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**CORRELATION OF EXTERNAL
EXPOSURE AND DOSE
EQUIVALENT RATES WITH
URANIUM SURFACE
CONTAMINATION**

**J. S. Bogard
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ORNL-6918

Assessment Technology Section
Life Sciences Division

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CONTENTS

LIST OF TABLES	v
LIST OF FIGURES	v
ACKNOWLEDGMENTS	vii
ABSTRACT	ix
ACRONYMS	xi
INTRODUCTION	1
CALCULATED VALUES	1
MEASURED VALUES	3
DISCUSSION	5
RECOMMENDATIONS	6
REFERENCES	7
APPENDIX A: Average Photon Energy in U-234	A-1
APPENDIX B: Average Photon Energy in Aged U-235	B-1
APPENDIX C: Average Photon Energy in Aged U-238	C-1

LIST OF TABLES

1	Average Photon Energies in Uranium Isotopes at the Oak Ridge Y-12 Plant	8
2	Relative Isotopic Activities in Aged D-38	9
3	Average Photon Energy in Aged D-38	10
4	Relative Isotopic Activities in Aged Oralloy	10
5	Average Photon Energy in Aged Oralloy	11
6	Measured Uranium Activities and Associated Dose-Equivalent Rates in Randomly Selected Samples with Measurable Contamination	12
7	Ratio of Dose-Equivalent Rate to Uranium Activity in Randomly Selected Samples with Measurable Contamination	13
8	Ratio of Dose-Equivalent Rate Measured at 1 Meter to Uranium Surface Contamination Measured at Contact	14

LIST OF FIGURES

1	Energy Response of the Bicron Micro Rem Meter	15
2	Dose Rate at 1 Meter vs. Contamination Level at Contact (Point Sources)	16
3	Dose Rate at 1 Meter vs. Activity Level at Contact (Distributed Sources)	17

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ABSTRACT

This report provides both calculated estimates and measured values of exposure in air and tissue dose from external penetrating radiation at a distance of 1 m from uranium contamination on surfaces at the Oak Ridge Y-12 Plant, in support of the Y-12 Site Radiological Characterization Study. Calculated values are based on the total energy from γ rays and X rays emitted by uranium and its short-lived daughters at secular equilibrium. Results of a small number of measurements are provided for comparison. Dose rate values derived here are limited to those of external penetrating radiation from distributed sources with limited surface area and from point sources.

Uranium contamination activity at the Y-12 Plant is reported in disintegrations per minute (dpm), where *disintegrations* refers to the radioactive decay of all uranium isotopes and their short-lived progeny. The average ionizing-photon energy per disintegration in depleted uranium (D-38), neglecting energies below 40 keV (cutoff energy for the dose-equivalent-rate instrument used for measurements), is 0.00601 MeV. Using this energy gives a calculated D-38 exposure rate per unit activity, at 1 m from the source, of 1.4×10^{-15} R/h per dpm and a dose equivalent (DE) rate per unit activity (at 1 m) of 1.3×10^{-15} rem/h per dpm. The total measurable gamma- and X-ray photon energy per disintegration in enriched uranium (Oralloy) is 0.00265 MeV, corresponding to a calculated exposure rate per unit activity at 1 m of 6.4×10^{-16} R/h per dpm and a DE rate per unit activity at 1 m of 5.8×10^{-16} rem/h per dpm.

Three sets of measurements were made using a Ludlum Model 3 ratemeter with a pancake probe for measuring total activity and a Bicron Micro Rem meter for measuring dose equivalent rate for comparison with the calculated results. The DE rate 1 m from a 4 in $\times$ 4 in $\times$ $\frac{1}{8}$ in (100 cm² $\times$ 0.32 cm thick) aged D-38 slab, used as a standard radiation source for dosimeter quality control required by the Department of Energy Laboratory Accreditation Program (DOELAP) for Personnel Dosimetry, was determined to be 5-6 μ rem/h. The corresponding DE rate at one meter per calculated unit activity for the aged D-38 slab is about 4×10^{-15} rem/h per dpm. Measurements of a large (0.9 m $\times$ 2.7 m $\times$ 7.6 cm thick) D-38 plate gave a DE rate of 0.7 mrem/h at 1 m and a surface activity, corrected for dead time, of 1.1×10^7 dpm/100 cm², corresponding to 7×10^{-13} rem/h per dpm/100 cm². The third set of measurements was made at 9 locations containing highly elevated levels of uranium contamination within the Y-12 Plant production area. Representative DE rates at 1 m per unit activity were calculated from the slope of DE rate with total surface activity (corrected for dead time) to be 3×10^{-12} rem/h per dpm for point sources and 8×10^{-13} rem/h per dpm/100 cm² for distributed sources.

