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A Neutron Activated Sample Activity and Dose Rate Calculator

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A Neutron Activated Sample

Activity and Dose Rate Calculator

by

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Dedication

To my exceptionally hard-working and understanding wife Alyssa, my fun-loving and energetic daughter Eliana who lost out on many hours of fun, and to my yet to be born son; you are my everything and without you and your understanding I wouldn’t be where I am today. Thank you, and I love you with all my heart.

Abstract

A Neutron Activated Sample Activity and Dose Rate Calculator

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This paper describes the development of a Microsoft (MS) Excel workbook calculator that estimates the dose rate of a neutron activated sample by calculating the activity and associated dose rate contributions of key isotopes. The goal of the calculator is to prove a simplified and reasonably accurate dose rate estimate that can be used by technicians, students, and instructors who routinely perform Neutron Activation Analysis on samples of known material compositions. Furthermore, the calculator can be used by personnel with little or no programming experience or access to more complicated analysis software. This paper outlines the research performed and assumptions made in the development of the calculator along with the methods used for testing its output. The calculator is mostly automated and requires no programming experience and only a limited knowledge of MS excel to operate. Though unable to compare against dose rates of activated sample results, this calculator provides activity result estimates within 5% of the Wise Uranium – Neutron Activation Calculator and a calculated exposure rate within 50% of the dose rates from gamma-ray constants.

Table of Contents

List of Tables 7

List of Figures 8

1.0 - Introduction 9

2.0 - Background 10

3.0 - Available NAA Activity Estimation Methods 13

4.0 - Neutron Activated Sample Activity Calculator 16

  4.1 - NAA Does Rate Calculator Purpose 16

  4.2 - Assumptions and Calculation Methods 16

  4.3 - Data Sourcing and Uses 21

  4.4 - Calculator Development and a Brief Process Description 25

  4.5 - Calculator Use – Basic Procedure 27

  4.6 - Limitations of Use and Possible Sources of Errors 32

  4.7 - Comparison Against Real-World and Known Standards 33

5.0 - Recommendations for Follow-On Efforts 39

6.0 - CONCLUSION 40

Appendix A – Identification of Key NAA Isotopes for this Study 41

Appendix B – Irradiation and Dose Rate Laboratory Procedure 44

Appendix C – Wise Uranium – Neutron Activation Calculator Reports 50

Bibliography 83

List of Tables

Table 1: NIST Standard Sample Mass % Variance 19

Table 2: Isotope Specific Gamma Ray Constants from Plexus Scientific 24

Table 3: Comparison of Calculator Predicted vs Wise Uranium Calculated Activity...... 35

Table 4: Activity Weighted Difference Between Calculator Predicted and Wise Uranium Calculated 36

Table 5: Calculator vs. Gamma Ray Constant Derived Dose Rate at 1 Meter................. 38

List of Figures

Figure 1: WISE Uranium – Neutron Activation Calculator User Interface 14

Figure 2: Mass Attenuation Coefficient for Air, Dry (Near Sea Level)(NIST, 2022)...... 22

Figure 3: Example Data Table from the Specific Gamma-Ray Constants with Current Emission Data Journal Article from Oak Ridge national Laboratory.......... 25

Figure 4: Dose Estimating Calculator Process Description.. 26

Figure 5: User Interface Tab Display 28

Figure 6: Calculated_DoseRate Tab Display.. 30

Figure 7: Target _DoseRate Tab Display 31

1.0 - Introduction

As is the nature of conducting Neutron Activation Analysis (NAA) of samples, there are many methods available to estimate irradiated sample activity and dose rates for the purposes of health safety. Many of those methods include calculation tools methods such as Python and Monte Carlo N-Particle (MCNP) which require coding knowledge and/or licensed software to perform. The purpose of this thesis is to develop and *beta test* a simplified dose rate estimating tool using Microsoft Excel to assist NAA technicians better manage their radiation safety program without needing extensive knowledge of programming, MCNP or other licensed software.

2.0 - Background

Known as the father of nuclear medicine (Niese, 2016), in 1934 George de Heversy used 600 mg of radium, 400 mg radon, and small amounts of beryllium to irradiate pure dysprosium with neutrons. This resulted in "exceedingly" active dysprosium and described as artificial radioactivity. In 1936, he again irradiated a combined yttrium/dysprosium sample with neutrons and was able to estimate the amount of dysprosium using the techniques learned, ushering in a new era of non-destructive chemical sample characterization.

Neutron Activation Analysis entered its stride shortly after its discovery by G. Heversy. Several fields emerged making use of NAA such as nuclear forensics, archaeology, soil sciences, geology, and the semiconductor industry (Elemental Analysis, Inc., 2022). For example, nuclear forensics uses gamma rays and/or neutrons to activate non-radioactive samples at crime scenes to determine the material composition and develop evidentiary correlation of samples for use in court (Neutron Activation Analysis, 2022). NAA has become a key method of determining minute traces of elements and is able to identify nearly 70% of the elements on the periodic table (Elemental Analysis, Inc., 2022).

The creation of radioactive material is fundamental to NAA and is a cornerstone to how it works but can be burdensome from a radioactive material storage and safety perspective. The NAA process requires that a sample is bombarded with neutrons to create isotopes of elements that are inherently unstable. In most cases, unstable elements emit photon radiation, among other types of radiation, at energies that statistically correlate to known energies signatures of known isotopes. Using highly sensitive detectors, the energy signatures given off by the activated sample can be measured and the elemental composition determined. This photon radiation, in sufficient quantities, is also energetic enough to be harmful to humans and animal life. Though small samples are typically used, the result is a sample of radioactive material that presents some level of danger to the people handling the sample and or the environment.

Radiation safety is fundamental to any occupation involving sources of ionizing radiation. From x-ray machines in hospitals to nuclear reactors, the danger associated with radiation increases with exposure regardless of risk model used. Fundamentally, ionizing radiation poses direct and indirect hazards to humans by interacting with the elements contained in our bodies creating new chemicals or damaging DNA structures. For the purposes of this study, only high energy photon radiation, called gamma rays, is being discussed for simplicity and its deep body penetrating nature. Gammas rays primarily interact with the electromagnetic cloud and cause the element(s) to become ions through the removal of an electron. Once ionized, elements/molecules can more freely form new chemicals which are inherently damaging to biological processes within the body. Radiation exposure limits are set by international, regional, and/or local governing entities to minimize the threat to workers and reduce risk for the local population.
The IAEA Occupational Radiation Protection Standard (GSG-7) provides an average effective dose allowance of 20 mSv (2.0 Rem) per year to the whole body and lens of the eye. (IAEA and International Labor Office, 2018) It further allows up to 500 mSv (50 Rem) to the extremities or skin. Conversely, the US Occupational Dose limits, set by 10

CFR 20 is 50 mSv (5.0 Rem) to the hole body, 150 mSv (15 Rem) to the lens of the eye, and 500 mSv(50 Rem) to the skin or an extremity. Proper activity and dose rate estimates would better enable the NAA technicians to take appropriate engineers and administrative controls to minimize exposure and help keep personnel dose As Low as Reasonably Achievable (ALARA).

3.0 - Available NAA Activity Estimation Methods

There are many different NAA data sources that, when aggregated and properly formatted, can be used to determine the activity and dose rate from neutron activated samples. This, however, can be difficult and requires extensive knowledge in database query languages or time-consuming formatting. Some examples of online databases for the aggregation of useful NAA data include the IAEA Nuclear Data Services, IAEA Live Chart, Korea Atomic Energy Research Institute, Brookhaven National Laboratory's NuDat 2.8 isotope database, Idaho National Laboratory GeCat isotope database, and National Institute of Standards and Technology (NIST) – Atomic Weights and Isotopic Compositions with Relative Atomic Masses Database. Each of these sources provide high-quality and accurate data according to their developers. Though useful, each database contains only the baseline physical description of the necessary data to conduct NAA analysis such as neutron cross-sections, half-lives, and decay schemes.

There are few online calculators that make use one or more of the above online databases and aggregates NAA data to a limited, but more useful, extent. The Wise Uranium - Neutron Activation Calculator is one of the most commonly used online calculator that makes use of IAEA isotope characteristics from the year 2003. Wise Uranium calculates isotope activity based on naturally occurring element masses input by the user and apportions the various isotopes (if any) according to mean abundances found in nature. The material quantity is then mathematically "activated" according to the user defined neutron flux (See Figure 1) and duration of irradiation and the resulting isotope quantities with activities are presented to the user in a tabulated report in Appendix C. Figure 1 is a screen shot of the Wise Uranium user interface and is a great example of the simplicity of the WISE Uranium calculator's user interface.

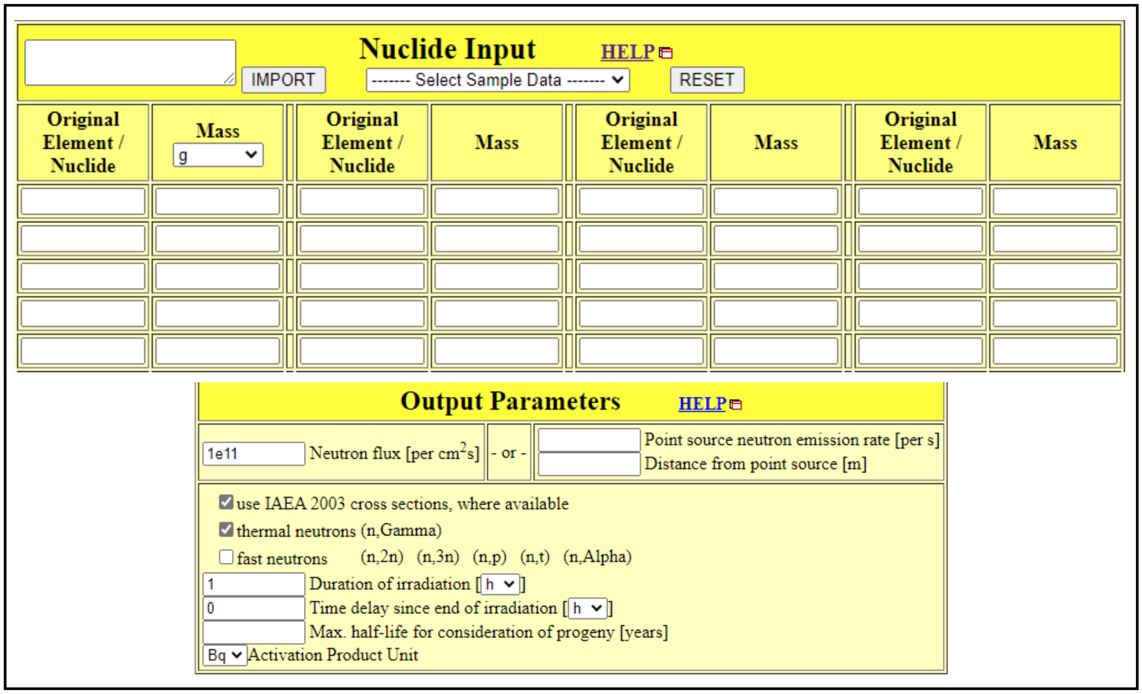

Figure 1: WISE Uranium – Neutron Activation Calculator User Interface

In 2021 a Neutron Activation Analysis Database (NAADB) was developed at UT Austin and further aggregates data from the afore mentioned WISE Neutron calculator, NuDat 2.8, and GeCat. NAADB has a clean and well-designed user interface and consolidates multiple data sources to a single location which simplifies the data acquisition process. NAADB's contribution to NAA is primarily NAA product isotope identification, target nuclide descriptions, and isotope decay chain evaluations.

Of the available online NAA calculation sources, WISE Uranium Neutron Activation Calculator provided the greatest value to this project as a benchmark comparison tool while the IAEA LiveChart provided most of the physical Isotope data.

4.0 - Neutron Activated Sample Activity Calculator

4.1 - NAA DOES RATE CALCULATOR PURPOSE

The purpose of developing this calculator is to improve and/or simplify the dose estimate of NAA irradiated samples as a means of supporting radiation safety and reduce unnecessary radiation exposure to the laboratory technician. The scope of this calculator is currently limited to a narrow number of samples but is easily expandable to include more sample types, so long as the technician has a working level of knowledge in excel. Specifically, four NIST sample types were chosen because they are the most common material matrices that undergo NAA at the University of Texas at Austin's NETL TRIGA Reactor. The goal is to provide a simple to use Microsoft excel platform for a technician to input a theorized thermal neutron flux value, sample type, quantity of the sample, and duration of exposure and receive useful information for both an analytical and radiation safety perspective. The tool is considered successful so long as its estimate is within a reasonable range of +/- 100% of actual. Unfortunately, the tool was not able to be compared against experimental dose rate data due to the NETL Reactor being unavailable throughout the development of this tool.

4.2 - ASSUMPTIONS AND CALCULATION METHODS

The development of this calculator was predicated on several key assumptions. The following is a detailed list of the assumptions used, why these assumptions were used, and how these assumptions were integrated into the calculator:

1. Thermal neutron flux is uniform, omnidirectional, and predictable throughout the irradiation period – For simplicity, it is assumed that neutron flux is uniform and that the flux can be approximated as a function of reactor power. Though many factors can influence the thermal neutron flux such as position within the reactor, age, and produced or fission produced neutron poisons it is assumed that the user would be able to predict an approximate thermal neutron flux. For example, a study in 2011 found that the Nuclear Engineering Teaching Laboratory (NETL) at the University of Texas at Austin 1 MW TRIGA Mark II research reactor can be accurately approximated to produce ~ 2.55 x 10^{12} n cm^{-2} s^{-1} when operated at full power for routine NAA. (Graham, 2011) Graham further stated that the flux of the above-mentioned test reactor could be accurately extrapolated across a wide range of reactor power levels meaning that the neutron flux can be accurately determined according to power without further testing.
2. The irradiated sample is considered thin (Lamarsh & Baratta, 2018) and does not experience particle or photon build-up. Since the neutron flux is uniform and omnidirectional and the sample size relatively small, it is assumed that the object behaves like a thin (or thin foil) object (i.e. it does not attenuate neutrons over a known thickness).. Therefore, the reaction (activation) rate and predicted activity of the sample can be approximated using the below equations:

$$R = N\sigma_{th}I$$

where R is the reaction rate (interactions per second), N is the number of atoms, σ_{th} is the thermal neutron (n,γ) cross section, and I is the thermal neutron flux (n cm^{-2} s^{-1}) produced in the reactor.

$$A = R[1 - e^{-\lambda_d t_{irr}}]$$

where A is the resulting activity of the sample product in disintegrations per second or Becquerels (Bq), R is the reaction rate (interactions per second), λ_d is the decay constant of the radioactive product, and t_{irr} is the duration of irradiation.

3. The irradiated sample is a point source for dose rate calculation purposes due to the very small volume that the sample occupies. This assumption is relevant from the measurement point of 5 cm and further from the centerline of the source.
4. Samples used for calculations are assumed to either be the mean material disposition identified by the National Institute of Standards and Technology (NIST) or a homogeneous aliquot of known elements to include its natural isotopic abundances. NIST Standard Reference Material 1632d – Trace Elements in Coal was used for calculator development and testing.
5. Only the NAA product isotopes identified in Appendix A, Tables A-1 through A-3, were assessed for simplicity and as identified as key product isotopes associated with NAA. (Landsberger, 1994) Epithermal neutrons were not evaluated but should be considered for inclusion in follow-on versions of this calculator. Furthermore, meta-stable isotopes and compound isotope products

(isotopes formed from multi-step products and decays) were also not included but should be considered for follow-on efforts.

6. The radiation contribution from product decay daughters was not assessed for simplicity purposes and relatively low contribution to total dose rate.
7. NIST standard sample mass variances/errors were deemed unnecessary to include in the calculator. Though the NIST standard sample mass variance was included in the calculator's data repository, variations of sample masses were very small.

Table 1: NIST Standard Sample Mass % Variance

Sample Mass % Variance	NIST Standard Sample Name			
	1632d	1633c	1547	2710a
	0.006%	0.030%	0.136%	0.015%

8. The summed radiation contribution included only decay intensities of 1.0% or higher. This decision was made to simplify the calculations and the infinitesimal contribution that photon emissions of intensity less than 1% made to overall dose rate.
9. The mass attenuation coefficient for dry air, near sea level, was used in determining the attenuation of the photon radiation as a function of distance. The energy specific mass attenuation coefficient was determined using linear interpolation and applied to each photon energy.
10. Irradiated sample self-shielding and sample container shielding were considered negligible and not included in the calculations.

