14E-12	2.86E-10	1.44E-09
Pb-212	1.21E-03		2.27E-12	1.64E-11	3.12E-11
Pb-214	5.10E-05		1.73E-12	5.66E-11	2.30E-10
Pd-107	6.50E+06	7.61E-07	7.61E-07	7.61E-07	7.61E-07
Pd-109	1.56E-03	2.43E+01	3.69E-15	2.96E-94	8.30E-192
Pd-111	4.45E-05	6.56E-04	0.00E+00	0.00E+00	0.00E+00
Pd-112	2.40E-03	1.57E+01	7.76E-10	2.28E-61	6.35E-125
Pm-146	5.53E+00	2.56E-08	2.53E-08	2.41E-08	2.26E-08
Pm-147	2.62E+00	5.40E+00	1.96E+01	1.99E+01	1.74E+01
Pm-148	1.52E-02	1.20E-01	3.01E-03	4.28E-05	1.92E-06
Pm-148m	1.13E-01	1.82E-02	1.10E-02	8.87E-04	3.97E-05
Pm-149	6.06E-03	1.43E+03	1.18E-01	4.52E-22	2.99E-47
Pm-150	3.06E-04	4.06E-03	5.43E-84	0.00E+00	0.00E+00
Pm-151	3.24E-03	4.66E+02	1.09E-05	7.55E-44	6.54E-91
Po-210	3.79E-01		2.69E-17	4.85E-14	7.37E-13
Po-211	1.64E-08		5.91E-15	7.88E-13	3.96E-12
Po-212	9.48E-15		1.45E-12	1.05E-11	2.00E-11
Po-213	1.33E-13		4.80E-15	1.05E-13	2.41E-13
Po-214	5.21E-12		1.73E-12	5.66E-11	2.30E-10
Po-215	5.65E-11		2.15E-12	2.86E-10	1.44E-09
Po-216	4.60E-09		2.33E-12	1.64E-11	3.12E-11
Po-218	5.90E-06		1.74E-12	5.66E-11	2.30E-10
Pr-142	2.18E-03	5.85E-03	2.70E-14	5.65E-71	7.04E-141
Pr-143	3.72E-02	2.93E+03	8.00E+02	3.77E-01	2.96E-05
Pr-144	3.29E-05	1.81E+02	1.68E+02	1.17E+02	7.45E+01