Possible reasons for the large discrepancy between calculated and measured results for the different sources and geometries are discussed, and recommendations are provided for resolving the differences.

ACRONYMS

Bq	becquerel
cm	centimeter
cpm	counts per minute
D-38	uranium depleted in the U-234 and U-235 isotopes
DE	dose equivalent
dpm	radioactive disintegrations per minute
g	gram
h	hour
in	inch
kg	kilogram
m	meter
MeV	million electron volts
R	roentgen

CORRELATION OF EXTERNAL EXPOSURE AND DOSE EQUIVALENT RATES WITH URANIUM SURFACE CONTAMINATION

Introduction

This report provides an estimate of exposure in air and tissue dose at a distance of 1 m from uranium contamination on surfaces at the Oak Ridge Y-12 Plant, in support of the Y-12 Site Radiological Characterization Study. Both calculated and measured values are reported. Calculated values are based on the total energy from γ rays and X rays emitted by uranium and its short-lived daughters at secular equilibrium. Results of a small number of measurements are also provided for comparison. Dose rate values derived here are limited to those from external penetrating radiation from point sources and sources with limited surface area. A discussion of the total effective dose equivalent from infinite plane sources of uranium contamination is found in a separate report [ORNL-6913]. The exposure which corresponds to a given level of uranium contamination is important in deciding when to document exposure rates of contaminated surfaces and in evaluating the usefulness of data from remote (*e.g.* aerial) detection systems.

Calculated Values

Estimates of external dose rates from uranium-contaminated surfaces can be derived by considering numbers and energies of γ rays and X rays emitted by uranium and its daughters in secular equilibrium. The dose rate in air from photons emitted by a point source, measured at a distance of 1 m from the source, is [Turner, 1992 (p. 208)]

$$\dot{D}_a (\text{rad/h}) \approx 0.46 C_s E, \quad (1)$$

where C_s is the source strength (in curies) and E is the total average photon energy (in MeV) per nuclear transformation. The exposure rate derived from this expression is

$$\dot{\Gamma} (\text{R/h}) \approx 0.53 C_s E, \quad (2)$$

since an absorbed dose of 0.876 rad in air corresponds to an exposure of 1 R. For C_d (in dpm), expression (2) becomes,

$$\dot{\Gamma} (\text{R/h}) \approx 2.4 \times 10^{-13} C_d E, \quad (3)$$

and the dose rate in tissue is

$$\dot{D}_t (\text{rad/h}) \approx 2.2 \times 10^{-13} C_d E, \quad (4)$$

using the conversion factors 2.22×10^{12} dpm/Ci and 0.95 rad/R (dose rate in tissue per unit exposure). Expression (4) is also approximately true for the dose equivalent (DE) rate (rem/h), since the quality factor for photons is unity.