11. Photon energies below 25 keVv were not assessed due to their high attenuation rate in air and thus very low contribution to dose rate at measurable distances from the source.
12. The dose rate in in Grays (Gy/hr) was calculated using the following calculations:

$$\dot{D}_i = \frac{\mathrm{kSE}\frac{\mu_t}{\rho}e^{-\mu D}}{4\pi r^2}$$

where $\dot{D}_i$ is the photon specific dose rate contribution in Gy/hr, k is the conversion factor used to convert flux rate to dose rate for Gy/hr with a value of 5.76×10^{-7}, S is the source strength, E is the photon energy in MeV, $\mu t/\rho$ is the mass absorption coefficient for the selected material (dry air at sea level), μ is the linear attenuation coefficient for the photons, D is the thickness of the shield, and r is the effective distance of the source to the dose measurement point.

$$S = A_P B_r I_\gamma$$

13. where AP is the activity of a given product isotope in disintegrations per second (Bq), Br is the branching ration for a given product isotope's decay scheme, and Iγ is the intensity of a given decay gamma ray associated with a given decay scheme.

$$\dot{D}_t = \sum \dot{D}_i$$

where $\dot{D}_t$ is the summed photon dose rate in Gy/hr.

4.3 - Data Sourcing and Uses

All NAA parent and target nuclide data was sourced from the IAEA's LiveChart of Nuclides – Advanced version database. IAEA's nuclide data was selected over other sources due to concerns over access reliability, export controls, and high-quality data formatting. For example, the Korea Atomic Energy Research Institute is frequently blocked on US government computers and the Knolls Atomic Power Laboratory does not provide an online version of their chart of nuclides. Specifically, the following information was sourced from the IAEA:

1. Natural Isotopic Abundance (where available)
2. Isotope Half-life
3. Decay Schemes (Branching Ratio)
4. Gamma Ray Energies and Intensities

All data was manually entered into the estimating calculator and represents a source of potential errors. The IAEA LiveChart has the option to download a more comprehensive data set that if properly formatted would provide greater accuracy and eliminate the need for hand-typing data. Future efforts should be made to develop a method for directly pulling data from the IAEA as a means of reducing the possibility of errors and updating the calculator's data to account for new data as it becomes available.

The linear attenuation coefficient for dry air at sea level was selected as the most reasonable and readily available value for calculating the attenuation of photons as a function of distance from the source. (See Figure 2) Some inherent errors will occur because of altitude and humidity when comparing the calculator's estimate with actual dose rates though these errors are expected to be small.

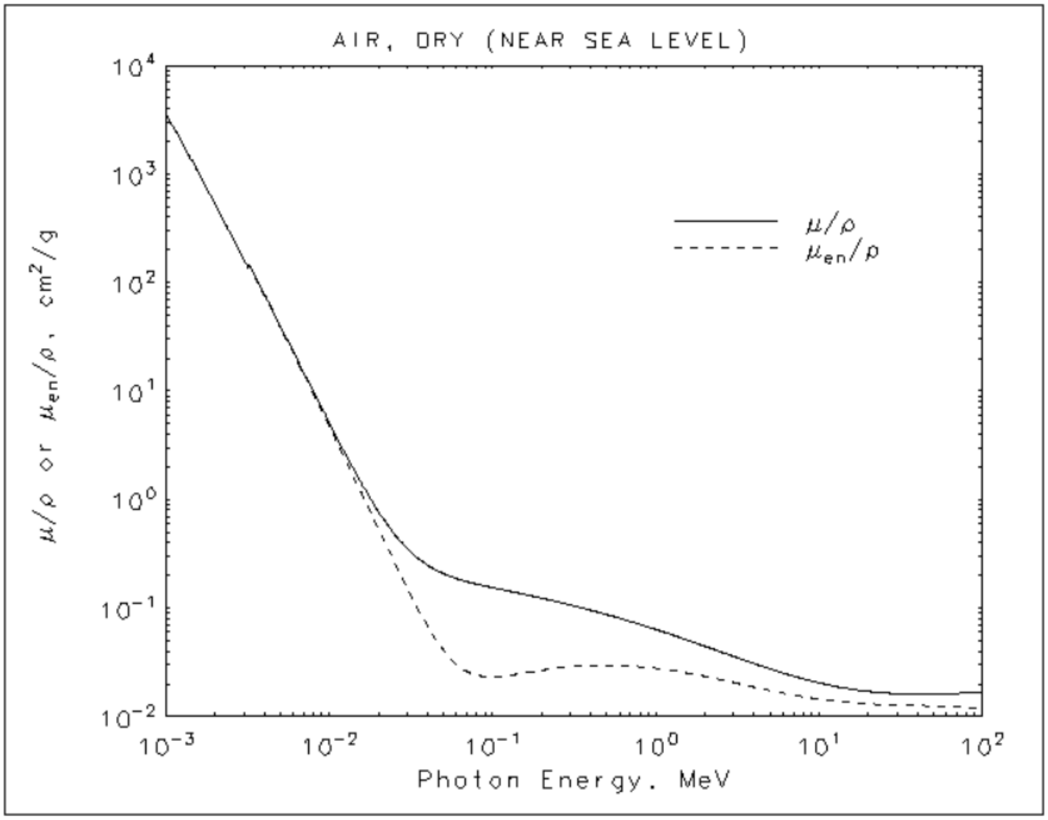

Figure 2: Mass Attenuation Coefficient for Air, Dry (Near Sea Level)(NIST, 2022)

Gamma Ray constants were used to verify the Calculator's gamma ray dose rate estimate in lieu of real-world data. Gamma ray constants (Γ) describe a typical isotopes' expected gamma dose rate at a known distance and are represented in units of Rem per hour at 1 meter per Curi (Rem m Ci^{-1} hr^{-1}). Since 3.7 x 10^{10} Bq equals one Curie of radioactivity and one Rem of gamma ray radiation approximately equals 10 mGy, the units then become:

$$\Gamma = \frac{1\ mGy \cdot 1\ m}{hr \cdot 3.7E9\ Bq}$$

or 1 milli-Grey per hour at 1 meter per 3.7 Giga-Becquerel

The Gamma Ray Constants were sourced from Plexus Scientific – Nuclear Solutions Division due to their easily available online data. Not all isotopes assessed in this study were included in Plexus's data set nor were the constants available in other publications. This is likely because most gamma ray constant data originated from early research done in the 1970's. This research, published in the January 1970 Radiological Health Handbook and updated in following editions, did not appear to evaluate all possible isotopes but focused on the more common natural or man-made isotopes. Table 2 below shows the available each of the gamma-ray constants that are relevant to this study.

Table 2: Isotope Specific Gamma Ray Constants from Plexus Scientific

Isotope Specific Gammay Ray Constants							
Isotope	Tau - Γ ($R\ Ci^{-1}\ hr^{-1}$)	Isotope	Tau - Γ ($R\ Ci^{-1}\ hr^{-1}$)	Isotope	Tau - Γ ($R\ Ci^{-1}\ hr^{-1}$)	Isotope	Tau - Γ ($R\ Ci^{-1}\ hr^{-1}$)
^{28}Al	0.882	^{239}U	0.134	^{239}Np$^{(b)}$	0.513	^{124}Sb	1.067
^{139}Ba	0.029	^{52}V	0.761	^{187}W	0.329	^{46}Sc	1.167
^{80}Br	0.080	^{76}As	0.274	^{69m}Zn	0.295	^{75}Se	0.860
^{80m}Br	0.703	^{198}Au	0.292	^{110m}Ag	1.652	^{113}Sn	0.179
^{49}Ca	1.338	^{82}Br	1.619	^{141}Ce	0.073	^{85}Sr	0.759
^{38}Cl	0.719	^{115m}In$^{(a)}$	0.197	^{51}Cr	0.023	^{182}Ta	0.772
^{60m}Co	0.003	^{72}Ga	1.456	^{134}Cs	0.999	^{160}Tb	0.662
^{165}Dy	0.023	^{77}Ge	0.716	^{60}Co	1.370	^{233}Pa$^{(b)}$	0.494
^{128}I	0.060	^{197}Hg	0.069	^{152}Eu	0.744	^{170}Tm	0.006
^{116m}In	1.354	^{166}Ho	0.023	^{59}Fe	0.662	^{175}Yb	0.030
^{42}K	0.143	^{42}K	0.143	^{181}Hf	0.393	^{65}Zn	0.330
^{27}Mg	0.536	^{99}Mo	0.113	^{203}Hg	0.253	^{95}Zr	0.465
^{56}Mn	0.924	^{24}Na	1.938	^{177m}Lu	0.781		
^{24}Na	1.938	^{109}Pd	0.000	^{147}Nd	0.139		
^{87m}Sr	0.296	^{122}Sb	0.304	^{58}Co$^{(a)}$	0.614		

Additional gamma ray constants were found in the Specific Gamma-Ray Dose Constants with Current Emission Data journal (Peplow, 2020) that compares ICRP 107 & ICRP 116 derived gamma constants against the Oak Ridge National Laboratory SCALE 6.2.3 (modeling and simulation suite) for 1192 unique isotopes. Figure 3 is an example of the data tables provided within the journal. Additional gamma ray constants were found in the Specific Gamma-Ray Dose Constants with Current Emission Data journal (Peplow, 2020) that compares ICRP 107 & ICRP 116 derived gamma constants against the Oak Ridge National Laboratory SCALE 6.2.3 (modeling and simulation suite) for 1192 unique isotopes. Figure 3 is an example of the data tables provided within the journal.

Table 4. Specific gamma-ray dose constants, Γ, computed from SCALE 6.2.3 gamma and x-ray emission data and ICRP 116 dose coefficients, with units of mSv h^{-1} MBq^{-1}.

Nuclide	Γ	Nuclide	Γ	Nuclide	Γ	Nuclide	Γ	Nuclide	Γ
4 Be 7	7.074×10^{-6}	53	1.326×10^{-4}	30 Zn 63	1.531×10^{-4}	33 As 69	1.582×10^{-4}	92	3.026×10^{-4}
		54	4.745×10^{-4}	65	7.222×10^{-5}	71	8.001×10^{-5}	93	1.159×10^{-4}
5 B 12	4.392×10^{-6}			69	8.371×10^{-10}	72	2.424×10^{-4}	94	1.465×10^{-4}
		24 Cr 48	6.259×10^{-5}	69m	5.927×10^{-5}	73	1.283×10^{-7}	95	1.035×10^{-4}
6 C 15	2.520×10^{-4}	49	1.500×10^{-4}	71	4.286×10^{-5}	74	1.058×10^{-4}	96	2.424×10^{-4}
		51	4.567×10^{-6}	71m	2.138×10^{-4}	75m	4.112×10^{-5}	97	1.929×10^{-4}
7 N 13	1.441×10^{-4}	55	7.717×10^{-8}	72	2.121×10^{-5}	76	5.584×10^{-5}		
16	3.165×10^{-4}			73	1.422×10^{-5}	77	1.155×10^{-6}	36 Kr 76	5.994×10^{-5}
		25 Mn 52	4.384×10^{-4}	74	1.208×10^{-4}	78	1.634×10^{-4}	77	1.474×10^{-4}
8 O 19	1.169×10^{-4}	54	1.107×10^{-4}	75	2.149×10^{-4}	79	4.645×10^{-6}	79	3.635×10^{-5}
		56	2.027×10^{-4}	76	6.971×10^{-5}	80	7.282×10^{-5}	79m	6.400×10^{-6}
9 F 20	1.861×10^{-4}	57	1.339×10^{-5}	77	2.368×10^{-4}	81	2.999×10^{-5}	81	1.604×10^{-6}
		58	6.065×10^{-6}	78	1.949×10^{-4}	82	3.585×10^{-5}	81m	1.900×10^{-5}
10 Ne 23	2.295×10^{-5}	68	3.411×10^{-4}	79	4.603×10^{-4}	82m	3.423×10^{-4}	83m	5.559×10^{-7}
				80	3.855×10^{-4}	83	2.907×10^{-4}	85	3.150×10^{-7}
11 Na 22	2.851×10^{-4}	26 Fe 55	2.340×10^{-14}	81	4.063×10^{-4}	84	3.472×10^{-4}	85m	2.261×10^{-5}
24	4.278×10^{-4}	59	1.474×10^{-4}	82	2.025×10^{-4}	85	1.091×10^{-4}	87	9.149×10^{-5}
24m	6.700×10^{-5}	65	2.101×10^{-4}	83	2.271×10^{-4}	86	4.041×10^{-4}	88	2.124×10^{-4}
25	5.533×10^{-5}					87	2.545×10^{-4}	89	2.205×10^{-4}
		27 Co 55	2.655×10^{-4}	31 Ga 66	2.741×10^{-4}	88	2.719×10^{-4}	90	1.636×10^{-4}
12 Mg 27	1.168×10^{-4}	56	4.238×10^{-4}	67	2.237×10^{-5}	89	5.635×10^{-5}	91	1.987×10^{-4}
28	1.747×10^{-4}	57	1.785×10^{-5}	68	1.337×10^{-4}	90	2.987×10^{-4}	92	1.770×10^{-4}
		58	1.307×10^{-4}	70	9.359×10^{-7}	91	1.614×10^{-4}	93	2.480×10^{-4}
13 Al 26	3.215×10^{-4}	58m	3.050×10^{-9}	72	3.251×10^{-4}	92	1.139×10^{-4}	94	1.457×10^{-4}
28	1.974×10^{-4}	60	3.062×10^{-4}	73	4.848×10^{-5}			95	3.794×10^{-4}
29	1.640×10^{-4}	60m	6.244×10^{-7}	74	3.455×10^{-4}	34 Se 72	7.504×10^{-6}	96	1.862×10^{-4}
30	3.372×10^{-4}	61	1.502×10^{-5}	74m	6.133×10^{-6}	73	1.556×10^{-4}	97	2.504×10^{-4}

Figure 3: Example Data Table from the Specific Gamma-Ray Constants with Current Emission Data Journal Article from Oak Ridge national Laboratory

Both gamma-ray constant data sources assumed some quantity of attenuation from tissue to calculate deep tissue (whole-body) exposure. The Oakridge Laboratory journal described that the initial gamma-ray constants (1970's) were extremely conservative and iteratively decreases (becomes more accurate) as newer modeling and simulation techniques are applied.

4.4 - CALCULATOR DEVELOPMENT AND A BRIEF PROCESS DESCRIPTION

The NAA Dose Estimating Calculator calculates a dose estimate based on inputs from the user, information gathered from the National Institute of Science and Technology (NIST) and the IAEA LiveChart database, and the calculations described above. Figure 4 is simplified description of how the calculator was developed.

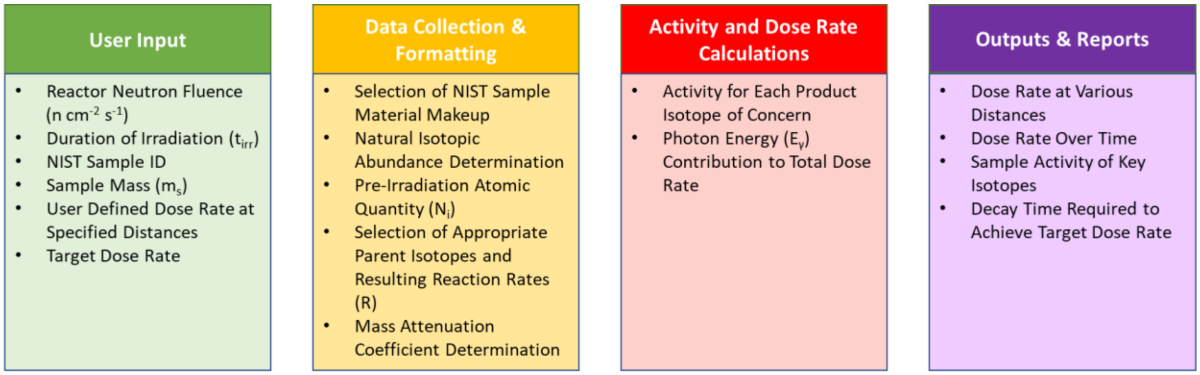

Figure 4: Dose Estimating Calculator Process Description

Beginning on the left of Figure 4, the user defines the parameters of the estimate by identifying the reactor flux, the duration of irradiation, the sample description and quantity, and the distances from the sample that are relevant to the user. The excel workbook then filters and projects the relevant information onto a formatted worksheet so that the data does not have to be manipulated by a macro. Once properly formatted, the various isotope activities and dose contributions are calculated and provided as raw data in the output tabs.

The calculator was developed with the user input tab being the central hub of the process. In it, the user inputs relevant parameters (described in greater detail below) that then causes the Data Collection & Formatting portion of the calculator to automatically update without the use of macros or other programming. For example, if the sample type is changed on the User Interface tab, the NIST Sample material composition is updated on the NIST Data Projection tab automatically to reflect the selected sample type and elemental quantities. The NIST Projection tab is used as a means of displaying the material composition of the selected sample and to preclude duplicate counting of the other sample types.

There are three key tabs where most of the calculations occur; the Short Lived, Medium-Lived, and Long-Lived tabs. Each of these tabs are constructed identically but only evaluate their respective target isotopes as described in Appendix A. These tabs make use of the material quantities outlined in the NIST Data Projector, the physical isotope data, and parameters identified in the User Interface to calculate activity and energy specific gamma-ray emission contribution to total dose rate attenuated to a user specified distance.   All output tabs make use of the parameters defined by the User Interface and the data calculated in the three key tabs.