Nuclide	half-life (yrs)	Original (Ci)	Decayed (Ci) - 30 days	Decayed (Ci) - 180 days	Decayed (Ci) - 365 days
Pr-144m	1.37E-05	1.73E+00	1.64E+00	1.14E+00	7.28E-01
Pr-145	6.83E-04	4.83E+02	2.91E-34	2.31E-215	0.00E+00
Pu-236	2.86E+00		1.81E-10	1.64E-10	1.45E-10
Pu-238	8.77E+01	1.82E-06	3.19E-06	3.18E-06	3.16E-06
Pu-239	2.41E+04	1.78E-02	2.60E-02	2.60E-02	2.60E-02
Pu-240	6.56E+03	3.31E-05	3.31E-05	3.31E-05	3.31E-05
Pu-241	1.44E+01	2.26E-05	2.25E-05	2.21E-05	2.15E-05
Pu-242	3.75E+05		2.10E-18	2.10E-18	2.10E-18
Ra-223	3.13E-02		2.15E-12	2.86E-10	1.44E-09
Ra-224	1.00E-02		2.34E-12	1.64E-11	3.12E-11
Ra-225	4.08E-02		1.03E-14	1.18E-13	2.57E-13
Ra-226	1.60E+03		2.35E-12	6.00E-11	2.37E-10
Ra-228	5.75E+00		5.26E-19	1.86E-17	7.51E-17
Rb-83	2.36E-01	2.61E-08	2.05E-08	6.14E-09	1.39E-09
Rb-84	8.98E-02	9.98E-07	5.29E-07	2.22E-08	4.43E-10
Rb-86	5.11E-02	4.40E-03	1.44E-03	5.46E-06	5.62E-09
Rb-87	4.92E+10	1.38E-09	1.38E-09	1.38E-09	1.38E-09
Rb-88	3.38E-05	2.20E+01	1.06E-75	0.00E+00	0.00E+00
Rh-102	5.67E-01	3.38E-08	3.06E-08	1.85E-08	9.96E-09
Rh-102m	3.74E+00	4.29E-09	4.23E-09	3.92E-09	3.57E-09
Rh-103m	1.07E-04	6.97E+02	4.10E+02	2.90E+01	1.11E+00
Rh-105	4.03E-03	1.37E+03	1.02E-03	2.30E-34	3.65E-72
Rh-106	9.44E-07	1.19E+01	1.13E+01	8.52E+00	6.05E+00
Rh-106m	2.49E-04	6.67E-04	3.57E-103	0.00E+00	0.00E+00
Rn-218	1.11E-09		3.47E-19	1.13E-17	4.59E-17
Rn-219	1.26E-07		2.15E-12	2.86E-10	1.44E-09
Rn-220	1.76E-06		2.33E-12	1.64E-11	3.12E-11
Rn-222	1.05E-02		1.74E-12	5.66E-11	2.30E-10
Ru-103	1.07E-01	7.05E+02	4.15E+02	2.94E+01	1.12E+00
Ru-105	5.07E-04	5.08E+01	7.77E-48	6.48E-292	0.00E+00
Ru-106	1.02E+00	1.19E+01	1.13E+01	8.52E+00	6.05E+00
Sb-119	4.36E-03	4.99E-09	1.05E-14	4.43E-43	4.45E-78
Sb-120m	1.58E-02	1.54E-07	4.17E-09	6.03E-17	1.29E-26
Sb-122	7.46E-03	1.53E-03	7.40E-07	1.96E-23	7.01E-44
Sb-124	1.65E-01	2.09E-03	1.48E-03	2.63E-04	3.13E-05
Sb-125	2.76E+00	2.65E-01	3.44E-01	3.20E-01	2.82E-01
Sb-126	3.38E-02	5.30E-01	9.84E-02	2.86E-05	6.87E-06
Sb-126m	3.64E-05	6.87E-06	0.00E+00	0.00E+00	0.00E+00
Sb-127	1.05E-02	1.92E+02	8.66E-01	1.62E-12	5.55E-27
Sb-128	1.03E-03	7.59E+00	6.68E-24	3.52E-144	1.60E-292