The average photon energy necessary for evaluating exposure rate, expression (3), or dose rate, expression (4), from a radioactive source or mixture can be determined using information in report DOE/TIC-11026, which includes γ -ray and X-ray emission energies, probabilities, and branching fractions,¹ for the known radionuclides. Photon emissions from uranium isotopes and their radioactive progeny have energies that span a wide range, from 1 keV to approximately 1 MeV. Only those energies that can be detected with instruments used by Y-12 Radiological Control technicians are considered here, however.² Dose equivalent rates from external penetrating radiation are measured at Y-12 using the Bicon Micro Rem meter with a nominal 40-keV cutoff. Figure 1 shows the measured response of this instrument [Rundo *et al.*, 1994; Moore, 1997]. A Micro Rem meter, calibrated using ^{137}Cs photons (662 keV), measures approximately 75% of the delivered dose of 38-keV X rays (nominal energy of the National Institute of Standards and Technology H50 beam code, used in testing), but response drops rapidly to less than 10% below 20 keV. Photons with energies below 40 keV are not considered in this analysis because of the low relative Micro Rem meter response. Table 1 lists average photon energies for ^{234}U , aged ^{235}U and aged ^{238}U – the radioisotopes most commonly encountered at the Y-12 Plant. The average energies in Table 1 were derived using photon emissions and average photon energy per decay (excluding energies below 40 keV) for uranium isotopes and their radioactive progeny that are listed in Appendix A (^{234}U), Appendix B (^{235}U) and Appendix C (^{238}U). The radioactive decay chain of each isotope is followed until a daughter radionuclide with a long (in human terms) half-life is encountered, effectively ending the chain for isotopes processed or refined from the ore during the last century. Progeny with short radiological half-lives are assumed to be in secular equilibrium with the parent (hence, *aged* ^{235}U and *aged* ^{238}U), but the chain-ending daughter and all subsequent progeny are considered to have no appreciable activity for purposes of this evaluation.

Two uranium isotopic mixtures are commonly encountered at the Y-12 Plant: *depleted uranium* (D-38) and *high enriched uranium* (Oralloy). Each of these mixtures, considered below in more detail, is produced as the result of gaseous diffusion of refined natural uranium³ (as uranium hexafluoride) through capillary systems that selectively pass the lighter ^{234}U and ^{235}U , enriching the diffused gases in these isotopes and separating them from the heavier ^{238}U .

Radioactivity in D-38 is due primarily to ^{238}U and its progeny. The contribution of other uranium isotopes and their progeny to the activity of this material is small because of the removal

¹Branching fraction is the relative number of atoms of a radioisotope which decay through a given mode.

²Total effective dose equivalent from uranium contamination is considered in a separate report [ORNL-6913].

³Uranium occurring naturally in ores contains approximately (by weight) 99.2739% ^{238}U , 0.7204% ^{235}U , and 0.0057% ^{234}U [EGG-2530, Table 2-1]. The activity of ^{234}U in the ore is nominally the same as that of the parent ^{238}U .

of ^{234}U and ^{235}U in the gaseous diffusion process. Depleted uranium contains approximately 99.75% ^{238}U , 0.25% ^{235}U , and 0.0005% ^{234}U by mass [EGG-2530, Table 2-1]. The external photon exposure rate for surfaces contaminated with D-38 is related to the sum of average photon energies per parent uranium disintegration, weighted by the relative contribution to total alpha radioactivity (since each uranium isotope decays with the emission of a single alpha particle) shown in Table 2, from ^{238}U and its short-half-life progeny (^{234}Th , $^{234\text{m}}\text{Pa}$, and ^{234}Pa), from ^{235}U and its short-half-life progeny (^{231}Th), and from ^{234}U (which has no short-half-life progeny). The resulting total average photon energy per disintegration (uranium and progeny) for D-38 (shown in Table 3) is 0.00601 MeV. This corresponds to a D-38 exposure rate per unit activity at a distance of 1 m, from expression (3), of 1.4×10^{-15} R/h per dpm. The corresponding D-38 DE rate per unit activity, from expression (4), is 1.3×10^{-15} rem/h per dpm.

Oralloy is a mixture of those isotopes found in normal uranium after it has been enriched in ^{235}U to weapons grade by gaseous diffusion. The distribution of uranium isotopes by mass in Oralloy is approximately 93% ^{235}U , 6% ^{238}U , and 1% ^{234}U (which is present in secular equilibrium with ^{238}U in the ore and is carried up the cascade in the diffusion process because its mass is close to that of ^{235}U). Although only 1% by weight, ^{234}U contributes almost 97% of the total alpha activity in Oralloy because of its relatively short half-life (Table 4). The photon exposure rate for Oralloy on surfaces is related to the sum of average photon energies per uranium atom disintegration (Table 1), weighted by the relative contribution to total radioactivity for each uranium isotope and its progeny in the mixture, from Table 4. The resulting total average photon energy per disintegration (uranium and progeny) in Oralloy (shown in Table 5) is 0.00265 MeV. This corresponds to an exposure rate at a distance of 1 m per unit activity of Oralloy, from expression (3), of 6.4×10^{-16} R/h per dpm. The corresponding DE rate per unit activity, from expression (4), is 5.8×10^{-16} rem/h per dpm.