4.5 - CALCULATOR USE – BASIC PROCEDURE

The Calculator is easy to use and provides dose rate and activity data that can be further refined by the user(s) to provide relevant and focused data for their needs. Effectively, the only user action required is on the User Interface Tab and on the Target Dose Rate Tab. The calculator is broken-up into three main parts:

1) User Interface

The user interface (See Figure 5) provides a single location where a calculator user can enter reactor parameters, sample type and mass, dose rate measurement distances from the sample, and decay times to evaluate dose rate changes over time. The user interface also allows the user to identify a target dose rate at a specified distance from the source. The calculator will calculate the conservative time required to allow the sample to decay to reach the target dose rate.

User Interface		
Reactor and Irradiation Parameters		
Neutron Flux	2.55E+12	n cm^{-2} s^{-1}
Time (irr)	10	s
NIST Type	2710a	
Sample Mass	0.5	grams
Evaluate Dose at Distance(s)		
1	5	cm
2	10	cm
3	30	cm
4	100	cm
Evaluate Dose at Time(s) after Irradiation		
1	10	Second(s)
2	30	Second(s)
3	1.5	Minute(s)
4	3	Minute(s)
5	6	Minute(s)
6	12	Minute(s)
7	24	Minute(s)
8	48	Minute(s)
9	96	Minute(s)
Target Dose Rate		
0.01		mGy/hr
Distance		
10		cm

Figure 5: User Interface Tab Display

<u>How to use</u>:

The user(s) updates each section in highlighted in green and selects the time appropriate units using drop down menus. Make sure to use drop down menus where available otherwise formatting error could occur.

Note: Ensure times selected for evaluation are in chronological order or the data will not make sense.

2) Data Consolidation and Calculations

This part of the calculator contains and makes use of all NIST, ICRP, IAEA, and various other data sources and carries out the bulk of all calculations that the calculator performs. Most of the data automatically changes according to the parameters defined by the user in the User Interface. All tabs containing the calculations and data are, or will be, hidden when the user opens the calculator. This was a conscious decision with the intent to minimize the chance that errors can be introduced into the calculations or data set. The user has the ability to add more sample types to the calculator but this will require some amount of formatting and adjusting formulas. The initial release of the calculator focuses on the four NIST standard reference samples listed:

1632d – Trace Elements in Coal

1633c – Trace elements in Coal Fly Ash

1547 – Peach Leaves

2710a – Montana I Soil

3) Output Worksheets

At the time of writing this paper, there were four output worksheets with semi-specific uses and scope. The decision to keep the output worksheets somewhat non-specific was intentional as was the inclusion of easily accessible data sets to allow the user to tailor each to their specific needs. The intent of each of the output tabs are described below:

a. Calculated_DoseRate - tab:

The Calculated_DoseRate – tab (Figure 5) aggregates dose rate data from various hidden tabs and displays the dose rate in both Gy/hr and mGy/hr. The dose rates presentation is further refined by breaking down the contribution from short, medium, and long-lived isotopes at user defined distances and decay times after irradiation. Within this tab are four example graphs for use by the user if they choose.

Calculated Dose Rate vs. Time										
R (cm) 5	Tirr (t = 0)	10 Second(s)	30 Second(s)	1.5 Minute(s)	3 Minute(s)	6 Minute(s)	12 Minute(s)	24 Minute(s)	48 Minute(s)	96 Minute(s)
LL - Dose	1.4E-09	1.4E-09	1.4E-09	1.4E-09	1.4E-09	1.4E-09	1.4E-09	1.4E-09	1.4E-09	1.4E-09
ML - Dose	1.4E-07	1.4E-07	1.4E-07	1.4E-07	1.4E-07	1.4E-07	1.4E-07	1.4E-07	1.4E-07	1.3E-07
SL - Dose	7.0E-05	6.5E-05	5.6E-05	4.0E-05	2.8E-05	1.4E-05	4.1E-06	8.2E-07	4.4E-07	3.5E-07
D_T (Gy/h)	7.04E-05	6.5E-05	5.6E-05	4.1E-05	2.8E-05	1.4E-05	4.2E-06	9.6E-07	5.8E-07	4.9E-07
D_T (mGy/h)	7.0E-02	6.5E-02	5.6E-02	4.1E-02	2.8E-02	1.4E-02	4.2E-03	9.6E-04	5.8E-04	4.9E-04
R (cm) 10	Tirr (t = 0)	10 Second(s)	30 Second(s)	1.5 Minute(s)	3 Minute(s)	6 Minute(s)	12 Minute(s)	24 Minute(s)	48 Minute(s)	96 Minute(s)
LL - Dose	3.5E-10	3.5E-10	3.5E-10	3.5E-10	3.5E-10	3.5E-10	3.5E-10	3.5E-10	3.5E-10	3.5E-10
ML - Dose	3.5E-08	3.5E-08	3.5E-08	3.5E-08	3.5E-08	3.5E-08	3.5E-08	3.5E-08	3.4E-08	3.3E-08
SL - Dose	1.8E-05	1.6E-05	1.4E-05	1.0E-05	6.9E-06	3.5E-06	1.0E-06	2.0E-07	1.1E-07	8.8E-08
D_T (Gy/h)	1.8E-05	1.6E-05	1.4E-05	1.0E-05	6.9E-06	3.5E-06	1.1E-06	2.4E-07	1.5E-07	1.2E-07
D_T (mGy/h)	1.8E-02	1.6E-02	1.4E-02	1.0E-02	6.9E-03	3.5E-03	1.1E-03	2.4E-04	1.5E-04	1.2E-04
R (cm) 30	Tirr (t = 0)	10 Second(s)	30 Second(s)	1.5 Minute(s)	3 Minute(s)	6 Minute(s)	12 Minute(s)	24 Minute(s)	48 Minute(s)	96 Minute(s)
LL - Dose	3.9E-11	3.9E-11	3.9E-11	3.9E-11	3.9E-11	3.9E-11	3.9E-11	3.9E-11	3.9E-11	3.9E-11
ML - Dose	3.9E-09	3.9E-09	3.9E-09	3.9E-09	3.9E-09	3.9E-09	3.9E-09	3.9E-09	3.8E-09	3.7E-09
SL - Dose	1.9E-06	1.8E-06	1.6E-06	1.1E-06	7.7E-07	3.8E-07	1.1E-07	2.3E-08	1.2E-08	9.7E-09
D_T (Gy/h)	2.0E-06	1.8E-06	1.6E-06	1.1E-06	7.7E-07	3.9E-07	1.2E-07	2.7E-08	1.6E-08	1.3E-08
D_T (mGy/h)	2.0E-03	1.8E-03	1.6E-03	1.1E-03	7.7E-04	3.9E-04	1.2E-04	2.7E-05	1.6E-05	1.3E-05
R (cm) 100	Tirr (t = 0)	10 Second(s)	30 Second(s)	1.5 Minute(s)	3 Minute(s)	6 Minute(s)	12 Minute(s)	24 Minute(s)	48 Minute(s)	96 Minute(s)
LL - Dose	3.5E-12	3.5E-12	3.5E-12	3.5E-12	3.5E-12	3.5E-12	3.5E-12	3.5E-12	3.5E-12	3.5E-12
ML - Dose	3.5E-10	3.5E-10	3.5E-10	3.5E-10	3.5E-10	3.5E-10	3.5E-10	3.5E-10	3.4E-10	3.3E-10
SL - Dose	1.7E-07	9.8E-08	8.1E-08	5.2E-08	3.2E-08	1.3E-08	3.2E-09	1.3E-09	1.1E-09	8.7E-10
D_T (Gy/h)	1.7E-07	9.9E-08	8.1E-08	5.2E-08	3.2E-08	1.4E-08	3.6E-09	1.6E-09	1.4E-09	1.2E-09
D_T (mGy/h)	1.7E-04	9.9E-05	8.1E-05	5.2E-05	3.2E-05	1.4E-05	3.6E-06	1.6E-06	1.4E-06	1.2E-06

Figure 6: Calculated_DoseRate Tab Display

b. Calculated_IsotopeData - tab:

The Calculated_IsotopeData tab provides a consolidated isotope parameters, activity, and dose rate contribution for each isotope. This tab also shows the results of the attenuation coefficient calculations. This tab is only a projection of the calculation tabs discussed in "Data Consolidation and Calculations" section.

c. Target_DoseRate - tab:

The Target_DoseRate tab's primary purpose is to calculate the decay time required for the sample to reach a target dose rate at a specified distance from the source. To calculate this, each of the isotopes needed to be individually decayed and their specific contribution to calculated dose rate tabulated at 5 second intervals. The table is extensive (~77k individual cells) but contains a wealth of information should the user desire to make use of the derived data within this tab.

Targe Dose Rate Decay Time	
Target Dose Rate	0.01
Target Distance	10
Time Interval (s)	5
Approximate Decay Time	
95.0	Second(s)

Figure 7: Target _DoseRate Tab Display

<u>How to use</u>:

The target dose rate and distance has already been defined on the user interface tab. The user must then ensure that the Time Interval (s) reflects the desired accuracy for decay time and the desired units for the decay time using a drop-down menu. For example, if the time interval was set to 100 seconds, then the worksheet will calculate the decay time to the closest 100 seconds. Conversely, if the interval was set to 1 second then the worksheet will calculate the decay time to the nearest 1 second. Having the interval set too high reduces accuracy while too low may mean the decay time occurs outside of the available data set. (Easily fixed by extending the data set further)

d. Physical_IsotopeData:

   The purpose of this tab is to provide all physical data regarding each of the isotopes to include gamma constants. This tab is mainly for the user to conduct spot checks of the proper operation of the calculator or as a quick look-up aid when performing other actions within the context of the calculator.

4.6 - LIMITATIONS OF USE AND POSSIBLE SOURCES OF ERRORS

At the time this paper is written the calculator is currently very limited in scope though it has the potential to be far more broadly useful if continued to be developed and refined. The following is a description of some of the limitations of use of the calculator:

1) The calculator can only evaluate four previously defined NIST samples.

2) The calculator does not allow the user to define a unique sample.
3) The calculator uses data available at the time of development and would need to be updated with new information as it becomes available.
4) Variance is not included in the dose estimate(s).
5) User(s) can unintentionally input errors if interfacing with hidden/locked tabs.
6) User(s) cannot evaluate shielding on dose rate.
7) Calculator was not compared against real-world activated samples.
8) The calculator assumed 100% detection efficiency. Some amount of energy calibration may be required when comparing against real-world dose rates.

4.7 - Comparison Against Real-World and Known Standards

A test procedure was developed with the goal of comparing predicted verses real world data. (See Appendix B) Unfortunately, this test procedure was not able to be used due to the University of Texas at Austin's Nuclear Engineering Teaching Lab TRIGA reactor being unavailable. As a result, the dose estimating calculator was primarily compared against the WISE Uranium – Neutron Activity Calculator and two sources of Gamma-Ray constants as the only means of determining the accuracy of the calculator's accuracy. The next logical step would be to evaluate the dose estimate calculator against real world data using the laboratory test procedure, or similar procedure, outlined in Appendix B.

Comparison with the Wise Uranium – Neutron Activation Calculator

As described earlier in this report, Wise Uranium – Neutron Activation Calculator is widely considered the gold standard for simple to use online NAA activity calculators. Wise Uranium was used to compare the Calculator's activity calculation against a known and well-respected calculation calculator. For this comparison, all NIST sample types were identical in mass (0.5g) and used the same power level yielding a neutron flux of 2.55×10^{12} n cm^{-2} s^{-1}. The full online calculator report for each sample type can be viewed in Appendix C.

Table 3: Comparison of Calculator Predicted vs Wise Uranium Calculated Activity

Isotope	NIST 1547a			NIST 1633c			NIST 1632d			NIST 2710a		
	Predicted Activity (Bq)	Wise - Neutron (Bq)	Difference (%)	Predicted Activity (Bq)	Wise - Neutron (Bq)	Difference (%)	Predicted Activity (Bq)	Wise - Neutron (Bq)	Difference (%)	Predicted Activity (Bq)	Wise - Neutron (Bq)	Difference (%)
^{110}Ag										3.1E+06	3.1E+06	2.8%
^{28}Al	8.2E+04	8.2E+04	0.2%	4.4E+05	4.6E+05	5.6%	3.0E+04	3.0E+04	0.2%	2.0E+05	2.0E+05	0.3%
^{165}Dy				5.5E+04	5.7E+04	4.8%				8.8E+03	8.7E+03	0.7%
^{66}Cu	6.8E+02	6.8E+02	0.5%	3.1E+04	3.3E+04	5.6%	1.1E+03	1.1E+03	0.4%	6.2E+03	6.2E+03	0.3%
^{56}Mn	1.4E+04	1.4E+04	0.1%	3.3E+04	3.3E+04	0.3%	1.8E+03	1.8E+03	0.1%	3.0E+03	3.0E+03	0.1%
^{139}Ba	2.8E+02	2.8E+02	0.3%	2.5E+01	2.7E+01	5.6%	9.1E+01	9.1E+01	0.2%	1.8E+03	1.8E+03	0.3%
^{187}W										6.9E+02	7.0E+02	2.1%
^{239}U				3.9E+02	4.1E+02	5.0%	2.2E+01	2.2E+01	0.2%	3.8E+02	3.8E+02	0.3%
^{24}Na				3.7E+01	4.1E+01	10.5%	6.4E+02	6.7E+02	5.2%	1.9E+02	2.0E+02	5.4%
^{24}Na				3.7E+01	4.1E+01	10.5%	6.4E+02	6.7E+02	5.2%	1.9E+02	2.0E+02	5.4%
^{140}La				2.1E+02	2.2E+02	3.6%				7.4E+01	7.3E+01	1.9%
^{72}Ga				1.5E+02	1.7E+02	7.6%				6.5E+01	6.5E+01	0.3%
^{42}K	7.3E+03	7.3E+03	0.5%	5.3E+01	5.6E+01	4.6%	3.3E+00	3.3E+00	0.8%	6.5E+01	6.5E+01	0.3%
^{42}K	7.3E+03	7.3E+03	0.5%	5.3E+01	5.6E+01	4.6%	3.3E+00	3.3E+00	0.8%	6.5E+01	6.5E+01	0.3%
^{49}Ca	8.0E+03	8.0E+03	0.0%	7.0E+01	7.4E+01	5.5%	7.4E+00	7.4E+00	0.0%	5.0E+01	5.0E+01	0.0%
^{38}Cl	2.5E+03	2.5E+03	0.3%				8.0E+01	8.0E+01	0.6%	5.0E+01	5.0E+01	0.0%
^{76}As	1.9E-01	2.0E-01	2.9%	5.7E+02	6.2E+02	8.2%	1.9E+01	1.9E+01	2.9%	4.7E+01	4.9E+01	2.9%
^{153}Sm				2.2E+02	2.3E+02	3.6%				4.7E+01	4.6E+01	1.4%
^{122}Sb				5.2E+00	5.7E+00	8.5%	2.7E-01	2.8E-01	3.4%	3.2E+01	3.3E+01	3.3%
^{197}Hg	1.7E-02	2.3E-02	25.3%	5.3E-01	7.5E-01	29.1%	4.9E-02	6.6E-02	25.1%	5.2E+00	7.0E+00	25.1%
^{46}Sc				1.7E+01	1.8E+01	5.4%	1.3E+00	1.3E+00	0.2%	4.4E+00	4.4E+00	0.1%
^{175}Yb				1.3E+01	1.4E+01	4.6%				3.4E+00	3.4E+00	0.8%
^{198}Au										2.3E+00	2.3E+00	0.1%
^{86}Rb	2.7E-01	2.6E-01	3.0%	1.6E+00	1.7E+00	2.5%	1.0E-01	9.8E-02	3.1%	1.6E+00	1.6E+00	3.1%
^{124}Sb				1.2E-01	1.3E-01	9.6%	6.3E-03	6.6E-03	4.6%	7.4E-01	7.7E-01	4.6%
^{51}Cr				7.0E+00	8.0E+00	12.3%	3.7E-01	4.0E-01	7.6%	6.3E-01	6.8E-01	7.6%
^{141}Ce				1.1E+00	1.3E+00	16.9%	7.1E-02	8.1E-02	12.1%	3.7E-01	4.2E-01	12.1%
^{152}Eu				1.7E+00	1.8E+00	6.4%	7.9E-02	8.0E-02	1.5%	3.0E-01	3.0E-01	1.0%
^{181}Hf				2.2E-01	2.4E-01	5.7%				2.6E-01	2.6E-01	0.3%
^{147}Nd				8.6E-01	8.7E-01	0.5%				2.2E-01	2.1E-01	5.2%
^{134}Cs				1.7E-01	1.8E-01	6.1%	1.1E-02	1.1E-02	0.7%	1.5E-01	1.5E-01	0.9%
^{60}Co				8.7E-01	9.2E-01	5.4%	6.9E-02	6.9E-02	0.2%	1.2E-01	1.2E-01	0.1%
^{65}Zn	2.5E-02	3.7E-02	32.8%	3.3E-01	5.1E-01	36.2%	1.8E-02	2.7E-02	32.7%	5.8E-02	8.6E-02	32.7%
^{203}Hg	3.0E-04	2.7E-04	11.2%	9.7E-03	9.2E-03	5.6%	8.9E-04	8.0E-04	11.6%	9.5E-02	8.5E-02	11.6%
^{160}Tb				4.0E-01	4.1E-01	3.4%				6.4E-02	6.2E-02	2.2%
^{182}Ta				9.6E-02	1.0E-01	5.6%				5.4E-02	5.5E-02	0.3%
^{59}Fe	2.0E-02	2.1E-02	4.4%	9.7E-02	1.1E-01	9.6%	6.9E-03	7.2E-03	4.5%	4.0E-02	4.2E-02	4.4%
^{95}Zr										1.9E-02	1.8E-02	3.0%
^{85}Sr	2.7E-03	2.0E-03	37.5%	4.7E-02	3.6E-02	30.1%	3.3E-03	2.4E-03	37.3%	1.3E-02	9.6E-03	37.0%
^{99}Mo	4.5E-04	4.7E-04	4.5%							1.3E-02	9.6E-03	37.0%
^{75}Se	3.5E-04	3.6E-04	3.6%	4.1E-02	4.5E-02	8.8%	3.8E-03	3.9E-03	3.6%	2.9E-03	3.0E-03	3.6%

By inspection, most of the larger isotope percent differences seen in Table 3 occur in the very low activities where minor differences in sourced data (such as microscopic cross sections and natural abundances) can have a deceptively large impact. To alleviate this, the percentage differences were weighted according to activity of the respective isotope and its contribution to total activity of the sample. This analysis could be further refined to weigh the differences according to each isotope's contribution to dose rate though it was deemed unnecessary for this study as it is unlikely to result in a significant departure from Table 4 results.