Nuclide	half-life (yrs)	Original (Ci)	Decayed (Ci) - 30 days	Decayed (Ci) - 180 days	Decayed (Ci) - 365 days
Sb-128m	1.98E-05	3.70E-05	0.00E+00	0.00E+00	0.00E+00
Sb-129	5.02E-04	2.54E+01	1.40E-48	7.05E-295	0.00E+00
Sb-130	7.51E-05	1.59E-08	0.00E+00	0.00E+00	0.00E+00
Se-77m	5.50E-07	4.17E-02	0.00E+00	0.00E+00	0.00E+00
Se-79	2.95E+05	4.01E-06	4.01E-06	4.01E-06	4.01E-06
Se-81	3.51E-05	1.08E-06	9.96E-234	0.00E+00	0.00E+00
Se-81m	1.09E-04	7.30E-07	6.75E-234	0.00E+00	0.00E+00
Sm-146	1.03E+08		4.79E-18	2.80E-17	5.50E-17
Sm-147	1.06E+11		7.88E-12	6.36E-11	1.25E-10
Sm-148	7.00E+15		3.62E-19	5.31E-19	5.45E-19
Sm-151	9.00E+01	1.08E-01	1.25E-01	1.24E-01	1.24E-01
Sm-153	5.30E-03	2.11E+02	4.60E-03	2.28E-26	4.11E-55
Sm-156	1.07E-03	5.68E+00	4.97E-23	2.56E-138	1.66E-280
Sn-117m	3.77E-02	1.88E-02	4.15E-03	2.17E-06	1.95E-10
Sn-119m	8.03E-01	1.73E-02	1.61E-02	1.13E-02	7.30E-03
Sn-121	3.09E-03	1.61E+01	5.20E-04	5.17E-04	5.13E-04
Sn-121m	4.39E+01	6.71E-04	6.70E-04	6.66E-04	6.61E-04
Sn-123	3.54E-01	8.15E-02	6.94E-02	3.10E-02	1.15E-02
Sn-125	2.64E-02	1.01E+01	1.17E+00	2.42E-05	4.04E-11
Sn-126	2.31E+05	6.87E-06	6.87E-06	6.87E-06	6.87E-06
Sn-127	2.40E-04	6.93E-02	4.27E-105	0.00E+00	0.00E+00
Sn-128	1.12E-04	3.04E-05	2.13E-225	0.00E+00	0.00E+00
Sr-85	1.78E-01	1.07E-08	7.76E-09	1.56E-09	2.16E-10
Sr-87m	3.21E-04	1.32E-06	2.61E-11	6.86E-25	1.22E-41
Sr-89	1.38E-01	8.33E+02	5.52E+02	7.05E+01	5.57E+00
Sr-90	2.88E+01	5.18E+00	5.17E+00	5.12E+00	5.06E+00
Sr-91	1.10E-03	2.02E+03	6.29E-20	1.84E-132	2.96E-271
Sr-92	3.03E-04	2.50E+01	8.24E-81	0.00E+00	0.00E+00
Tb-160	1.98E-01	2.98E-05	2.24E-05	5.31E-06	9.01E-07
Tb-161	1.89E-02	1.31E-01	6.45E-03	1.87E-09	1.61E-17
Tc-99	2.11E+05	4.56E-04	7.56E-04	7.56E-04	7.56E-04
Tc-99m	6.86E-04	7.42E+03	3.86E+00	1.42E-16	7.63E-37
Te-123	6.00E+14		1.35E-23	5.47E-23	7.42E-23
Te-123m	3.26E-01	1.55E-07	1.30E-07	5.44E-08	1.86E-08
Te-125m	1.57E-01	3.07E-03	2.47E-02	6.83E-02	6.81E-02
Te-127	1.07E-03	1.74E+02	2.76E+00	7.59E-01	2.34E-01
Te-127m	2.98E-01	1.19E+00	2.00E+00	7.74E-01	2.39E-01
Te-129	1.32E-04	4.47E+01	8.34E+00	3.78E-01	8.31E-03
Te-129m	9.20E-02	2.45E+01	1.32E+01	5.99E-01	1.32E-02
Te-131	4.75E-05	1.25E+02	6.40E-06	4.82E-42	1.35E-86