Measured Values

Three sets of measurements were made for comparison with the calculated results. The first set was a single measurement of the exposure rate at a distance of 1 m from an aged depleted-uranium slab having a surface area of approximately 100 cm² and used as a reference for dosimeter calibrations. The second set consisted of measurements of activity and of exposure rates at contact, 30 cm, and 1 m from a large (25,000 cm²) D-38 plate in the Third Mill area of Y-12 Building 9215. The third set consisted of activity determinations and measurements of the exposure rates at contact, 30 cm, and 1 m from 9 locations within the Y-12 Plant production area containing levels of contamination of about 1,000 dpm, or greater, at contact. The results of the measurements are presented and discussed below.

An instrument often used for measuring the activity of uranium contamination at the Y-12 Plant, and which was chosen for contamination measurements in this study, is the Ludlum Model 3 instrument package with a pancake probe which is sensitive to both beta particles and photons from

X-ray and gamma radiation. Results from this instrument are reported in activity units of disintegrations per minute (dpm), where *disintegrations* refers to all the radioactive transformations of uranium atoms and their short-lived progeny. The response of this instrument, a non-paralyzable system, must be corrected for detector dead time τ at elevated count rates. The dead-time correction to determine a true count rate n from a measured count rate m and dead time τ is [Knoll, 1979 (p. 97)]

$$n = \frac{m}{1 - m\tau} \quad (5)$$

The dead-time values used were $\tau = 80 \mu\text{s}$ [Ludlum, 1997] for measured count rates below 50,000 cpm and $\tau = 124 \mu\text{s}$ [Coleman, 1993] for measured count rates exceeding 50,000 cpm. Measured count rates, which are not routinely corrected for dead time by Y-12 Radiological Control technicians, were determined from the reported activities A_R (dpm) as $m = A_R/6$ for point sources and $m = A_R/30$ for distributed sources.⁴ The count rates were then corrected for dead time using expression (5), and new activities were calculated from the estimated true count rates.

The Radiation Standards and Calibration Laboratory (RaSCaL) at Oak Ridge National Laboratory maintains a slab of aged depleted uranium as a standard radiation source for dosimeter quality control required by the Department of Energy Laboratory Accreditation Program (DOELAP) for Personnel Dosimetry. The slab measures 4 in $\times$ 4 in $\times$ 1/8 in (100 cm² $\times$ 0.32 cm thick) and contains approximately 0.6 kg depleted uranium. The net DE rate above this slab was determined at a distance of 1 m, using a Bicron Micro Rem meter, to be 5-6 $\mu\text{rem/h}$ [Halliburton]. The activity associated with this mass of D-38 is determined from its total specific activity⁵ of 3.84×10^4 Bq/g (Table 2) to be about 1.4×10^9 dpm. This slab effectively approximates a point source for DE rate measured at 1 m, and the DE rate can therefore be correlated with total source activity. The corresponding measured DE rate at 1 m per unit activity for the aged D-38 slab with this geometry is about 4×10^{-15} rem/h per dpm.

Radiological measurements of a plate of D-38 metal with dimensions 3 feet (0.9 m) $\times$ 9 feet (2.7 m) $\times$ 3 inches (7.6 cm) thick in the Third Mill area of Building 9215 indicated net activities (in dpm/100 cm²) of 6,300,000 at contact, 4,200,000 at 30 cm, and 900,000 at 1 m. Net dose equivalent rates were determined to be 5 mrem/h at contact, 2 mrem/h at 30 cm, and 0.7 mrem/h at 1 m (Table 6). This plate, with its large surface area (25,000 cm²), does not approximate a point source for DE rate measured at 1 m, so the DE rate should be correlated with activity per unit area. The DE rate at 1 m per unit area activity at contact for this plate is determined from these measurements to be 7×10^{-13} rem/h per dpm/100 cm², after dead-time correction of the surface

⁴Y-12 Radiological Control Procedure Y75-56-FO-515INS, Section B, specifies that reported activities are calculated as the product of count rate from this instrument and a factor, which is 6 dpm/cpm for point sources and 30 dpm/cpm for distributed sources.