Table 4: Activity Weighted Difference Between Calculator Predicted and Wise Uranium Calculated

Activity Weighted Difference				
Sample Name	NIST 1547a	NIST 1633c	NIST 1632d	NIST 2710a
Tool - Weighted	0.20%	5.21%	0.36%	2.66%
WISE - Weighted	0.20%	5.22%	0.37%	2.65%

The calculator's comparison with the online Wise Uranium calculator yielded an acceptable data consistency and proved that the calculator is functioning as expected and within acceptable variances from alternate calculating methods. It is impossible to determine the exact reasons for the relatively minor differences without having the online calculator's source code, data sources used at the time (ex. 2004 - IAEA), and assumptions made. The results are considered acceptable and confirmation of the calculator's estimate of irradiated activity.

The Calculator's dose rate calculation was compared against available Gamma Ray Constants (Γ) values resourced from Plexus Scientific – Nuclear Solutions Division's web site (Plexus Scientific, 2022) and from an Oak Ridge National Laboratory journal written in 2020 that makes use of improved ICRP107, ICRP 116 data, and improved SCALE 6.2.3 simulation algorithms. This comparison was performed in three steps:

1) Calculate a NIST Samples activity and the Calculator's estimated Dose Rate
2) Calculate the Dose Rate based on the two different gamma-ray constants. The following equations were used to calculate the dose rate.

$$\dot{D}_i = A_i \Gamma$$

   where A_i is activity of a specific isotope and Γ is the gamma ray constant for the same isotope paying particular attention to unit conversion. Of note, the Oak Ridge constants were in mSv/hr while the calculator and the Plexus constants were in units of mGy/hr. For gamma-ray photons, this is nearly a one-to-one mGy to mSv conversion. For the purposes of this evaluation, 1 mGy = 1 mSv.
3) Calculate the % Difference from the Calculator's calculated dose rate to the gamma-ray constant calculated distance at one meter.

The comparison of the calculated dose rates in Table 4 below shows that using gamma-ray constants with the calculated activity would result in an estimated dose that is 40-50% lower than the dose rate calculated by the calculator. This is presumed to be a result of the superior modeling and simulation software used by the authors of the ICRP and research team at Oak Ridge National Laboratory (SCALE) as well as the use of voxel phantoms and soft/hard tissue photon interactions.   The shown dose estimate difference of 40-50% is considered acceptable for this study since the calculator's calculation is considered a general guide and conservative in nature.

Table 5: Calculator vs. Gamma Ray Constant Derived Dose Rate at 1 Meter

Dose Rate Comparison			
Calculation Method	Dose Rate mGy/hr	Dose Rate mSy/hr	% Difference from Tool
Tool - Calculated	7.75E-05		
Plexus - Γ	4.78E-05		38%
SCALE - Γ		3.96E-05	49%

5.0 - Recommendations for Follow-On Efforts

Though useful in its current form, the NIST Standard Sample NAA Dose Rate Calculator should be expanded for greater functionality and consistency of data sourcing. The following is a list of recommended follow-on efforts to improve functionality and accuracy of this tool.

- Develop a means of drawing data directly from the source database - Throughout the development, multiple sources of data were used and often requiring hard-coding (typed by hand) data into the workbook. This is a potential source of errors.
- Consolidate calculation worksheets and reduce redundant calculations/processes – MS Excel began to experience lag and would sometime become unresponsive or miss character entries. This would require the user to shut down the application and re-open it to clear the various conditions. Though infrequent, these issues are indicative of potentially nearing the limit of MS Excels ability to handle the many continuous calculations throughout the workbook.
- The Calculator's scope is currently narrow - develop a means of allowing the user to input a unique sample and its associated material composition. Additionally, a means of easily adding new NIST standard sample types without extensive formatting and adjusting of formulas in the NIST Data Projector tab should be developed
- The output tabs don't currently provide a universally useful and printable form/worksheet for the end user – A standard form should be developed in collaboration with multiple potential users/test reactor technicians.

6.0 - CONCLUSION

With the many technicians, professors, and students operating or working near the many test reactors it's easy to see that dose management and practicing ALARA principles can sometimes be an afterthought in the pursuit of high-quality education and experimentation. This calculator was developed to provide a simple to use and conservatively accurate dose and activity calculation for use by someone without much programming or modeling software experience. This paper, and accompanying excel calculator, demonstrates that it is possible to a reasonable degree of accuracy predict the dose rate of a NAA standard sample using key isotopes. With additional efforts and refinements, this estimate calculator could become a commonly used dose rate reduction calculator for any Neutron Activation Analysis technician.

Appendix A – Identification of Key NAA Isotopes for this Study

This appendix provides a detailed list of isotopes that were used throughout this study for the purposes of predicting dose rate. (Landsberger, 1994)

Table A-1
Properties of reactions producing short-lived radionuclides

Element	Isotope	Half-Life (s)	Key Gamma-Ray Energies (kEv)
Ag	^{110}Ag	2.E+01	657.8
Al	^{28}Al	1.E+02	1178.9
Ba	^{139}Ba	5.E+03	165.9
Br	^{80}Br	1.E+03	616.2
Br	^{80m}Br	2.E+04	37.1
Ca	^{49}Ca	5.E+02	3084.4
Cl	^{38}Cl	2.E+03	1642.4, 2167.5
Co	^{60m}Co	6.E+02	58.6
Cu	^{66}Cu	3.E+02	1039.4
Dy	^{165}Dy	8.E+03	94.7
F	^{20}F	1.E+01	1633.8
I	^{128}I	1.E+03	442.3
In	^{116m}In	3.E+03	416.9, 1097.3
K	^{42}K	4.E+04	1524.7
Mg	^{27}Mg	6.E+02	843.8, 1014.4
Mn	^{56}Mn	9.E+03	846.7, 1810.7
Na	^{24}Na	5.E+04	1368.6, 2754.1
Se	^{77m}Se	2.E+01	161.7
Sb	^{122m}Sb	3.E+02	61.5
Si	$^{29}Al^{(a)}$	4.E+02	1273
Sr	^{87m}Sr	1.E+04	388.4
Ti	^{51}Ti	3.E+02	320.1
U	^{239}U	1.E+03	74.6
V	^{52}V	2.E+02	1434.1

Note:

(a) Si is detected by the ^{29}Si (n,p) ^{29}Al reaction.

Table A-2
Properties of reactions producing medium-lived radionuclides

Element	Isotope	Half-Life (s)	Key Gamma-Ray Energies (kEv)
As	^{76}As	9.E+04	559.1
Au	^{198}Au	2.E+05	411.8
Br	^{82}Br	1.E+05	554.3, 776.5
Cd	^{115m}In [(a)]	2.E+04	336.3
Ga	^{72}Ga	5.E+04	834.0, 629.9
Ge	^{77}Ge	4.E+04	264.4
Hg	^{197}Hg	2.E+05	77.4
Ho	^{166}Ho	1.E+05	80.6
K	^{42}K	4.E+04	1524.7
La	^{140}La	1.E+05	1596.2, 328.8, 487.0
Mo	^{99}Mo	2.E+05	140.5
Na	^{24}Na	5.E+04	1368.6, 2754.1
Pd	^{109}Pd	5.E+04	88.0
Sb	^{122}Sb	2.E+05	564.0
Sm	^{153}Sm	2.E+05	103.2
U	^{239}Np [(b)]	2.E+05	277.7
W	^{187}W	9.E+04	85.8
Zn	^{69m}Zn	5.E+04	438.6

Note:

(a) Cd is determined using the $^{114}Cd(n,p)$ ^{115}Cd -> ^{115}In reaction

(b) U is determined using the $^{238}U(n,\gamma\beta)$ ^{239}U -> ^{239}Np reaction

Table A-3
Properties of reactions producing long-lived radionuclides

Element	Isotope	Half-Life (s)	Key Gamma-Ray Energies (kEv)
Ag	^{110m}Ag	2.E+07	657.8
Ce	^{141}Ce	3.E+06	145.4
Cr	^{51}Cr	2.E+06	320.0
Cs	^{134}Cs	7.E+07	795.8
Co	^{60}Co	2.E+08	1173.2, 1332.4
Eu	^{152}Eu	4.E+08	1408.0
Fe	^{59}Fe	4.E+06	1099.2, 1291.6
Hf	^{181}Hf	4.E+06	482.2
Hg	^{203}Hg	4.E+06	279.2
Lu	^{177m}Lu	1.E+07	378.5
Nd	^{147}Nd	1.E+06	91.1
Ni	^{58}Co[a]	6.E+06	810.8
Rb	^{86}Rb	2.E+06	1076.6
Sb	^{124}Sb	5.E+06	1691.0
Sc	^{46}Sc	7.E+06	889.3, 1120.5
Se	^{75}Se	1.E+07	136.0, 264.7, 400.7
Sn	^{113}Sn	1.E+07	391.7
Sr	^{85}Sr	6.E+06	514.0
Ta	^{182}Ta	1.E+07	1221.4
Tb	^{160}Tb	6.E+06	879.4
Th	^{233}Pa[b]	2.E+06	311.9
Tm	^{170}Tm	1.E+07	84.3
Yb	^{175}Yb	4.E+05	396.3
Zn	^{65}Zn	2.E+07	1115.5
Zr	^{95}Zr	6.E+06	756.7

Note:

(a) Ni is determined using the $^{58}Ni(n,p)\ ^{58}Co$ reaction

(b) Th is determined using the $^{232}Th(n,\gamma\beta)\ ^{233}Th \text{ ->} ^{233}Pa$ reaction

Appendix B – Irradiation and Dose Rate Laboratory Procedure

Purpose: To evaluate the accuracy/correlation of the calculator's calculated dose rate to actual real-world data and to determine the reliability of the predicted dose to actual dose.

Materials/Equipment:

5 - 2 ml Sample Vials

At least 1-gram NIST Standard Samples for the following types:

1632d – Trace Elements in Coal

1633c – Trace elements in Coal Fly Ash

1547 – Peach Leaves

2710a – Montana I Soil

Preparation:

Radiation Detector - Select two identical appropriate radiation detectors that can accommodate up to 1 Gy/hr and down to 1.0 uGy/hr or reads in equivalent R/hr. A simple ion chamber detector with a sufficiently large detection volume should suffice.

Detector Energy Efficiency Calibration (if required) - Conduct a detector efficiency calculation for the detector being used. Using a series of sources emitting energy across a spectrum that encompasses the energies likely produced. This is especially true if the detector does not compensate for lower energy gamma rays producing a higher reaction rate and higher energy gammas.

Dose Rate Measurement Area - Select a measuring location that would allow sufficient room for taking measurements. For best results, the lab should be sufficiently large to allow for the detectors to be up to 1 meter away from the source and allow the measuring technician to easily move the probes while practicing As Low as Reasonably Achievable (ALARA) radiation dose principles. Ideally, the surface that the sample is placed upon is constructed of either low-Z material such as poly or very thin high-Z material to minimize scatter.

Sample and Detector Placement – Using tape (or other acceptable marking) to identify the location that the sample will be placed for each measurement. Measure and mark 1 cm, 10 cm, 30 cm, and 100 cm distances from the center of the sample placement mark. Repeat this step 180^{o} off the original radius markings.

Rehearsals – It is recommended that the survey technician conducts a rehearsal of one full sample measurement to reduce the technician's exposure and to practice ALARA principles.

Sample Vial Preparation - Prepare and **label** the sample vials as described below:

The blank is being used to determine any contributing dose associated with the irradiation of the sample container. Seal the sample vial according to local procedures.

Blk - Blank Sample

The first sample will contain approximately 0.5 grams of **NIST 1632d** and sealed according to local procedures

A - First Sample Label

The second sample will contain approximately 0.5 grams of **NIST 1633c** and sealed according to local procedures

B - Second Sample Label

The third sample will contain approximately 0.5 grams of **NIST 1547** and sealed according to local procedures

C - Third Sample Label

The fourth sample will contain approximately 0.5 grams of **NIST 2710a** and sealed according to local procedures

D - Fourth Sample Label

Note: It is vitally important the weight of the sample be as accurate as possible.

Irradiation and Testing Procedure:

Irradiate each of the five (5) samples 5 to 10 minutes apart for 10 seconds at constant flux of $2.55E10^{12}$ neutrons per cm^2 per second or an equivalent reactor power of 950 kW. Annotate exact time of start and completion of irradiation. Conduct a consistent dose rate measurement at each of the distances described above and input dose rate data in the below tables:

Dose Rate Measuring Procedure:

Using two identical radiation detectors, conduct a series of 1-minute counts to determine the absorbed dose being emitted from the irradiated source at 1 cm, 10 cm, 30 cm, & 100 cm distances. Both meters should be 180^{o} apart to reduce the likelihood of scatter radiation interference. Furthermore, both detectors should have identical geometry and orientation relative to the source to minimize variance.

Analysis:

Use the dose rate estimation calculator using an appropriate energy efficiency factor (if applicable) to compare actual results to predicted results.

Sample ID: ____________________

Sample Measured Dose Rate After Irradiation															
Distance	1 - Min (Time - ____:____)			10 - Min (Time - ____:____)			30 - Min (Time - ____:____)			1 - Hr (Time - ____:____)			24 - Hrs (Time - ___:____)		
	A	B	Avg.	A	B	Avg.	A	B	Avg.	A	B	Avg.	A	B	Avg.
5 cm															
10 cm															
30 cm															
100 cm															

Sample ID: ____________________

Sample Measured Dose Rate After Irradiation															
Distance	1 - Min (Time - ____:____)			10 - Min (Time - ____:____)			30 - Min (Time - ____:____)			1 - Hr (Time - ____:____)			24 - Hrs (Time - ___:____)		
	A	B	Avg.	A	B	Avg.	A	B	Avg.	A	B	Avg.	A	B	Avg.
5 cm															
10 cm															
30 cm															
100 cm															

Sample ID: ____________________

Sample Measured Dose Rate After Irradiation															
Distance	1 - Min (Time - ____:____)			10 - Min (Time - ____:____)			30 - Min (Time - ____:____)			1 - Hr (Time - ____:____)			24 - Hrs (Time - ___:____)		
	A	B	Avg.	A	B	Avg.	A	B	Avg.	A	B	Avg.	A	B	Avg.
5 cm															
10 cm															
30 cm															
100 cm															

Sample ID: ____________________

Sample Measured Dose Rate After Irradiation															
Distance	1 - Min (Time - ____:____)			10 - Min (Time - ____:____)			30 - Min (Time - ____:____)			1 - Hr (Time - ____:____)			24 - Hrs (Time - ___:____)		
	A	B	Avg.	A	B	Avg.	A	B	Avg.	A	B	Avg.	A	B	Avg.
5 cm															
10 cm															
30 cm															
100 cm															

Sample ID: ____________________

Sample Measured Dose Rate After Irradiation															
Distance	1 - Min (Time - ____:____)			10 - Min (Time - ____:____)			30 - Min (Time - ____:____)			1 - Hr (Time - ____:____)			24 - Hrs (Time - ___:____)		
	A	B	Avg.	A	B	Avg.	A	B	Avg.	A	B	Avg.	A	B	Avg.
5 cm															
10 cm															
30 cm															
100 cm															

Appendix C – Wise Uranium – Neutron Activation Calculator Reports

This appendix contains the activity reports for each of the four NIST Standard samples. Of note, the reports contain some duplicate isotopes due to how the data was processed from the excel program and uploaded onto the Wise website. The duplicate masses were noted and excluded from the activation comparison.