Nuclide	half-life (yrs)	Original (Ci)	Decayed (Ci) - 30 days	Decayed (Ci) - 180 days	Decayed (Ci) - 365 days
Te-131m	3.42E-03	4.77E+02	2.84E-05	2.14E-41	5.99E-86
Te-132	8.28E-03	5.35E+03	8.12E+00	6.55E-14	2.72E-31
Te-133	2.38E-05	2.37E-05	4.58E-240	0.00E+00	0.00E+00
Te-133m	1.05E-04	1.11E-04	2.03E-239	0.00E+00	0.00E+00
Te-134	7.95E-05	5.86E-07	0.00E+00	0.00E+00	0.00E+00
Th-227	5.12E-02		5.43E-12	3.42E-10	1.55E-09
Th-228	1.91E+00		2.87E-12	1.69E-11	3.16E-11
Th-229	7.34E+03		2.24E-14	1.35E-13	2.73E-13
Th-230	7.54E+04	2.29E-08	1.09E-07	5.40E-07	1.07E-06
Th-231	2.91E-03	5.28E-03	5.28E-03	5.28E-03	5.28E-03
Th-232	1.41E+10		1.07E-16	6.39E-16	1.30E-15
Th-234	6.60E-02	1.56E-03	5.05E-03	7.57E-03	7.60E-03
Tl-206	7.99E-06		1.13E-21	3.49E-19	3.01E-18
Tl-207	9.08E-06		2.13E-12	2.85E-10	1.43E-09
Tl-208	5.81E-06		8.14E-13	5.89E-12	1.12E-11
Tl-209	4.11E-06		1.02E-16	2.25E-15	5.14E-15
Tl-210	2.47E-06		3.64E-16	1.19E-14	4.82E-14
Tm-170	3.52E-01	5.57E-09	4.74E-09	2.11E-09	7.79E-10
Tm-171	1.92E+00	3.51E-06	3.43E-06	2.96E-06	2.46E-06
Tm-172	7.26E-03	4.61E-04	7.38E-07	7.32E-24	7.07E-45
U-232	6.89E+01		1.04E-10	1.04E-10	1.05E-10
U-233	1.59E+05	2.89E-09	2.89E-09	2.89E-09	2.90E-09
U-234	2.46E+05	1.14E-01	1.14E-01	1.14E-01	1.14E-01
U-235	7.04E+08	5.28E-03	5.28E-03	5.28E-03	5.28E-03
U-235m	4.95E-05		2.60E-02	2.60E-02	2.60E-02
U-236	2.34E+07	2.63E-05	2.63E-05	2.63E-05	2.63E-05
U-237	1.85E-02	1.39E+02	6.38E+00	1.31E-06	5.28E-10
U-238	4.47E+09	7.60E-03	7.60E-03	7.60E-03	7.60E-03
Xe-129m	2.43E-02	3.30E-08	3.17E-09	2.61E-14	1.40E-20
Xe-131m	3.24E-02	6.41E+00	7.00E+00	1.76E-03	3.50E-08
Xe-133	1.44E-02	7.13E+03	1.62E+02	3.96E-07	9.46E-18
Xe-133m	6.00E-03	2.96E+02	3.08E-02	7.42E-23	2.76E-48
Xe-135	1.04E-03	4.35E+03	1.34E-20	3.63E-139	2.12E-285
Xe-135m	2.91E-05	1.70E+02	8.78E-31	9.90E-196	0.00E+00
Y-87	9.10E-03	1.31E-08	2.52E-11	6.62E-25	1.18E-41
Y-88	2.92E-01	1.53E-07	1.26E-07	4.75E-08	1.43E-08
Y-89m	4.96E-07	8.03E-02	0.00E+00	0.00E+00	0.00E+00
Y-90	7.31E-03	3.35E+00	5.17E+00	5.12E+00	5.06E+00
Y-90m	3.64E-04	4.55E-05	5.18E-73	0.00E+00	0.00E+00
Y-91	1.60E-01	8.95E+02	6.38E+02	1.08E+02	1.21E+01

Nuclide	half-life (yrs)	Original (Ci)	Decayed (Ci) - 30 days	Decayed (Ci) - 180 days	Decayed (Ci) - 365 days
Y-91m	9.45E-05	1.30E+03	4.01E-20	1.17E-132	1.89E-271
Y-92	4.04E-04	3.70E+02	2.65E-59	0.00E+00	0.00E+00
Y-93	1.16E-03	2.44E+03	1.25E-18	4.38E-125	2.23E-256
Zn-69	1.07E-04	2.74E-06	4.85E-22	8.47E-101	6.21E-198
Zn-69m	1.57E-03	2.55E-06	4.52E-22	7.89E-101	5.79E-198
Zn-71m	4.52E-04	1.69E-05	3.13E-60	0.00E+00	0.00E+00
Zn-72	5.31E-03	4.71E-02	1.03E-06	5.09E-30	9.18E-59
Zr-89	8.94E-03	2.75E-09	4.73E-12	7.15E-26	6.43E-43
Zr-93	1.53E+06	1.06E-04	1.08E-04	1.08E-04	1.08E-04
Zr-95	1.75E-01	9.18E+02	6.63E+02	1.31E+02	1.77E+01
Zr-97	1.91E-03	4.35E+03	4.94E-10	9.37E-75	1.41E-154

* Blank values indicate isotopes with zero initial activity, but that grow in during decay.