⁵Note that this *total* specific activity, which includes activities of all the beta-emitting progeny at secular equilibrium, differs from the *alpha* specific activity of 4×10^{-7} Ci/g (1.5×10^4 Bq/g) given in EGG-2530 (Table 2-8).

activity measurement (Table 7).

Surveys conducted in the paved-surfaces portion of the Y-12 Site Characterization Study revealed some areas with highly elevated contamination. Nine such areas, chosen because of the levels of contamination and ease of access, were evaluated for both activity and DE rate at contact, 30 cm, and 1 m. No attempt was made to determine isotopic composition of the associated contamination, but it is presumed to be D-38, based on materials being handled in the area at the time. Beta-gamma activity measurements were made in accordance with Y-12 Plant Procedures using a Ludlum Model 3 pancake meter, and DE measurements were made using a Bicron Micro Rem meter. Results of the surveys are summarized in Table 6 and are presented separately for point sources (activity in units of 'dpm') and distributed sources (activity in 'dpm/100 cm²'). The DE rate at 1 m is plotted against the activity at contact in Figure 2 (point sources) and Figure 3 (distributed sources). The corresponding DE rates at 1 m per unit activity, determined as the slopes of these plots, are 3×10^{-12} rem/h per dpm (point sources) and 8×10^{-13} rem/h per dpm/100 cm² (distributed sources).

Discussion

Calculated and measured dose-equivalent rates corresponding to uranium contamination are summarized in Table 10. Values calculated from D-38 photon energies (1.3×10^{-15} rem/h per dpm) and derived from D-38 slab measurements (4×10^{-15} rem/h per dpm) agree quite well, but they and the value calculated for Oralloy (5.8×10^{-16} rem/h per dpm) are 2 to 3 orders of magnitude lower than the value (3×10^{-12} rem/h per dpm) measured in point-source paved-surface contamination. A number of factors not quantitatively evaluated in this analysis might explain the widely differing results. These factors include (but are not necessarily limited to):

- Bremsstrahlung production from high-energy beta particles can contribute significantly to the photon intensity from uranium, but is highly variable, depending on enrichment (beta intensity and energy) and on the atomic number of the shield material [Turner, 1992 (pp. 92-93)];
- Self-absorption of photons by uranium can significantly reduce exposure, but depends on chemical form (effective atomic number) of the uranium and its density thickness (determined by the uranium compound's density and geometry);
- Radiological disequilibrium in newly processed⁶ uranium (which might constitute part of the contamination on paved surfaces within the Y-12 Plant) may invalidate the comparison of measurement results from uncharacterized contamination and

⁶Processed within a few days prior to measurement for Oralloy, or within a few months, for D-38. Aged uranium, on which calculations in this report are based, is that in which secular equilibrium of the short-half-life progeny has been re-established after separation of the parent ²³⁵U or ²³⁸U by processing.

those from the standard uranium slab, or from calculations that assume secular equilibrium of the short-half-life progeny;

- Radioisotopes other than uranium or its daughters could be present in uncharacterized contamination.

Air attenuation does not significantly reduce either photon intensity or energy in this case, amounting to less than 1% loss over the range 0.04 - 1.00 MeV [RHH (p. 135)]. Calculations of the dose-equivalent rate did not consider bremsstrahlung production, which underestimates the dose rate, and they ignore self-absorption of photons by assuming a perfect (massless) point source, which results in an overestimate of the dose rate. Measurement results from the standard D-38 slab include both the effects of bremsstrahlung production and self-absorption in 0.6 g of uranium, which is not a typical contamination geometry. Contamination on paved surfaces within the Y-12 Plant, from which measured values were taken, was not assayed or characterized for isotopic content. The degree of radiological equilibrium was not established, and the presence of interference from other radionuclides was not precluded in these measurements.