1632d – Trace Elements in Coal

Search Mode

- (●) Forward (Search activation products)
- ( ) Reverse (Search original nuclides)

Nuclide Input HELP

Zn 6.45E-06 IMPORT ------- Select Sample Data ------- RESET

Original Element / Nuclide	Mass [g]	Original Element / Nuclide	Mass	Original Element / Nuclide	Mass	Original Element / Nuclide	Mass
Al	4.56E-05	Sr	3.18E-05	Cr	6.85E-06		
Ba	2.02E-05	Ti	2.39E-04	Cs	2.99E-07		
Ca	7.20E-06	U	2.59E-07	Co	1.71E-06		
Cl	5.71E-06	V	1.19E-05	Eu	1.09E-07		
Co	1.71E-06	As	3.05E-06	Fe	3.75E-05		
Cu	2.92E-06	Cd	4.00E-08	Hg	4.64E-08		
K	5.47E-06	Hg	4.64E-08	Rb	3.68E-06		
Mg	1.80E-04	K	5.47E-06	Sb	2.23E-07		
Mn	6.55E-06	Na	1.48E-04	Sc	1.45E-06		
Na	1.48E-04	Sb	2.23E-07	Se	6.45E-07		
Se	6.45E-07	U	2.59E-07	Sr	3.18E-05		
Sb	2.23E-07	Zn	6.45E-06	Th	7.14E-07		
Si	8.25E-05	Ce	5.85E-06	Zn	6.45E-06		

Output Parameters HELP

2.55e12 Neutron flux [per cm^2s] - or - Point source neutron emission rate [per s] / Distance from point source [m]

- [x] use IAEA 2003 cross sections, where available
- [x] thermal neutrons (n,Gamma)
- [ ] fast neutrons (n,2n) (n,3n) (n,p) (n,t) (n,Alpha)

10 Duration of irradiation [s]
0 Time delay since end of irradiation [h]
Max. half-life for consideration of progeny [years]
Bq Activation Product Unit

Neutron flux = 2.550e12 per cm^{2}s
Irradiation = 10 s; Delay = 0 h

Original Nuclide **Reaction** **Activation (->) & Decay (~>) Products** **Half-Life**

45.60 µg Aluminum:

45.60 µg **Al-27** (n,G) -> 30.12 kBq **Al-28** (2.240 m)

20.20 µg Barium:

20.25 ng **Ba-130** (n,G) -> 14.15 mBq **Ba-131** (11.80 d)
~> 58.61 nBq **Cs-131** (9.690 d)

19.59 ng **Ba-132** (n,G) -> 30.32 µBq **Ba-133** (10.74 a)

14.54 µg **Ba-138** (n,G) -> 91.31 Bq **Ba-139** (82.70 m)

7.200 µg Calcium:

6.959 µg **Ca-40** (n,G) -> 171.9 nBq **Ca-41** (140.0e3 a)

164.7 ng **Ca-44** (n,G) -> 2.491 mBq **Ca-45** (163.0 d)

330.2 pg **Ca-46** (n,G) -> 140.6 µBq **Ca-47** (4.530 d)
~> 1.683 nBq **Sc-47** (3.351 d)

16.11 ng **Ca-48** (n,G) -> 7.400 Bq **Ca-49** (8.716 m)
~> 7.458 mBq **Sc-49** (57.40 m)

5.710 µg Chlorine:

4.267 µg **Cl-35** (n,G) -> 5.953 µBq **Cl-36** (301.0e3 a)

1.442 µg **Cl-37** (n,G) -> 79.84 Bq **Cl-38** (37.21 m)

1.710 µg Cobalt:

1.710 µg **Co-59** (n,G) -> 68.99 mBq **Co-60** (5.271 a)

2.920 µg Copper:

2.000 µg **Cu-63** (n,G) -> 33.42 Bq **Cu-64** (12.70 h)

919.8 ng **Cu-65** (n,G) -> 1.056 kBq **Cu-66** (5.100 m)

5.470 µg Potassium:

5.083 µg **K-39** (n,G) -> 0 Bq **K-40** (1.280e9 a)

385.7 ng **K-41** (n,G) -> 3.264 Bq **K-42** (12.36 h)

180.0 µg Magnesium:
(not found)

6.550 µg Manganese:

6.550 µg **Mn-55** (n,G) -> 1.824 kBq **Mn-56** (2.578 h)

148.0 µg Sodium:

148.0 µg **Na-23** (n,G) -> 672.5 Bq **Na-24** (15.00 h)

645.0 ng Selenium:

5.432 ng **Se-74** (n,G) -> 3.912 mBq **Se-75** (119.8 d)

149.5 ng **Se-78** (n,G) -> 3.781 nBq **Se-79** (65.00e3 a)

324.9 ng **Se-80** (n,G) -> 23.69 Bq **Se-81** (18.50 m)

61.54 ng **Se-82** (n,G) -> 253.9 mBq **Se-83** (22.50 m)
~> 102.3 µBq **Br-83** (2.390 h)
~> 35.89 nBq **Kr-83m** (1.830 h)

223.0 ng Antimony:

126.8 ng **Sb-121** (n,G) -> 282.4 mBq **Sb-122** (2.700 d)

96.12 ng **Sb-123** (n,G) -> 6.559 mBq **Sb-124** (60.20 d)

82.50 µg Silicon:

2.729 µg **Si-30** (n,G) -> 10.98 Bq **Si-31** (157.3 m)

31.80 µg Strontium:

170.5 ng **Sr-84** (n,G) -> 2.392 mBq **Sr-85** (64.84 d)

26.34 µg **Sr-88** (n,G) -> 4.238 mBq **Sr-89** (50.50 d)

239.0 µg Titanium:
(not found)

259.0 ng Uranium:

13.82 pg **U-234** (n,G) -> 0 Bq **U-235** (703.8e6 a)
~> 0 Bq **Th-231** (25.52 h)
~> 0 Bq **Pa-231** (32.76e3 a)
~> 0 Bq **Ac-227** (21.77 a)

~> 0 Bq **Th-227** (18.71 d)
~> 0 Bq **Ra-223** (11.43 d)
~> 0 Bq **Rn-219** (3.960 s)
~> 0 Bq **Po-215** (1.780e-3 s)
~> 0 Bq **Pb-211** (36.10 m)
~> 0 Bq **Bi-211** (2.140 m)
~> 0 Bq **Tl-207** (4.770 m)
~> 0 Bq **Po-211** (516.0e-3 s)
~> 0 Bq **Fr-223** (21.80 m)

1.841 ng **U-235** (n,G) -> 0 Bq **U-236** (23.41e6 a)
~> 0 Bq **Th-232** (14.05e9 a)
~> 0 Bq **Ra-228** (5.750 a)
~> 0 Bq **Ac-228** (6.130 h)
~> 0 Bq **Th-228** (1.913 a)
~> 0 Bq **Ra-224** (3.660 d)
~> 0 Bq **Rn-220** (55.60 s)
~> 0 Bq **Po-216** (150.0e-3 s)
~> 0 Bq **Pb-212** (10.64 h)
~> 0 Bq **Bi-212** (60.55 m)
~> 0 Bq **Po-212** (305.0e-3 us)
~> 0 Bq **Tl-208** (3.070 m)

257.1 ng **U-238** (n,G) -> 21.77 Bq **U-239** (23.54 m)
~> 371.2 µBq **Np-239** (2.355 d)
~> 0 Bq **Pu-239** (24.06e3 a)
~> 0 Bq **U-235** (703.8e6 a)
~> 0 Bq **Th-231** (25.52 h)
~> 0 Bq **Pa-231** (32.76e3 a)
~> 0 Bq **Ac-227** (21.77 a)
~> 0 Bq **Th-227** (18.71 d)
~> 0 Bq **Ra-223** (11.43 d)
~> 0 Bq **Rn-219** (3.960 s)
~> 0 Bq **Po-215** (1.780e-3 s)
~> 0 Bq **Pb-211** (36.10 m)
~> 0 Bq **Bi-211** (2.140 m)
~> 0 Bq **Tl-207** (4.770 m)
~> 0 Bq **Po-211** (516.0e-3 s)
~> 0 Bq **Fr-223** (21.80 m)

11.90 µg Vanadium:
(not found)

3.050 µg Arsenic:

3.050 µg **As-75** (n,G) -> 19.33 Bq **As-76** (26.32 h)

40.00 ng Cadmium:

471.1 pg **Cd-106** (n,G) -> 2.025 mBq **Cd-107** (6.490 h)

341.7 pg **Cd-108** (n,G) -> 605.1 nBq **Cd-109** (464.0 d)

9.609 ng **Cd-112** (n,G) -> 0 Bq **Cd-113** (9.300e15 a)

11.64 ng **Cd-114** (n,G) -> 1.921 mBq **Cd-115** (53.46 h)
~> 412.1 nBq **In-115m** (4.486 h)
~> 0 Bq **In-115** (5.100e15 a)

3.080 ng **Cd-116** (n,G) -> 2.365 mBq **Cd-117** (2.490 h)
~> 1.078 µBq **In-117m** (116.5 m)
~> 249.8 nBq **In-117** (43.80 m)
~> 0 Bq **Sn-117m** (13.61 d)

46.40 ng Mercury:

90.66 pg **Hg-196** (n,G) -> 65.74 mBq **Hg-197** (64.10 h)

13.82 ng **Hg-202** (n,G) -> 800.3 µBq **Hg-203** (46.60 d)

5.470 µg Potassium:

5.083 µg **K-39** (n,G) -> 0 Bq **K-40** (1.280e9 a)

385.7 ng **K-41** (n,G) -> 3.264 Bq **K-42** (12.36 h)

148.0 µg Sodium:

148.0 µg **Na-23** (n,G) -> 672.5 Bq **Na-24** (15.00 h)

223.0 ng Antimony:

126.8 ng **Sb-121** (n,G) -> 282.4 mBq **Sb-122** (2.700 d)

96.12 ng **Sb-123** (n,G) -> 6.559 mBq **Sb-124** (60.20 d)

259.0 ng Uranium:

13.82 pg **U-234** (n,G) -> 0 Bq **U-235** (703.8e6 a)
~> 0 Bq **Th-231** (25.52 h)
~> 0 Bq **Pa-231** (32.76e3 a)
~> 0 Bq **Ac-227** (21.77 a)
~> 0 Bq **Th-227** (18.71 d)
~> 0 Bq **Ra-223** (11.43 d)
~> 0 Bq **Rn-219** (3.960 s)
~> 0 Bq **Po-215** (1.780e-3 s)
~> 0 Bq **Pb-211** (36.10 m)
~> 0 Bq **Bi-211** (2.140 m)
~> 0 Bq **Tl-207** (4.770 m)
~> 0 Bq **Po-211** (516.0e-3 s)
~> 0 Bq **Fr-223** (21.80 m)

1.841 ng **U-235** (n,G) -> 0 Bq **U-236** (23.41e6 a)
~> 0 Bq **Th-232** (14.05e9 a)

~> 0 Bq **Ra-228** (5.750 a)
~> 0 Bq **Ac-228** (6.130 h)
~> 0 Bq **Th-228** (1.913 a)
~> 0 Bq **Ra-224** (3.660 d)
~> 0 Bq **Rn-220** (55.60 s)
~> 0 Bq **Po-216** (150.0e-3 s)
~> 0 Bq **Pb-212** (10.64 h)
~> 0 Bq **Bi-212** (60.55 m)
~> 0 Bq **Po-212** (305.0e-3 us)
~> 0 Bq **Tl-208** (3.070 m)

257.1 ng **U-238** (n,G) -> 21.77 Bq **U-239** (23.54 m)
~> 371.2 µBq **Np-239** (2.355 d)
~> 0 Bq **Pu-239** (24.06e3 a)
~> 0 Bq **U-235** (703.8e6 a)
~> 0 Bq **Th-231** (25.52 h)
~> 0 Bq **Pa-231** (32.76e3 a)
~> 0 Bq **Ac-227** (21.77 a)
~> 0 Bq **Th-227** (18.71 d)
~> 0 Bq **Ra-223** (11.43 d)
~> 0 Bq **Rn-219** (3.960 s)
~> 0 Bq **Po-215** (1.780e-3 s)
~> 0 Bq **Pb-211** (36.10 m)
~> 0 Bq **Bi-211** (2.140 m)
~> 0 Bq **Tl-207** (4.770 m)
~> 0 Bq **Po-211** (516.0e-3 s)
~> 0 Bq **Fr-223** (21.80 m)

6.450 µg Zinc:

3.064 µg **Zn-64** (n,G) -> 26.61 mBq **Zn-65** (243.9 d)

1.259 µg **Zn-68** (n,G) -> 4.148 Bq **Zn-69** (57.00 m)

5.850 µg Cerium:

10.78 ng **Ce-136** (n,G) -> 169.3 mBq **Ce-137** (9.000 h)
~> 0 Bq **La-137** (60.00e3 a)

14.39 ng **Ce-138** (n,G) -> 95.26 µBq **Ce-139** (137.6 d)

5.168 µg **Ce-140** (n,G) -> 81.20 mBq **Ce-141** (32.50 d)

656.4 ng **Ce-142** (n,G) -> 401.9 mBq **Ce-143** (33.00 h)
~> 1.189 µBq **Pr-143** (13.56 d)

6.850 µg Chromium:

286.2 ng **Cr-50** (n,G) -> 404.9 mBq **Cr-51** (27.70 d)

299.0 ng Cesium:

299.0 ng **Cs-133** (n,G) -> 11.14 mBq **Cs-134** (2.062 a)

1.710 µg Cobalt:

1.710 µg **Co-59** (n,G) -> 68.99 mBq **Co-60** (5.271 a)

109.0 ng Europium:

51.74 ng **Eu-151** (n,G) -> 79.81 mBq **Eu-152** (13.33 a)
~> 0 Bq **Gd-152** (108.0e12 a)

57.25 ng **Eu-153** (n,G) -> 4.477 mBq **Eu-154** (8.800 a)

37.50 µg Iron:

2.100 µg **Fe-54** (n,G) -> 10.93 mBq **Fe-55** (2.700 a)

116.7 ng **Fe-58** (n,G) -> 7.240 mBq **Fe-59** (44.53 d)

46.40 ng Mercury:

90.66 pg **Hg-196** (n,G) -> 65.74 mBq **Hg-197** (64.10 h)

13.82 ng **Hg-202** (n,G) -> 800.3 µBq **Hg-203** (46.60 d)

3.680 µg Rubidium:

2.638 µg **Rb-85** (n,G) -> 98.42 mBq **Rb-86** (18.66 d)

1.041 µg **Rb-87** (n,G) -> 14.27 Bq **Rb-88** (17.80 m)

223.0 ng Antimony:

126.8 ng **Sb-121** (n,G) -> 282.4 mBq **Sb-122** (2.700 d)

96.12 ng **Sb-123** (n,G) -> 6.559 mBq **Sb-124** (60.20 d)

1.450 µg Scandium:

1.450 µg **Sc-45** (n,G) -> 1.288 Bq **Sc-46** (83.83 d)

645.0 ng Selenium:

5.432 ng **Se-74** (n,G) -> 3.912 mBq **Se-75** (119.8 d)

149.5 ng **Se-78** (n,G) -> 3.781 nBq **Se-79** (65.00e3 a)

324.9 ng **Se-80** (n,G) -> 23.69 Bq **Se-81** (18.50 m)

61.54 ng **Se-82** (n,G) -> 253.9 mBq **Se-83** (22.50 m)
~> 102.3 µBq **Br-83** (2.390 h)
~> 35.89 nBq **Kr-83m** (1.830 h)

31.80 µg Strontium:

170.5 ng **Sr-84** (n,G) -> 2.392 mBq **Sr-85** (64.84 d)

26.34 µg **Sr-88** (n,G) -> 4.238 mBq **Sr-89** (50.50 d)

714.0 ng Thorium:

714.0 ng **Th-232** (n,G) -> 179.5 Bq **Th-233** (22.30 m)
~> 267.0 µBq **Pa-233** (27.00 d)
~> 0 Bq **U-233** (158.5e3 a)
~> 0 Bq **Th-229** (7.340e3 a)
~> 0 Bq **Ra-225** (14.80 d)
~> 0 Bq **Ac-225** (10.00 d)
~> 0 Bq **Fr-221** (4.800 m)
~> 0 Bq **At-217** (32.30e-3 s)
~> 0 Bq **Bi-213** (45.65 m)
~> 0 Bq **Po-213** (4.200 us)
~> 0 Bq **Pb-209** (3.253 h)
~> 0 Bq **Tl-209** (2.200 m)

6.450 µg Zinc:

3.064 µg **Zn-64** (n,G) -> 26.61 mBq **Zn-65** (243.9 d)

1.259 µg **Zn-68** (n,G) -> 4.148 Bq **Zn-69** (57.00 m)

NIST 1633c – Trace Elements in Coal Fly Ash

Search Mode

- (selected) Forward (Search activation products)
- Reverse (Search original nuclides)