Appendix B. Nuclear waste disposition and treatment practices in the United States

Classification for Land Burial

10 CFR Part 61.55, "Waste Classification" establishes criteria and limits for each of the three classes of waste (A, B, and C) that can be disposed of in near surface disposal sites.[i] Waste that is not acceptable for near-surface disposal is waste for which form and disposal methods must be in general more stringent than those specified for Class C waste. The waste class is determined by the concentration of either long-lived or short-lived radionuclides, or the combination of both. If waste contains only the radionuclides listed in the Table B-1, classification is determined as follows:

- If the concentration does not exceed 0.1 times the value in Table B-1, the waste is Class A.
- If the concentration exceeds 0.1 time the value in Table B-1 but does not exceed the value in Table B-1, the waste is Class C.
- If the concentration exceeds the value in Table B-1, the waste is not generally acceptable for near-surface disposal.
- For wastes containing mixtures of radionuclides listed in Table B-1, the total concentration shall be determined by the sum of fractions rule described below.

Table B-1. Table 1 from 10 CFR Part 61.55

Radionuclide	Concentration
C-14	8 Ci/m^3
C-14 in activated metal	80 Ci/m^3
Ni-59 in activated metal	220 Ci/m^3
Nb-94 in activated metal	0.2 Ci/m^3
Tc-99	3 Ci/m^3
I-129	0.08 Ci/m^3
Alpha emitting transuranic nuclides with half-life greater than 5 years	100 nCi/g
Pu-241	3,500 nCi/g
Cm-242	20,000 nCi/g

If the waste does not contain any of the radionuclides listed in Table B-1, classification shall be determined based on the concentrations shown in Table B-2 as follows:

- If the concentration does not exceed the value in Column 1, the waste is Class A.
- If the concentration exceeds the value in Column 1, but does not exceed the value in Column 2, the waste is Class B.
- If the concentration exceeds the value in Column 2, but does not exceed the value in Column 3, the waste is Class C.
- If the concentration exceeds the value in Column 3, the waste is not generally acceptable for near-surface disposal.
- For wastes containing mixtures of nuclides listed in Table B-2, the total concentration shall be determined by the sum of fractions rule described below.

Table B-2. Table 2 from 10 CFR Part 61.55

Radionuclide	Concentration (Ci/m^3)		
	Col. 1	**Col. 2**	**Col. 3**
Total of all nuclides with less than 5 year half-life	700	[a]	[a]
H-3	40	[a]	[a]
Co-60	700	[a]	[a]
Ni-63	3.5	70	700
Ni-63 in activated metal	35	700	7000
Sr-90	0.04	150	7000
Cs-137	1	44	4600

[a] There are no limits established for these radionuclides in Class B or C wastes. Practical considerations such as the effects of external radiation and internal heat generation on transportation, handling, and disposal will limit the concentrations for these wastes. These wastes shall be Class B unless the concentrations of other nuclides in Table B-2 determine the waste to the Class C independent of these nuclides.

If radioactive waste does not contain any nuclides listed in either Table B-1 or Table B-2, it is classified as Class A. If the waste contains a mixture of radionuclides, some of which are listed in Table B-1, and some of which are listed in Table B-2, classification shall be determined as follows:

- If the concentration of a nuclide listed in Table B-1 does not exceed 0.1 times the value listed in Table B-1, the class shall be that determined by the concentration of nuclides listed in Table B-2.
- If the concentration of a nuclide listed in Table B-1 exceeds 0.1 times the value listed in Table B-1 but does not exceed the value in Table B-1, the waste shall be Class C, provided the concentration of nuclides listed in Table B-2 does not exceed the value shown in Column 3 of Table B-2.

For determining classification for waste that contains a mixture of radionuclides, it is necessary to determine the sum of fractions by dividing each nuclide's concentration by the appropriate limit and adding the resulting values. The appropriate limits must all be taken from the same column of the same table. The sum of the fractions for the column must be less than 1.0 if the waste class is to be determined by that column. Example: A waste contains Sr-90 in a concentration of 50 Ci/m^3 and Cs-137 in a concentration of 22 Ci/m^3. Since the concentrations both exceed the values in Column 1, Table 2, they must be compared to Column 2 values. For Sr-90 fraction 50/150=0.33; for Cs-137 fraction, 22/44=0.5; the sum of the fractions=0.83. Since the sum is less than 1.0, the waste is Class B.