Recommendations

A single value of dose rate per unit activity of uranium contamination cannot be concluded from the results of this study, since the individual values vary over 3 orders of magnitude. The values reported here can be used, however, to bracket an acceptable range for use in making decisions affecting implementation of the Y-12 Site Radiological Characterization Study. Improved estimates can be obtained by addressing the complicating factors enumerated in the **Discussion**. Additional data, including DE and contamination level measurements and isotopic characterization, from uranium contamination found on paved surfaces at the Y-12 Plant would be particularly helpful.

References

- Coleman R. L. Coleman (1993), **Beta Dose Rate Evaluations with a Geiger-Mueller Pancake Detector** (Master's Thesis, The University of Tennessee, Knoxville)
- DOE/TIC-11206 D. C. Kocher (1981), *Radioactive Decay Data Tables*, Report DOE/TIC-11206 (U. S. Department of Energy, Technical Information Center, Washington, D.C.)
- EGG-2530 B. L. Rich, S. L. Hinnefeld, C. R. Lagerquist, W. G. Mansfield, L. H. Munson, and E. R. Wagner (1988), *Health Physics Manual of Good Practices for Uranium Facilities*, Idaho National Engineering Laboratory Report No. EGG-2530 (available from U. S. Department of Energy, Office of Scientific and Technical Information, Oak Ridge, Tennessee)
- Halliburton R. E. Halliburton, Oak Ridge National Laboratory, personal communication (June, 1996)
- Knoll G. F. Knoll (1979), **Radiation Detection and Measurement** (John Wiley & Sons, New York)
- Ludlum R. Ludlum (1997), Personal Communication.
- Moore T. Moore, Harshaw/Bicron Radiation Measurement Products, personal communication of energy response testing results at Battelle National Laboratory, conducted 5/23-2/94, for Micro Rem survey meter (1/97).
- ORNL-6913 J. S. Bogard, R. N. Hamm, J. C. Ashley, C. A. England, J. E. Turner, D. E. Swenson, and K. S. Brown, *Total Effective Dose Equivalent Associated with Fixed Uranium Surface Contamination*, ORNL-6913, Martin Marietta Energy Research Corporation, Oak Ridge National Laboratory, 1997.
- RHH Bureau of Radiological Health (1970), **Radiological Health Handbook**, Public Health Service Publication No. 2016 (U.S. Department of Health, Education, and Welfare, available from Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402)
- Rundo, *et al.* J. A. Rundo, J. G. Johnston, R. J. Dmytryk, K. J. Velbeck, and J. G. Bellian, "Environmental Gamma Radiation Monitoring Instrumentation; Evaluation and Performance," presented at the 39th Annual Meeting of the Health Physics Society, San Francisco, California, June 26 - 30, 1994.
- Turner J. E. Turner (1992), **Atoms, Radiation, and Radiation Protection** (McGraw Hill, New York)

Table 1. Average Photon Energies in Uranium Isotopes at the Oak Ridge Y-12 Plant

Parent and Short-Lived Daughters ^a	Average Photon Energy per Parent U Disintegration (MeV)
<u>²³⁸U (no short-lived progeny)</u>	
²³⁴ U	0.000112
<u>Aged ²³⁵U</u>	
²³⁵ U	0.148494
²³¹ Th	<u>0.010347</u>
Total for Aged ²³⁵ U	0.158841
<u>Aged ²³⁸U</u>	
²³⁸ U	0.000064
²³⁴ Th	0.007796
^{234m} Pa	0.005440
²³⁴ Pa	<u>0.002761</u>
Total for Aged ²³⁸ U	0.016062

^aAt least 7 days are assumed to have passed since any chemical processing of the metal in aged ²³⁵U, and at least 7 months in aged ²³⁸U, so that secular equilibrium of the short-half-life progeny is established.