Nuclide Input

HELP

Zn 1.24E-04 | IMPORT | ------- Select Sample Data ------- | RESET

Original Element / Nuclide	Mass [g]	Original Element / Nuclide	Mass	Original Element / Nuclide	Mass	Original Element / Nuclide	Mass
Al	7.02E-04	Si	1.13E-03	Sm	1.00E-05	Ni	6.98E-05
Ba	5.95E-06	Sr	4.76E-04	U	4.89E-06	Rb	6.21E-05
Ca	7.22E-05	Ti	3.83E-05	Zn	1.24E-04	Sb	4.53E-06
Co	2.27E-05	U	4.89E-06	Ce	9.52E-05	Sc	1.99E-05
Cu	9.18E-05	V	1.51E-04	Cr	1.36E-04	Se	7.35E-06
Dy	9.89E-06	As	9.84E-05	Cs	4.96E-06	Sr	4.76E-04
In	7.40E-08	Cd	4.01E-07	Co	2.27E-05	Ta	8.35E-07
K	9.37E-05	Ga	2.91E-05	Eu	2.47E-06	Tb	1.65E-06
Mg	2.63E-05	Hg	5.31E-07	Fe	5.55E-04	Th	1.22E-05
Mn	1.27E-04	K	9.37E-05	Hf	3.17E-06	Yb	4.07E-06
Na	9.02E-06	La	4.60E-05	Hg	5.31E-07	Zn	1.24E-04
Se	7.35E-06	Na	9.02E-06	Lu	6.98E-07		
Sb	4.53E-06	Sb	4.53E-06	Nd	4.60E-05		

Output Parameters

HELP

2.55e12 Neutron flux [per cm^2s] - or - Point source neutron emission rate [per s] / Distance from point source [m]

- [x] use IAEA 2003 cross sections, where available
- [x] thermal neutrons (n,Gamma)
- [ ] fast neutrons (n,2n) (n,3n) (n,p) (n,t) (n,Alpha)

10 Duration of irradiation [s]

0 Time delay since end of irradiation [h]

Max. half-life for consideration of progeny [years]

Bq Activation Product Unit

Neutron flux = 2.550e12 per cm^{2}s
Irradiation = 10 s; Delay = 0 h

Original Nuclide	**Reaction**	**Activation (->) & Decay (~>) Products**	**Half-Life**

702.0 µg Aluminum:

702.0 µg **Al-27** (n,G) -> 463.8 kBq **Al-28** (2.240 m)

5.950 µg Barium:

5.966 ng **Ba-130** (n,G) -> 4.170 mBq **Ba-131** (11.80 d)
~> 17.26 nBq **Cs-131** (9.690 d)

5.772 ng **Ba-132** (n,G) -> 8.931 µBq **Ba-133** (10.74 a)

4.284 µg **Ba-138** (n,G) -> 26.89 Bq **Ba-139** (82.70 m)

72.20 µg Calcium:

69.79 µg **Ca-40** (n,G) -> 1.724 µBq **Ca-41** (140.0e3 a)

1.652 µg **Ca-44** (n,G) -> 24.98 mBq **Ca-45** (163.0 d)

3.311 ng **Ca-46** (n,G) -> 1.410 mBq **Ca-47** (4.530 d)
~> 16.88 nBq **Sc-47** (3.351 d)

161.5 ng **Ca-48** (n,G) -> 74.21 Bq **Ca-49** (8.716 m)
~> 74.79 mBq **Sc-49** (57.40 m)

22.70 µg Cobalt:

22.70 µg **Co-59** (n,G) -> 915.8 mBq **Co-60** (5.271 a)

91.80 µg Copper:

62.88 µg **Cu-63** (n,G) -> 1.050 kBq **Cu-64** (12.70 h)

28.91 µg **Cu-65** (n,G) -> 33.21 kBq **Cu-66** (5.100 m)

9.890 µg Dysprosium:

5.694 ng **Dy-156** (n,G) -> 439.8 mBq **Dy-157** (8.100 h)
~> 0 Bq **Tb-157** (150.0 a)

9.612 ng **Dy-158** (n,G) -> 2.232 mBq **Dy-159** (144.4 d)

2.803 µg **Dy-164** (n,G) -> 57.39 kBq **Dy-165** (2.334 h)

74.00 ng Indium:

3.129 ng **In-113** (n,G) -> 46.91 Bq **In-114** (71.90 s)

93.70 µg Potassium:

87.08 µg **K-39** (n,G) -> 1.151 nBq **K-40** (1.280e9 a)

6.607 µg **K-41** (n,G) -> 55.91 Bq **K-42** (12.36 h)

26.30 µg Magnesium:

(not found)

127.0 µg Manganese:

127.0 µg **Mn-55** (n,G) -> 35.37 kBq **Mn-56** (2.578 h)

9.020 µg Sodium:

9.020 µg **Na-23** (n,G) -> 40.98 Bq **Na-24** (15.00 h)

7.350 µg Selenium:

61.90 ng **Se-74** (n,G) -> 44.58 mBq **Se-75** (119.8 d)

1.703 µg **Se-78** (n,G) -> 43.09 nBq **Se-79** (65.00e3 a)

3.703 µg **Se-80** (n,G) -> 270.0 Bq **Se-81** (18.50 m)

701.2 ng **Se-82** (n,G) -> 2.893 Bq **Se-83** (22.50 m)
~> 1.166 mBq **Br-83** (2.390 h)
~> 408.9 nBq **Kr-83m** (1.830 h)

4.530 µg Antimony:

2.577 µg **Sb-121** (n,G) -> 5.737 Bq **Sb-122** (2.700 d)

1.952 µg **Sb-123** (n,G) -> 133.2 mBq **Sb-124** (60.20 d)

1.130 mg Silicon:

37.38 µg **Si-30** (n,G) -> 150.4 Bq **Si-31** (157.3 m)

476.0 µg Strontium:

2.552 µg **Sr-84** (n,G) -> 35.81 mBq **Sr-85** (64.84 d)

394.3 µg **Sr-88** (n,G) -> 63.44 mBq **Sr-89** (50.50 d)

38.30 µg Titanium:

(not found)

4.890 µg Uranium:

261.1 pg **U-234** (n,G) -> 0 Bq **U-235** (703.8e6 a)
~> 0 Bq **Th-231** (25.52 h)
~> 0 Bq **Pa-231** (32.76e3 a)
~> 0 Bq **Ac-227** (21.77 a)
~> 0 Bq **Th-227** (18.71 d)
~> 0 Bq **Ra-223** (11.43 d)
~> 0 Bq **Rn-219** (3.960 s)
~> 0 Bq **Po-215** (1.780e-3 s)
~> 0 Bq **Pb-211** (36.10 m)
~> 0 Bq **Bi-211** (2.140 m)
~> 0 Bq **Tl-207** (4.770 m)
~> 0 Bq **Po-211** (516.0e-3 s)
~> 0 Bq **Fr-223** (21.80 m)

34.76 ng **U-235** (n,G) -> 0 Bq **U-236** (23.41e6 a)
~> 0 Bq **Th-232** (14.05e9 a)
~> 0 Bq **Ra-228** (5.750 a)
~> 0 Bq **Ac-228** (6.130 h)
~> 0 Bq **Th-228** (1.913 a)
~> 0 Bq **Ra-224** (3.660 d)
~> 0 Bq **Rn-220** (55.60 s)
~> 0 Bq **Po-216** (150.0e-3 s)
~> 0 Bq **Pb-212** (10.64 h)
~> 0 Bq **Bi-212** (60.55 m)
~> 0 Bq **Po-212** (305.0e-3 us)
~> 0 Bq **Tl-208** (3.070 m)

4.855 µg **U-238** (n,G) -> 411.1 Bq **U-239** (23.54 m)
~> 7.009 mBq **Np-239** (2.355 d)
~> 0 Bq **Pu-239** (24.06e3 a)
~> 0 Bq **U-235** (703.8e6 a)
~> 0 Bq **Th-231** (25.52 h)
~> 0 Bq **Pa-231** (32.76e3 a)
~> 0 Bq **Ac-227** (21.77 a)
~> 0 Bq **Th-227** (18.71 d)
~> 0 Bq **Ra-223** (11.43 d)
~> 0 Bq **Rn-219** (3.960 s)
~> 0 Bq **Po-215** (1.780e-3 s)
~> 0 Bq **Pb-211** (36.10 m)
~> 0 Bq **Bi-211** (2.140 m)
~> 0 Bq **Tl-207** (4.770 m)
~> 0 Bq **Po-211** (516.0e-3 s)
~> 0 Bq **Fr-223** (21.80 m)

151.0 µg Vanadium:
(not found)

98.40 µg Arsenic:

98.40 µg **As-75** (n,G) -> 623.7 Bq **As-76** (26.32 h)

401.0 ng Cadmium:

4.722 ng **Cd-106** (n,G) -> 20.30 mBq **Cd-107** (6.490 h)

3.426 ng **Cd-108** (n,G) -> 6.067 µBq **Cd-109** (464.0 d)

96.33 ng **Cd-112** (n,G) -> 0 Bq **Cd-113** (9.300e15 a)

116.7 ng **Cd-114** (n,G) -> 19.25 mBq **Cd-115** (53.46 h)
~> 4.132 µBq **In-115m** (4.486 h)
~> 0 Bq **In-115** (5.100e15 a)

30.88 ng **Cd-116** (n,G) -> 23.71 mBq **Cd-117** (2.490 h)
~> 10.81 µBq **In-117m** (116.5 m)
~> 2.504 µBq **In-117** (43.80 m)
~> 0 Bq **Sn-117m** (13.61 d)

29.10 µg Gallium:

17.29 µg **Ga-69** (n,G) -> 3.522 kBq **Ga-70** (21.15 m)

11.81 µg **Ga-71** (n,G) -> 165.0 Bq **Ga-72** (14.10 h)

531.0 ng Mercury:

1.037 ng **Hg-196** (n,G) -> 752.4 mBq **Hg-197** (64.10 h)

158.2 ng **Hg-202** (n,G) -> 9.159 mBq **Hg-203** (46.60 d)

93.70 µg Potassium:

87.08 µg **K-39** (n,G) -> 1.151 nBq **K-40** (1.280e9 a)

6.607 µg **K-41** (n,G) -> 55.91 Bq **K-42** (12.36 h)

46.00 µg Lanthanum:

45.96 µg **La-139** (n,G) -> 219.5 Bq **La-140** (40.27 h)

9.020 µg Sodium:

9.020 µg **Na-23** (n,G) -> 40.98 Bq **Na-24** (15.00 h)

4.530 µg Antimony:

2.577 µg **Sb-121** (n,G) -> 5.737 Bq **Sb-122** (2.700 d)

1.952 µg **Sb-123** (n,G) -> 133.2 mBq **Sb-124** (60.20 d)

10.00 µg Samarium:

296.7 ng **Sm-144** (n,G) -> 1.225 mBq **Sm-145** (340.0 d)
~> 0 Bq **Pm-145** (17.70 a)

Sm-146 (n,G) -> **Sm-147** (106.0e9 a)

737.9 ng **Sm-150** (n,G) -> 1.844 mBq **Sm-151** (90.00 a)

2.687 µg **Sm-152** (n,G) -> 230.7 Bq **Sm-153** (46.70 h)

2.313 µg **Sm-154** (n,G) -> 998.8 Bq **Sm-155** (22.10 m)
~> 22.13 µBq **Eu-155** (4.960 a)

4.890 µg Uranium:

261.1 pg **U-234** (n,G) -> 0 Bq **U-235** (703.8e6 a)
~> 0 Bq **Th-231** (25.52 h)
~> 0 Bq **Pa-231** (32.76e3 a)
~> 0 Bq **Ac-227** (21.77 a)
~> 0 Bq **Th-227** (18.71 d)
~> 0 Bq **Ra-223** (11.43 d)
~> 0 Bq **Rn-219** (3.960 s)
~> 0 Bq **Po-215** (1.780e-3 s)
~> 0 Bq **Pb-211** (36.10 m)
~> 0 Bq **Bi-211** (2.140 m)
~> 0 Bq **Tl-207** (4.770 m)
~> 0 Bq **Po-211** (516.0e-3 s)
~> 0 Bq **Fr-223** (21.80 m)

34.76 ng **U-235** (n,G) -> 0 Bq **U-236** (23.41e6 a)
~> 0 Bq **Th-232** (14.05e9 a)
~> 0 Bq **Ra-228** (5.750 a)
~> 0 Bq **Ac-228** (6.130 h)
~> 0 Bq **Th-228** (1.913 a)
~> 0 Bq **Ra-224** (3.660 d)
~> 0 Bq **Rn-220** (55.60 s)
~> 0 Bq **Po-216** (150.0e-3 s)
~> 0 Bq **Pb-212** (10.64 h)
~> 0 Bq **Bi-212** (60.55 m)
~> 0 Bq **Po-212** (305.0e-3 us)
~> 0 Bq **Tl-208** (3.070 m)

4.855 µg **U-238** (n,G) -> 411.1 Bq **U-239** (23.54 m)
~> 7.009 mBq **Np-239** (2.355 d)
~> 0 Bq **Pu-239** (24.06e3 a)
~> 0 Bq **U-235** (703.8e6 a)
~> 0 Bq **Th-231** (25.52 h)
~> 0 Bq **Pa-231** (32.76e3 a)
~> 0 Bq **Ac-227** (21.77 a)
~> 0 Bq **Th-227** (18.71 d)
~> 0 Bq **Ra-223** (11.43 d)
~> 0 Bq **Rn-219** (3.960 s)

~> 0 Bq **Po-215** (1.780e-3 s)
~> 0 Bq **Pb-211** (36.10 m)
~> 0 Bq **Bi-211** (2.140 m)
~> 0 Bq **Tl-207** (4.770 m)
~> 0 Bq **Po-211** (516.0e-3 s)
~> 0 Bq **Fr-223** (21.80 m)

124.0 µg Zinc:

58.91 µg **Zn-64** (n,G) -> 511.6 mBq **Zn-65** (243.9 d)

24.21 µg **Zn-68** (n,G) -> 79.75 Bq **Zn-69** (57.00 m)

95.20 µg Cerium:

175.4 ng **Ce-136** (n,G) -> 2.755 Bq **Ce-137** (9.000 h)
~> 0 Bq **La-137** (60.00e3 a)

234.2 ng **Ce-138** (n,G) -> 1.550 mBq **Ce-139** (137.6 d)

84.11 µg **Ce-140** (n,G) -> 1.321 Bq **Ce-141** (32.50 d)

10.68 µg **Ce-142** (n,G) -> 6.541 Bq **Ce-143** (33.00 h)
~> 19.35 µBq **Pr-143** (13.56 d)

136.0 µg Chromium:

5.682 µg **Cr-50** (n,G) -> 8.039 Bq **Cr-51** (27.70 d)

4.960 µg Cesium:

4.960 µg **Cs-133** (n,G) -> 184.9 mBq **Cs-134** (2.062 a)

22.70 µg Cobalt:

22.70 µg **Co-59** (n,G) -> 915.8 mBq **Co-60** (5.271 a)

2.470 µg Europium:

1.172 µg **Eu-151** (n,G) -> 1.808 Bq **Eu-152** (13.33 a)
~> 0 Bq **Gd-152** (108.0e12 a)

1.297 µg **Eu-153** (n,G) -> 101.4 mBq **Eu-154** (8.800 a)

555.0 µg Iron:

31.09 µg **Fe-54** (n,G) -> 161.9 mBq **Fe-55** (2.700 a)

1.727 µg **Fe-58** (n,G) -> 107.1 mBq **Fe-59** (44.53 d)

3.170 µg Hafnium:

4.943 ng **Hf-174** (n,G) -> 27.46 mBq **Hf-175** (70.00 d)

1.124 µg **Hf-180** (n,G) -> 236.9 mBq **Hf-181** (42.40 d)

531.0 ng Mercury:

1.037 ng **Hg-196** (n,G) -> 752.4 mBq **Hg-197** (64.10 h)

158.2 ng **Hg-202** (n,G) -> 9.159 mBq **Hg-203** (46.60 d)

698.0 ng Lutetium:

679.7 ng **Lu-175** (n,G) -> 0 Bq **Lu-176** (36.00e9 a)

18.32 ng **Lu-176** (n,G) -> 3.995 Bq **Lu-177** (6.710 d)

46.00 µg Neodymium:

7.999 µg **Nd-146** (n,G) -> 867.1 mBq **Nd-147** (10.98 d)
~> 36.30 nBq **Pm-147** (2.623 a)
~> 0 Bq **Sm-147** (106.0e9 a)

2.712 µg **Nd-148** (n,G) -> 80.80 Bq **Nd-149** (1.730 h)
~> 1.465 mBq **Pm-149** (53.08 h)

2.691 µg **Nd-150** (n,G) -> 262.4 Bq **Nd-151** (12.44 m)
~> 8.910 mBq **Pm-151** (28.40 h)
~> 0 Bq **Sm-151** (90.00 a)

69.80 µg Nickel:

47.04 µg **Ni-58** (n,G) -> 16.42 µBq **Ni-59** (75.00e3 a)

2.644 µg **Ni-62** (n,G) -> 2.173 mBq **Ni-63** (96.00 a)