The concentration of a radionuclide may be determined by indirect methods such as the use of scaling factors which relate the inferred concentration of one radionuclide to another that is measured, or radionuclide material accountability, if there is reasonable assurance that the indirect methods can be correlated with actual measurements. The concentration of a radionuclide may be averaged over the volume of the waste, or weight of the waste if the units are expressed as nanocuries per gram.

Waste Disposition Guidelines

Title 10 of the *Code of Federal Regulations* (10 CFR) Part 61, "Licensing Requirement for Land Disposal of Radioactive Waste" provides procedures, criteria, and terms and conditions for the licensing of facilities for the disposal of radioactive waste.[ii] Part 61.55 provides guidance on the waste classification criteria.[i] In order to determine the waste classification the concentration of radionuclides in the waste stream must be known. 10 CFR 61.55 (a) (8) *Determination of concentrations in wastes* states "The concentration of a radionuclide may be determined by indirect methods such as use of scaling factors which relate the inferred concentration of one radionuclide to another that is measured, or radionuclide material accountability, if there is reasonable assurance that the indirect methods can be correlated with actual measurements. The concentration of a radionuclide may be averaged over the volume of the waste, or weight of the waste if the units are expressed as nanocuries per gram."[i] To provide additional guidance on complying with this requirement the NRC has provided a Concentration Averaging (CA) Branch Technical Position (BTP).[iii]

As part of developing the land disposal licensing requirements, the NRC has implemented an approach for managing the risk to a hypothetical individual who could inadvertently intrude on low level waste (LLW). A 100-year institutional control program is specified in the regulation to ensure individuals will not intrude into the disposal facility after it is closed. The 100-year period allows for substantial decay of the shorter lived radionuclides; however, after 100 years no credit can be taken for institutional controls. After the 100-year institutional control period ends, the NRC postulates that an individual unknowingly intrudes on the disposal site. To protect this individual the NRC developed the waste classification system that requires segregation of LLW into classes based upon radionuclides concentrations and also requires greater control measures for wastes with higher concentrations.

As discussed in the previous section, three classes (A, B, and C) are defined for LLW, and the controls used to manage risk, such as engineered barriers, increase with increasing waste class.

The concentration limits for various radionuclides in the 10 CFR Part 61 waste classification system in 10 CFR 61.55 were developed for *average* concentrations of wastes. The NRC does not specify in the regulations how radiological "hot spots" are to be averaged, other than to specify in 10 CFR Part 61.55(a)(8) that averaging of waste concentrations is acceptable; however, the regulations do not define the conditions and constraints on such averaging. The CA BTB is designed to answer questions such as the following:

- "How much waste above the class limits is permissible in a waste mixture?"
- "How much more concentrated than the limit can a portion of this waste be?"
- "Over what volume are these concentrations to be measured?"
- "How much credit can be taken for non-radioactive material that is mixed with LLW?"

In regards to the last question, non-radioactive material is sometimes added to LLW to make it more physically or chemically stable, but the CA BTP states that "***extreme measures of adding non-radioactive material, diluting the waste to circumvent stricter disposal requirements, should not be used***."

The CA BTP provides further guidance on blending and calculating average concentrations of waste for both blendable waste streams and waste streams containing discrete items. In general, blendable wastes are subject to fewer averaging constraints than discrete items because blendable wastes are generally not expected to have hot spots that could pose a hazard to an inadvertent intruder.

Waste Treatment Considerations

There are currently four commercial waste disposal facilities in the U.S. licensed to accept class A, B, and C LLW for disposal. A summary of these facilities is provided in Table B-3. Waste generators can either work directly with these disposal facilities, preparing waste meeting the waste acceptance criteria of the disposal site in house, or can engage a waste broker for these services.