Table 2. Relative Isotopic Activities in Aged D-38

Isotope	Mass Fraction in Mixture (%)	Half-Life (y)	Alpha Particles per Disintegration	Number of Progeny at Secular Equilibrium	Specific Alpha Activity (Bq g ⁻¹)		Relative Alpha Activity in Mixture ^a
					Isotopic	In Mixture	
²³⁴ U	0.0005	2.5×10 ⁵	1	0	2.26×10 ⁸	1.13×10 ³	0.0828
²³⁵ U	0.25	7.0×10 ⁸	1	1	8.04×10 ⁴	2.01×10 ²	0.0147
²³⁸ U	99.75	4.5×10 ⁹	1	2	1.23×10 ⁴	1.23×10 ⁴	0.9025
D-38 total specific alpha activity:						1.36×10 ⁴	
D-38 total specific activity: ^b						3.84×10 ⁴	

NOTE: D-38 is considered *aged* after at least 7 months have passed since any chemical processing of the metal, so that secular equilibrium of the short-half-life progeny of ²³⁵U and ²³⁸U is established.

^aThe number of significant figures shown are those considered appropriate for use in the calculation of the weighted sum of average photon energies, which was then rounded.

^bThe total specific activity in D-38 is the sum of the total specific activities for each isotope. Total specific activity of an isotope is obtained as the product of the specific alpha activity of that isotope in the mixture and the number of radioisotopes with that specific activity (parent and progeny at secular equilibrium).

Table 3. Average Photon Energy in Aged D-38

Isotope	Average Energy per Parent U (Alpha) Disintegration (MeV)	Relative Alpha Activity in Mixture	Average Energy per U Disintegration in Mixture (MeV)	Number of Radionuclides in Chain	Average Energy per Nuclide Disintegration (MeV)
²³⁴ U	0.000111	0.0828	0.000009	1	0.000009
Aged	0.158841	0.0147	0.002335	2	0.001170
Aged	0.016062	0.9025	0.014496	3 ^a	0.004832
Total Average Photon Energy per Disintegration					0.00601

NOTE: D-38 is considered *aged* after at least 7 months have passed since any chemical processing of the metal, so that secular equilibrium of the short-half-life progeny of ²³⁵U and ²³⁸U is established.

^aProgeny of ²³⁸U include ²³⁴Th, ²³⁴Pa, and ^{234m}Pa. The isomers ²³⁴Pa and ^{234m}Pa are considered as a single radionuclide in the computation of average energy per nuclide disintegration, since the sum of their branching ratios is unity.

Table 4. Relative Isotopic Activities in Aged Oralloy

Isotope	Mass Fraction in Mixture (%)	Half-Life (y)	Number of Alpha Particles per Disintegration	Specific Alpha Activity (Bq g ⁻¹)		Relative Alpha Activity in Mixture ^a
				Isotopic	In Mixture	
²³⁴ U	1	2.5×10 ⁵	1	2.26×10 ⁸	2.26×10 ⁶	0.9677
²³⁵ U	93	7.0×10 ⁸	1	8.04×10 ⁴	7.48×10 ⁴	0.0320
²³⁸ U	6	4.5×10 ⁹	1	1.23×10 ⁴	7.41×10 ²	0.0003
Oralloy total specific activity:					2.44×10 ⁶	

NOTE: Oralloy is considered *aged* after at least 7 months have passed since any chemical processing of the metal, so that secular equilibrium of the short-half-life progeny of ²³⁵U and ²³⁸U is established.

^aThe number of significant figures shown are those considered appropriate for use in the calculation of the weighted sum of average photon energies, which was then rounded.

Table 5. Average Photon Energy in Aged Oralloy

Isotope	Average Energy per Parent U (Alpha) Disintegration (MeV)	Relative Alpha Activity in Mixture	Average Energy per U Disintegration in Mixture (MeV)	Number of Radionuclides in Chain	Average Energy per Nuclide Disintegration (MeV)
^{234}U	0.0001115	0.9677	0.000108	1	0.000108
Aged ^{235}U	0.1588410	0.0320	0.005083	2	0.002542
Aged ^{238}U	0.0160618	0.0003	0.000005	3 ^a	0.000002
Total Average Photon Energy per Disintegration					0.002650

NOTE: Oralloy is considered *aged* after at least 7 months have passed since any chemical processing of the metal, so that secular equilibrium of the short-half-life progeny of ^{235}U and ^{238}U is established.