691.9 ng **Ni-64** (n,G) -> 20.67 Bq **Ni-65** (2.520 h)

62.10 µg Rubidium:

44.52 µg **Rb-85** (n,G) -> 1.660 Bq **Rb-86** (18.66 d)

17.57 µg **Rb-87** (n,G) -> 240.9 Bq **Rb-88** (17.80 m)

4.530 µg Antimony:

2.577 µg **Sb-121** (n,G) -> 5.737 Bq **Sb-122** (2.700 d)

1.952 µg **Sb-123** (n,G) -> 133.2 mBq **Sb-124** (60.20 d)

19.90 µg Scandium:

19.90 µg **Sc-45** (n,G) -> 17.68 Bq **Sc-46** (83.83 d)

7.350 µg Selenium:

61.90 ng **Se-74** (n,G) -> 44.58 mBq **Se-75** (119.8 d)

1.703 µg **Se-78** (n,G) -> 43.09 nBq **Se-79** (65.00e3 a)

3.703 µg **Se-80** (n,G) -> 270.0 Bq **Se-81** (18.50 m)

701.2 ng **Se-82** (n,G) -> 2.893 Bq **Se-83** (22.50 m)
~> 1.166 mBq **Br-83** (2.390 h)
~> 408.9 nBq **Kr-83m** (1.830 h)

476.0 µg Strontium:

2.552 µg **Sr-84** (n,G) -> 35.81 mBq **Sr-85** (64.84 d)

394.3 µg **Sr-88** (n,G) -> 63.44 mBq **Sr-89** (50.50 d)

835.0 ng Tantalum:

834.9 ng **Ta-181** (n,G) -> 101.3 mBq **Ta-182** (115.0 d)

1.650 µg Terbium:

1.650 µg **Tb-159** (n,G) -> 412.2 mBq **Tb-160** (72.30 d)

12.20 µg Thorium:

12.20 µg **Th-232** (n,G) -> 3.068 kBq **Th-233** (22.30 m)
~> 4.562 mBq **Pa-233** (27.00 d)
~> 0 Bq **U-233** (158.5e3 a)
~> 0 Bq **Th-229** (7.340e3 a)
~> 0 Bq **Ra-225** (14.80 d)
~> 0 Bq **Ac-225** (10.00 d)
~> 0 Bq **Fr-221** (4.800 m)
~> 0 Bq **At-217** (32.30e-3 s)
~> 0 Bq **Bi-213** (45.65 m)
~> 0 Bq **Po-213** (4.200 us)
~> 0 Bq **Pb-209** (3.253 h)
~> 0 Bq **Tl-209** (2.200 m)

4.070 µg Ytterbium:

5.530 ng **Yb-168** (n,G) -> 291.5 mBq **Yb-169** (32.01 d)

1.301 µg **Yb-174** (n,G) -> 13.90 Bq **Yb-175** (4.190 d)

525.5 ng **Yb-176** (n,G) -> 13.24 Bq **Yb-177** (1.900 h)
~> 79.18 µBq **Lu-177** (6.710 d)

124.0 µg Zinc:

58.91 µg **Zn-64** (n,G) -> 511.6 mBq **Zn-65** (243.9 d)

24.21 µg **Zn-68** (n,G) -> 79.75 Bq **Zn-69** (57.00 m)

NIST 1547 – Peach Leaves

Search Mode

- (●) Forward (Search activation products)
- ( ) Reverse (Search original nuclides)

Nuclide Input HELP

Zn 8.99E-06 [IMPORT] [------- Select Sample Data -------] [RESET]

Original Element / Nuclide	Mass (g)	Original Element / Nuclide	Mass	Original Element / Nuclide	Mass	Original Element / Nuclide	Mass
Al	1.24E-04	Hg	1.59E-08				
Ba	6.19E-05	K	1.22E-02				
Ca	7.80E-03	Mo	3.02E-08				
Cl	1.81E-04	Zn	8.99E-06				
Cu	1.88E-06	Fe	1.10E-04				
K	1.22E-02	Hg	1.59E-08				
Mg	2.16E-03	Ni	3.45E-07				
Mn	4.89E-05	Rb	9.83E-06				
Se	6.00E-08	Se	6.00E-08				
Sr	2.65E-05	Sr	2.65E-05				
V	1.84E-07	Zn	8.99E-06				
As	3.10E-08						
Cd	1.31E-08						

Output Parameters HELP

2.55e12 Neutron flux [per cm^2s] - or - Point source neutron emission rate [per s] / Distance from point source [m]

- [x] use IAEA 2003 cross sections, where available
- [x] thermal neutrons (n,Gamma)
- [ ] fast neutrons (n,2n) (n,3n) (n,p) (n,t) (n,Alpha)

10 Duration of irradiation [s]
0 Time delay since end of irradiation [h]
Max. half-life for consideration of progeny [years]
Bq Activation Product Unit

Neutron flux = 2.550e12 per cm^2s
Irradiation = 10 s; Delay = 0 h

Original Nuclide **Reaction** **Activation (->) & Decay (~>) Products** **Half-Life**

124.0 µg Aluminum:

124.0 µg **Al-27** (n,G) -> 81.92 kBq **Al-28** (2.240 m)

61.90 µg Barium:

62.07 ng **Ba-130** (n,G) -> 43.38 mBq **Ba-131** (11.80 d)
~> 179.6 nBq **Cs-131** (9.690 d)

60.05 ng **Ba-132** (n,G) -> 92.91 µBq **Ba-133** (10.74 a)

44.57 µg **Ba-138** (n,G) -> 279.8 Bq **Ba-139** (82.70 m)

7.800 mg Calcium:

7.539 mg **Ca-40** (n,G) -> 186.2 µBq **Ca-41** (140.0e3 a)

178.4 µg **Ca-44** (n,G) -> 2.698 Bq **Ca-45** (163.0 d)

357.7 ng **Ca-46** (n,G) -> 152.3 mBq **Ca-47** (4.530 d)
~> 1.823 µBq **Sc-47** (3.351 d)

17.45 µg **Ca-48** (n,G) -> 8.017 kBq **Ca-49** (8.716 m)
~> 8.080 Bq **Sc-49** (57.40 m)

181.0 µg Chlorine:

135.2 µg **Cl-35** (n,G) -> 188.7 µBq **Cl-36** (301.0e3 a)

45.73 µg **Cl-37** (n,G) -> 2.531 kBq **Cl-38** (37.21 m)

1.880 µg Copper:

1.287 µg **Cu-63** (n,G) -> 21.51 Bq **Cu-64** (12.70 h)

592.2 ng **Cu-65** (n,G) -> 680.3 Bq **Cu-66** (5.100 m)

12.20 mg Potassium:

11.33 mg **K-39** (n,G) -> 147.4 nBq **K-40** (1.280e9 a)

860.2 µg **K-41** (n,G) -> 7.280 kBq **K-42** (12.36 h)

2.160 mg Magnesium:
(not found)

48.90 µg Manganese:

48.90 µg **Mn-55** (n,G) -> 13.62 kBq **Mn-56** (2.578 h)

60.00 ng Selenium:

505.3 pg **Se-74** (n,G) -> 363.9 µBq **Se-75** (119.8 d)

13.90 ng **Se-78** (n,G) -> 0 Bq **Se-79** (65.00e3 a)

30.23 ng **Se-80** (n,G) -> 2.204 Bq **Se-81** (18.50 m)

5.724 ng **Se-82** (n,G) -> 23.61 mBq **Se-83** (22.50 m)
~> 9.519 µBq **Br-83** (2.390 h)
~> 3.338 nBq **Kr-83m** (1.830 h)

26.50 µg Strontium:

142.1 ng **Sr-84** (n,G) -> 1.994 mBq **Sr-85** (64.84 d)

21.95 µg **Sr-88** (n,G) -> 3.531 mBq **Sr-89** (50.50 d)

184.0 ng Vanadium:
(not found)

31.00 ng Arsenic:

31.00 ng **As-75** (n,G) -> 196.4 mBq **As-76** (26.32 h)

13.10 ng Cadmium:

154.2 pg **Cd-106** (n,G) -> 663.3 µBq **Cd-107** (6.490 h)

111.9 pg **Cd-108** (n,G) -> 198.2 nBq **Cd-109** (464.0 d)

3.146 ng **Cd-112** (n,G) -> 0 Bq **Cd-113** (9.300e15 a)

3.812 ng **Cd-114** (n,G) -> 629.1 µBq **Cd-115** (53.46 h)
~> 134.9 nBq **In-115m** (4.486 h)
~> 0 Bq **In-115** (5.100e15 a)

1.009 ng **Cd-116** (n,G) -> 774.6 µBq **Cd-117** (2.490 h)
~> 353.3 nBq **In-117m** (116.5 m)
~> 81.81 nBq **In-117** (43.80 m)
~> 0 Bq **Sn-117m** (13.61 d)

15.90 ng Mercury:

31.06 pg **Hg-196** (n,G) -> 22.53 mBq **Hg-197** (64.10 h)

4.739 ng **Hg-202** (n,G) -> 274.2 µBq **Hg-203** (46.60 d)

12.20 mg Potassium:

11.33 mg **K-39** (n,G) -> 147.4 nBq **K-40** (1.280e9 a)

860.2 µg **K-41** (n,G) -> 7.280 kBq **K-42** (12.36 h)

30.20 ng Molybdenum:

4.294 ng **Mo-92** (n,G) -> 0 Bq **Mo-93** (3.500e3 a)
~> 0 Bq **Nb-93m** (13.60 a)

7.437 ng **Mo-98** (n,G) -> 465.9 µBq **Mo-99** (66.00 h)
~> 65.27 nBq **Tc-99m** (6.020 h)
~> 0 Bq **Tc-99** (213.0e3 a)

3.028 ng **Mo-100** (n,G) -> 72.88 mBq **Mo-101** (14.62 m)
~> 296.0 µBq **Tc-101** (14.20 m)

8.990 µg Zinc:

4.271 µg **Zn-64** (n,G) -> 37.09 mBq **Zn-65** (243.9 d)

1.755 µg **Zn-68** (n,G) -> 5.781 Bq **Zn-69** (57.00 m)

110.0 µg Iron:

6.162 µg **Fe-54** (n,G) -> 32.08 mBq **Fe-55** (2.700 a)

342.3 ng **Fe-58** (n,G) -> 21.23 mBq **Fe-59** (44.53 d)

15.90 ng Mercury:

31.06 pg **Hg-196** (n,G) -> 22.53 mBq **Hg-197** (64.10 h)

4.739 ng **Hg-202** (n,G) -> 274.2 µBq **Hg-203** (46.60 d)

345.0 ng Nickel:

232.5 ng **Ni-58** (n,G) -> 81.16 nBq **Ni-59** (75.00e3 a)

13.07 ng **Ni-62** (n,G) -> 10.74 µBq **Ni-63** (96.00 a)

3.419 ng **Ni-64** (n,G) -> 102.2 mBq **Ni-65** (2.520 h)

9.830 µg Rubidium:

7.048 µg **Rb-85** (n,G) -> 262.9 mBq **Rb-86** (18.66 d)

2.781 µg **Rb-87** (n,G) -> 38.13 Bq **Rb-88** (17.80 m)

60.00 ng Selenium:

505.3 pg **Se-74** (n,G) -> 363.9 µBq **Se-75** (119.8 d)

13.90 ng **Se-78** (n,G) -> 0 Bq **Se-79** (65.00e3 a)

30.23 ng **Se-80** (n,G) -> 2.204 Bq **Se-81** (18.50 m)

5.724 ng **Se-82** (n,G) -> 23.61 mBq **Se-83** (22.50 m)
~> 9.519 µBq **Br-83** (2.390 h)
~> 3.338 nBq **Kr-83m** (1.830 h)

26.50 µg Strontium:

142.1 ng **Sr-84** (n,G) -> 1.994 mBq **Sr-85** (64.84 d)

21.95 µg **Sr-88** (n,G) -> 3.531 mBq **Sr-89** (50.50 d)

8.990 µg Zinc:

4.271 µg **Zn-64** (n,G) -> 37.09 mBq **Zn-65** (243.9 d)

1.755 µg **Zn-68** (n,G) -> 5.781 Bq **Zn-69** (57.00 m)

NIST 2710a – Montana I Soil

Search Mode

- (●) Forward (Search activation products)
- ( ) Reverse (Search original nuclides)

Nuclide Input HELP

Zr 1.00E-04 | IMPORT | ------- Select Sample Data ------- | RESET

Original Element / Nuclide	Mass [g]	Original Element / Nuclide	Mass	Original Element / Nuclide	Mass	Original Element / Nuclide	Mass
Ag	2.00E-05	Sb	2.63E-05	Sb	2.63E-05	Hg	4.94E-06
Al	2.98E-04	Si	1.56E-03	Sm	2.00E-06	Lu	1.55E-07
Ba	3.96E-04	Sr	1.28E-04	U	4.56E-06	Nd	1.10E-05
Ca	4.82E-05	Ti	1.56E-05	W	9.50E-05	Ni	4.00E-06
Co	3.00E-06	U	4.56E-06	Zn	2.09E-05	Rb	5.85E-05
Cu	1.71E-05	V	4.10E-05	Ag	2.00E-05	Sb	2.63E-05
Dy	1.50E-06	As	7.70E-06	Ce	3.00E-05	Sc	4.95E-06
In	3.50E-06	Au	1.00E-07	Cr	1.15E-05	Se	5.00E-07
K	1.09E-04	Cd	6.15E-06	Cs	4.13E-06	Sr	1.28E-04
Mg	3.67E-05	Hg	4.94E-06	Co	3.00E-06	Ta	4.50E-07
Mn	1.07E-05	K	1.09E-04	Eu	4.10E-07	Tb	2.50E-07
Na	4.47E-05	La	1.53E-05	Fe	2.16E-04	Th	9.05E-06
Se	5.00E-07	Na	4.47E-05	Hf	3.50E-06	Yb	1.00E-06
Zn	2.09E-05						
Zr	1.00E-04						

Output Parameters HELP

2.55e12	Neutron flux [per $cm^2 s$]	- or -	Point source neutron emission rate [per s] / Distance from point source [m]

- [x] use IAEA 2003 cross sections, where available
- [x] thermal neutrons (n,Gamma)
- [ ] fast neutrons (n,2n) (n,3n) (n,p) (n,t) (n,Alpha)

10	Duration of irradiation [s]
0	Time delay since end of irradiation [h]
	Max. half-life for consideration of progeny [years]
Bq	Activation Product Unit

Neutron flux = 2.550e12 per cm^2s
Irradiation = 10 s; Delay = 0 h

Original Nuclide **Reaction** **Activation (->) & Decay (~>) Products** **Half-Life**

20.00 µg Silver:

10.27 µg **Ag-107** (n,G) -> 263.8 kBq **Ag-108** (2.370 m)

9.726 µg **Ag-109** (n,G) -> 3.063 MBq **Ag-110** (24.60 s)

298.0 µg Aluminum:

298.0 µg **Al-27** (n,G) -> 196.8 kBq **Al-28** (2.240 m)

396.0 µg Barium:

397.1 ng **Ba-130** (n,G) -> 277.5 mBq **Ba-131** (11.80 d)
~> 1.149 µBq **Cs-131** (9.690 d)

384.1 ng **Ba-132** (n,G) -> 594.4 µBq **Ba-133** (10.74 a)

285.1 µg **Ba-138** (n,G) -> 1.790 kBq **Ba-139** (82.70 m)

48.20 µg Calcium:

46.59 µg **Ca-40** (n,G) -> 1.151 µBq **Ca-41** (140.0e3 a)

1.102 µg **Ca-44** (n,G) -> 16.67 mBq **Ca-45** (163.0 d)

2.210 ng **Ca-46** (n,G) -> 941.5 µBq **Ca-47** (4.530 d)
~> 11.27 nBq **Sc-47** (3.351 d)

107.8 ng **Ca-48** (n,G) -> 49.54 Bq **Ca-49** (8.716 m)
~> 49.93 mBq **Sc-49** (57.40 m)

3.000 µg Cobalt:

3.000 µg **Co-59** (n,G) -> 121.0 mBq **Co-60** (5.271 a)

17.10 µg Copper:

11.71 µg **Cu-63** (n,G) -> 195.7 Bq **Cu-64** (12.70 h)

5.386 µg **Cu-65** (n,G) -> 6.188 kBq **Cu-66** (5.100 m)

1.500 µg Dysprosium:

863.6 pg **Dy-156** (n,G) -> 66.71 mBq **Dy-157** (8.100 h)
~> 0 Bq **Tb-157** (150.0 a)

1.457 ng **Dy-158** (n,G) -> 338.6 µBq **Dy-159** (144.4 d)

425.2 ng **Dy-164** (n,G) -> 8.704 kBq **Dy-165** (2.334 h)

3.500 µg Indium:

148.0 ng **In-113** (n,G) -> 2.219 kBq **In-114** (71.90 s)

109.0 µg Potassium:

101.3 µg **K-39** (n,G) -> 2.303 nBq **K-40** (1.280e9 a)

7.685 µg **K-41** (n,G) -> 65.04 Bq **K-42** (12.36 h)