Table B-3. Commercial Waste Disposal Facilities

Name	Location	Class Accepted	Restrictions
Clive Disposal Facility (EnergySolutions)	UT	A	Accepts from all regions
Waste Control Specialists	TX	A, B, C	Accepts from outside generators with approval of the Texas compact
Barnwell Disposal Facility (EnergySolutions)	SC	A, B, C	Only accepts from the Atlantic Compact (SC, NJ, CT)
US Ecology	WA	A, B, C	Only accepts from the Northwest and Rocky Mountain Compacts

In house treatment would require characterization and classification of the waste stream(s), identification of the appropriate disposal facility, and finally the design of the waste pretreatment and final waste form that meets the disposal facility waste acceptance criteria. This would require upfront planning and testing performed on simulated waste, followed by validation with actual waste streams once the facility is operational.

An alternative to in-house treatment is to engage a waste broker to handle many of the aspects of waste handling and disposal. A waste broker is a company that is licensed to transfer radioactive waste to licensed radioactive waste disposal or treatment facilities. Their services can range from as minimal as an interface between the waste generator and the disposal site, or as comprehensive as providing training and developing procedures at the waste generator.[iv] Table B-4 summarizes some of the main differences between the use of in-house waste treatment and engaging services from a waste broker.

Table B-4. Comparison of In-House Treatment Versus use of a Waste Broker[iv]

In-House Treatment	Waste Broker
Engage individual disposal facilities	Determine the appropriate disposal facility
Develop waste form	Characterize and develop waste treatment strategy
Dedicate facility/personnel to waste treatment	Perform waste treatment
Personnel for waste compliance/handling	Provide assistance with waste profiles/packaging
Dedicate facility for decay storage	Provides “hold for decay” service

Completion of a detailed cost and risk evaluation is recommended to compare the costs and feasibility of various in-house or waste broker strategies, including capital and operating costs in the assessment. Several inputs to the study that should be considered are included below[iv]:

- Floor plan
  - In-house: Initial cost associated with a radioactive materials waste handling, treatment, and storage area. Operation, monitoring, and maintenance of the workspace is an ongoing expense.
  - Waste Broker: Smaller waste handling and storage footprint. Reduced equipment leads to reduced maintenance cost. Monitoring cost is similar; however, contamination risk is reduced due to reduced handling.
- Characterization
  - In-house: Ongoing characterization for classification of waste encumbers analytical resources.
  - Waste Broker: Can provide sampling and characterization services as required when in-house capabilities are unavailable.
- Waste Treatment

  - In-house: Development and demonstration of a waste treatment strategy. Includes capital cost for equipment, ongoing solidification materials costs, potential generation of additional waste streams generated by cleaning solidification equipment.
  - Waste Broker: Performs initial testing using simulants to demonstrate treatment of components that need treatment in addition to stabilization, if necessary. Confirms treatment/solidification with initial waste sample. Selects method for treatment/ solidification to ensure waste form meets the waste acceptance criteria of the disposal site.
- Waste Handling – Comprised of packaging, preparation of manifests, and transportation management
  - In-house: Unless storage facilities are designed to hold sufficient waste for infrequent treatment and disposal, dedicated personnel are required to handle, track, and dispose of the waste stream(s).
  - Waste Broker: Provides trained personnel with experience in waste handing. The use of experienced personnel can reduce risk associated with waste handling.
- Disposal Site Interface
  - In-house: Prior to initial shipments, the facility will be required to obtain certification by the disposal site in accordance with the site's quality assurance generator certification program.
  - Waste Broker: Many already have quality assurance approval from disposal sites. May file applications and proposed agreements on behalf of the waste generator.

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[i] Waste Classification, 10 CFR § 61.55 (2001)
[ii] Licensing Requirement for Land Disposal of Radioactive Waste, 10 CFR § 61 (1982).
[iii] Concentration Averaging and Encapsulation Branch Technical Position, Revision 1, Volume 1, U.S. Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguards, February 2015.
[iv] Cozzi, A.D. and F.C. Johnson, Waste Management Strategies for Production of Mo-99. 2017, Savannah River National Laboratory: Aiken, SC.