36.70 µg Magnesium:
(not found)

10.70 µg Manganese:

10.70 µg **Mn-55** (n,G) -> 2.980 kBq **Mn-56** (2.578 h)

44.70 µg Sodium:

44.70 µg **Na-23** (n,G) -> 203.1 Bq **Na-24** (15.00 h)

500.0 ng Selenium:

4.211 ng **Se-74** (n,G) -> 3.032 mBq **Se-75** (119.8 d)

115.9 ng **Se-78** (n,G) -> 2.931 nBq **Se-79** (65.00e3 a)

251.9 ng **Se-80** (n,G) -> 18.37 Bq **Se-81** (18.50 m)

47.70 ng **Se-82** (n,G) -> 196.8 mBq **Se-83** (22.50 m)
~> 79.32 µBq **Br-83** (2.390 h)
~> 27.82 nBq **Kr-83m** (1.830 h)

26.30 µg Antimony:

14.96 µg **Sb-121** (n,G) -> 33.30 Bq **Sb-122** (2.700 d)

11.33 µg **Sb-123** (n,G) -> 773.6 mBq **Sb-124** (60.20 d)

1.560 mg Silicon:

51.61 µg **Si-30** (n,G) -> 207.6 Bq **Si-31** (157.3 m)

128.0 µg Strontium:

686.5 ng **Sr-84** (n,G) -> 9.631 mBq **Sr-85** (64.84 d)

106.0 µg **Sr-88** (n,G) -> 17.06 mBq **Sr-89** (50.50 d)

15.60 µg Titanium:

(not found)

4.560 µg Uranium:

243.4 pg **U-234** (n,G) -> 0 Bq **U-235** (703.8e6 a)
~> 0 Bq **Th-231** (25.52 h)
~> 0 Bq **Pa-231** (32.76e3 a)
~> 0 Bq **Ac-227** (21.77 a)
~> 0 Bq **Th-227** (18.71 d)
~> 0 Bq **Ra-223** (11.43 d)
~> 0 Bq **Rn-219** (3.960 s)
~> 0 Bq **Po-215** (1.780e-3 s)
~> 0 Bq **Pb-211** (36.10 m)
~> 0 Bq **Bi-211** (2.140 m)
~> 0 Bq **Tl-207** (4.770 m)
~> 0 Bq **Po-211** (516.0e-3 s)
~> 0 Bq **Fr-223** (21.80 m)

32.42 ng **U-235** (n,G) -> 0 Bq **U-236** (23.41e6 a)
~> 0 Bq **Th-232** (14.05e9 a)
~> 0 Bq **Ra-228** (5.750 a)
~> 0 Bq **Ac-228** (6.130 h)
~> 0 Bq **Th-228** (1.913 a)
~> 0 Bq **Ra-224** (3.660 d)
~> 0 Bq **Rn-220** (55.60 s)
~> 0 Bq **Po-216** (150.0e-3 s)
~> 0 Bq **Pb-212** (10.64 h)
~> 0 Bq **Bi-212** (60.55 m)
~> 0 Bq **Po-212** (305.0e-3 us)
~> 0 Bq **Tl-208** (3.070 m)

4.527 µg **U-238** (n,G) -> 383.4 Bq **U-239** (23.54 m)
~> 6.536 mBq **Np-239** (2.355 d)
~> 0 Bq **Pu-239** (24.06e3 a)
~> 0 Bq **U-235** (703.8e6 a)
~> 0 Bq **Th-231** (25.52 h)
~> 0 Bq **Pa-231** (32.76e3 a)
~> 0 Bq **Ac-227** (21.77 a)
~> 0 Bq **Th-227** (18.71 d)
~> 0 Bq **Ra-223** (11.43 d)
~> 0 Bq **Rn-219** (3.960 s)
~> 0 Bq **Po-215** (1.780e-3 s)
~> 0 Bq **Pb-211** (36.10 m)
~> 0 Bq **Bi-211** (2.140 m)
~> 0 Bq **Tl-207** (4.770 m)
~> 0 Bq **Po-211** (516.0e-3 s)
~> 0 Bq **Fr-223** (21.80 m)

41.00 µg Vanadium:

(not found)

7.700 µg Arsenic:

7.700 µg **As-75** (n,G) -> 48.80 Bq **As-76** (26.32 h)

100.0 ng Gold:

100.0 ng **Au-197** (n,G) -> 2.289 Bq **Au-198** (2.696 d)

6.150 µg Cadmium:

72.43 ng **Cd-106** (n,G) -> 311.4 mBq **Cd-107** (6.490 h)

52.54 ng **Cd-108** (n,G) -> 93.04 µBq **Cd-109** (464.0 d)

1.477 µg **Cd-112** (n,G) -> 0 Bq **Cd-113** (9.300e15 a)

1.789 µg **Cd-114** (n,G) -> 295.3 mBq **Cd-115** (53.46 h)
~> 63.37 µBq **In-115m** (4.486 h)
~> 0 Bq **In-115** (5.100e15 a)

473.6 ng **Cd-116** (n,G) -> 363.6 mBq **Cd-117** (2.490 h)
~> 165.8 µBq **In-117m** (116.5 m)
~> 38.40 µBq **In-117** (43.80 m)
~> 0 Bq **Sn-117m** (13.61 d)

4.940 µg Mercury:

9.653 ng **Hg-196** (n,G) -> 6.999 Bq **Hg-197** (64.10 h)

1.472 µg **Hg-202** (n,G) -> 85.21 mBq **Hg-203** (46.60 d)

109.0 µg Potassium:

101.3 µg **K-39** (n,G) -> 2.303 nBq **K-40** (1.280e9 a)

7.685 µg **K-41** (n,G) -> 65.04 Bq **K-42** (12.36 h)

15.30 µg Lanthanum:

15.28 µg **La-139** (n,G) -> 73.02 Bq **La-140** (40.27 h)

44.70 µg Sodium:

44.70 µg **Na-23** (n,G) -> 203.1 Bq **Na-24** (15.00 h)

26.30 µg Antimony:

14.96 µg **Sb-121** (n,G) -> 33.30 Bq **Sb-122** (2.700 d)

11.33 µg **Sb-123** (n,G) -> 773.6 mBq **Sb-124** (60.20 d)

2.000 µg Samarium:

59.35 ng **Sm-144** (n,G) -> 245.0 µBq **Sm-145** (340.0 d)
~> 0 Bq **Pm-145** (17.70 a)

Sm-146 (n,G) -> **Sm-147** (106.0e9 a)

147.5 ng **Sm-150** (n,G) -> 368.8 µBq **Sm-151** (90.00 a)

537.5 ng **Sm-152** (n,G) -> 46.14 Bq **Sm-153** (46.70 h)

462.7 ng **Sm-154** (n,G) -> 199.7 Bq **Sm-155** (22.10 m)
~> 4.427 µBq **Eu-155** (4.960 a)

4.560 µg Uranium:

243.4 pg **U-234** (n,G) -> 0 Bq **U-235** (703.8e6 a)
~> 0 Bq **Th-231** (25.52 h)
~> 0 Bq **Pa-231** (32.76e3 a)
~> 0 Bq **Ac-227** (21.77 a)
~> 0 Bq **Th-227** (18.71 d)
~> 0 Bq **Ra-223** (11.43 d)
~> 0 Bq **Rn-219** (3.960 s)
~> 0 Bq **Po-215** (1.780e-3 s)
~> 0 Bq **Pb-211** (36.10 m)
~> 0 Bq **Bi-211** (2.140 m)
~> 0 Bq **Tl-207** (4.770 m)
~> 0 Bq **Po-211** (516.0e-3 s)
~> 0 Bq **Fr-223** (21.80 m)

32.42 ng **U-235** (n,G) -> 0 Bq **U-236** (23.41e6 a)
~> 0 Bq **Th-232** (14.05e9 a)
~> 0 Bq **Ra-228** (5.750 a)
~> 0 Bq **Ac-228** (6.130 h)
~> 0 Bq **Th-228** (1.913 a)
~> 0 Bq **Ra-224** (3.660 d)
~> 0 Bq **Rn-220** (55.60 s)
~> 0 Bq **Po-216** (150.0e-3 s)
~> 0 Bq **Pb-212** (10.64 h)
~> 0 Bq **Bi-212** (60.55 m)
~> 0 Bq **Po-212** (305.0e-3 us)
~> 0 Bq **Tl-208** (3.070 m)

4.527 µg **U-238** (n,G) -> 383.4 Bq **U-239** (23.54 m)
~> 6.536 mBq **Np-239** (2.355 d)
~> 0 Bq **Pu-239** (24.06e3 a)
~> 0 Bq **U-235** (703.8e6 a)
~> 0 Bq **Th-231** (25.52 h)
~> 0 Bq **Pa-231** (32.76e3 a)

~> 0 Bq **Ac-227** (21.77 a)
~> 0 Bq **Th-227** (18.71 d)
~> 0 Bq **Ra-223** (11.43 d)
~> 0 Bq **Rn-219** (3.960 s)
~> 0 Bq **Po-215** (1.780e-3 s)
~> 0 Bq **Pb-211** (36.10 m)
~> 0 Bq **Bi-211** (2.140 m)
~> 0 Bq **Tl-207** (4.770 m)
~> 0 Bq **Po-211** (516.0e-3 s)
~> 0 Bq **Fr-223** (21.80 m)

95.00 µg Tungsten:

92.99 ng **W-180** (n,G) -> 15.76 mBq **W-181** (121.2 d)

29.18 µg **W-184** (n,G) -> 442.4 mBq **W-185** (75.10 d)

27.48 µg **W-186** (n,G) -> 704.0 Bq **W-187** (23.90 h)
~> 0 Bq **Re-187** (50.00e9 a)

20.90 µg Zinc:

9.929 µg **Zn-64** (n,G) -> 86.24 mBq **Zn-65** (243.9 d)

4.081 µg **Zn-68** (n,G) -> 13.44 Bq **Zn-69** (57.00 m)

20.00 µg Silver:

10.27 µg **Ag-107** (n,G) -> 263.8 kBq **Ag-108** (2.370 m)

9.726 µg **Ag-109** (n,G) -> 3.063 MBq **Ag-110** (24.60 s)

30.00 µg Cerium:

55.29 ng **Ce-136** (n,G) -> 868.4 mBq **Ce-137** (9.000 h)
~> 0 Bq **La-137** (60.00e3 a)

73.82 ng **Ce-138** (n,G) -> 488.5 µBq **Ce-139** (137.6 d)

26.50 µg **Ce-140** (n,G) -> 416.4 mBq **Ce-141** (32.50 d)

3.366 µg **Ce-142** (n,G) -> 2.061 Bq **Ce-143** (33.00 h)
~> 6.097 µBq **Pr-143** (13.56 d)

11.50 µg Chromium:

480.5 ng **Cr-50** (n,G) -> 679.8 mBq **Cr-51** (27.70 d)

4.130 µg Cesium:

4.130 µg **Cs-133** (n,G) -> 153.9 mBq **Cs-134** (2.062 a)

3.000 µg Cobalt:

3.000 µg **Co-59** (n,G) -> 121.0 mBq **Co-60** (5.271 a)

410.0 ng Europium:

194.6 ng **Eu-151** (n,G) -> 300.2 mBq **Eu-152** (13.33 a)
~> 0 Bq **Gd-152** (108.0e12 a)

215.3 ng **Eu-153** (n,G) -> 16.84 mBq **Eu-154** (8.800 a)

216.0 µg Iron:

12.10 µg **Fe-54** (n,G) -> 63.01 mBq **Fe-55** (2.700 a)

672.2 ng **Fe-58** (n,G) -> 41.70 mBq **Fe-59** (44.53 d)

3.500 µg Hafnium:

5.457 ng **Hf-174** (n,G) -> 30.31 mBq **Hf-175** (70.00 d)

1.242 µg **Hf-180** (n,G) -> 261.5 mBq **Hf-181** (42.40 d)

4.940 µg Mercury:

9.653 ng **Hg-196** (n,G) -> 6.999 Bq **Hg-197** (64.10 h)

1.472 µg **Hg-202** (n,G) -> 85.21 mBq **Hg-203** (46.60 d)

155.0 ng Lutetium:

150.9 ng **Lu-175** (n,G) -> 0 Bq **Lu-176** (36.00e9 a)

4.068 ng **Lu-176** (n,G) -> 887.3 mBq **Lu-177** (6.710 d)

11.00 µg Neodymium:

1.912 µg **Nd-146** (n,G) -> 207.3 mBq **Nd-147** (10.98 d)
~> 8.683 nBq **Pm-147** (2.623 a)
~> 0 Bq **Sm-147** (106.0e9 a)

648.6 ng **Nd-148** (n,G) -> 19.32 Bq **Nd-149** (1.730 h)
~> 350.5 µBq **Pm-149** (53.08 h)

643.6 ng **Nd-150** (n,G) -> 62.76 Bq **Nd-151** (12.44 m)
~> 2.130 mBq **Pm-151** (28.40 h)
~> 0 Bq **Sm-151** (90.00 a)

4.000 µg Nickel:

2.695 µg **Ni-58** (n,G) -> 941.0 nBq **Ni-59** (75.00e3 a)

151.5 ng **Ni-62** (n,G) -> 124.5 µBq **Ni-63** (96.00 a)

39.65 ng **Ni-64** (n,G) -> 1.184 Bq **Ni-65** (2.520 h)

58.50 µg Rubidium:

41.94 µg **Rb-85** (n,G) -> 1.564 Bq **Rb-86** (18.66 d)

16.55 µg **Rb-87** (n,G) -> 226.9 Bq **Rb-88** (17.80 m)

26.30 µg Antimony:

14.96 µg **Sb-121** (n,G) -> 33.30 Bq **Sb-122** (2.700 d)

11.33 µg **Sb-123** (n,G) -> 773.6 mBq **Sb-124** (60.20 d)

4.950 µg Scandium:

4.950 µg **Sc-45** (n,G) -> 4.399 Bq **Sc-46** (83.83 d)

500.0 ng Selenium:

4.211 ng **Se-74** (n,G) -> 3.032 mBq **Se-75** (119.8 d)

115.9 ng **Se-78** (n,G) -> 2.931 nBq **Se-79** (65.00e3 a)

251.9 ng **Se-80** (n,G) -> 18.37 Bq **Se-81** (18.50 m)

47.70 ng **Se-82** (n,G) -> 196.8 mBq **Se-83** (22.50 m)
~> 79.32 µBq **Br-83** (2.390 h)
~> 27.82 nBq **Kr-83m** (1.830 h)

128.0 µg Strontium:

686.5 ng **Sr-84** (n,G) -> 9.631 mBq **Sr-85** (64.84 d)

106.0 µg **Sr-88** (n,G) -> 17.06 mBq **Sr-89** (50.50 d)

450.0 ng Tantalum:

449.9 ng **Ta-181** (n,G) -> 54.61 mBq **Ta-182** (115.0 d)

250.0 ng Terbium:

250.0 ng **Tb-159** (n,G) -> 62.45 mBq **Tb-160** (72.30 d)

9.050 µg Thorium:

9.050 µg **Th-232** (n,G) -> 2.276 kBq **Th-233** (22.30 m)
~> 3.384 mBq **Pa-233** (27.00 d)
~> 0 Bq **U-233** (158.5e3 a)
~> 0 Bq **Th-229** (7.340e3 a)

~> 0 Bq **Ra-225** (14.80 d)
~> 0 Bq **Ac-225** (10.00 d)
~> 0 Bq **Fr-221** (4.800 m)
~> 0 Bq **At-217** (32.30e-3 s)
~> 0 Bq **Bi-213** (45.65 m)
~> 0 Bq **Po-213** (4.200 us)
~> 0 Bq **Pb-209** (3.253 h)
~> 0 Bq **Tl-209** (2.200 m)

1.000 µg Ytterbium:

1.358 ng **Yb-168** (n,G) -> 71.62 mBq **Yb-169** (32.01 d)

319.6 ng **Yb-174** (n,G) -> 3.415 Bq **Yb-175** (4.190 d)

129.1 ng **Yb-176** (n,G) -> 3.253 Bq **Yb-177** (1.900 h)
~> 19.45 µBq **Lu-177** (6.710 d)

20.90 µg Zinc:

9.929 µg Zn-64 (n,G) -> 86.24 mBq Zn-65 (243.9 d)

4.081 µg Zn-68 (n,G) -> 13.44 Bq Zn-69 (57.00 m)

100.0 µg Zirconium:

17.32 µg Zr-92 (n,G) -> 9.136 nBq Zr-93 (1.530e6 a)
~> 0 Bq Nb-93m (13.60 a)

17.78 µg Zr-94 (n,G) -> 18.19 mBq Zr-95 (63.98 d)
~> 20.61 nBq Nb-95 (35.15 d)
~> 1.411 nBq Nb-95m (86.60 h)

2.901 µg Zr-96 (n,G) -> 105.8 mBq Zr-97 (16.90 h)
~> 5.571 mBq Nb-97m (60.00 s)
~> 7.493 µBq Nb-97 (72.10 m)

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