^aProgeny of ^{238}U include ^{234}Th , ^{234}Pa , and $^{234\text{m}}\text{Pa}$. The isomers ^{234}Pa and $^{234\text{m}}\text{Pa}$ are considered as a single radionuclide in the computation of average energy per nuclide disintegration, since the sum of their branching ratios is unity.

Table 6. Measured Uranium Activities and Associated Dose-Equivalent Rates in Randomly Selected Samples with Measurable Contamination

Description	Size (cm)	Geometry	Net Response ^a (dpm)			Net Dose Equivalent Rate ^b (μ rem/h)		
			Contact	30 cm	1 m	Contact	30 cm	1 m
Chip	0.25×0.33	Point	950	0	0	5	0	0
Chip	0.25×0.25	Point	6,000	50	0	10	0	0
Rock (U)	0.5×0.5	Point	15,000	250	250	13	0	0
Chip	0.5×2.5	Point	33,000	250	0	15	2	1

Description	Size (cm)	Geometry	Net Response ^a (dpm/100 cm ²)			Net Dose Equivalent ^b Rate (μ rem/h)		
			Contact	30 cm	1 m	Contact	30 cm	1 m
Fixed	40 cm ²	Distributed	8,000	550	300	3	1	1
Wood	1×15	Distributed	11,000	150	0	5	0	0
Fixed	40 cm ²	Distributed	70,000	650	120	7	4	2
Fixed	60×180	Distributed	70,000	40,000	10,000	88	23	8
U Oxide	100 cm ²	Distributed	150,000	5,000	300	130	10	3
D-38 Plate	91×274	Distributed	210,000	140,000	30,000	5	2	0.7

^aMeasured using a Ludlum Model 3 meter and Model 44-9 pancake probe.

^bMeasured using a Bicron Micro Rem meter with nominal 40-keV cutoff.

Table 7. Ratio of Dose-Equivalent Rate to Uranium Activity in Randomly Selected Samples with Measurable Contamination

Description	Size (cm)	Geometry	Net Activity ^a (dpm)		Net DE Rate ^c ($\mu\text{rem/h}$)	DE Rate per Unit Corrected Activity (rem/h per dpm)
			Measured	Corrected for Dead Time ^b		
Chip	0.25×0.33	Point	5.7×10^3	5.7×10^3	0	0
Chip	0.25×0.25	Point	3.6×10^4	3.6×10^4	0	0
Rock (U)	0.5×0.5	Point	9.0×10^4	9.2×10^4	0	0
Chip	0.5×2.5	Point	2.0×10^5	2.5×10^5	1	5×10^{-12}

Description	Size (cm)	Geometry	Net Activity ^a (dpm/100 cm ²)		Net DE Rate ^c ($\mu\text{rem/h}$)	DE Rate per Unit Corrected Activity (rem/h per dpm/100 cm ²)
			Measured	Corrected for Dead Time ^b		
Fixed	40 cm ²	Distributed	2.4×10^5	2.4×10^5	1	4×10^{-12}
Wood	1×15	Distributed	3.3×10^5	3.3×10^5	0	0
Fixed	40 cm ²	Distributed	2.1×10^6	2.4×10^6	2	8×10^{-13}
Fixed	60×180	Distributed	2.1×10^6	2.4×10^6	8	3×10^{-12}
U Oxide	100 cm ²	Distributed	4.5×10^6	6.5×10^6	3	5×10^{-13}
D-38 Plate	91×274	Distributed	6.3×10^6	1.1×10^7	700	7×10^{-13}

^aCount rates were measured at contact with the source using a Ludlum Model 3 count-rate meter and Model 44-9 pancake probe. Activity (dpm) was determined after subtracting background using conversion factors of 6 dpm/cpm for point sources and 30 dpm/cpm for distributed sources.

^bA non-paralyzable system with dead times of $\tau=80 \mu\text{s}$ (count rates $<50,000 \text{ cpm}$) and $\tau=124 \mu\text{s}$ (count rates $\geq 50,000 \text{ cpm}$) is assumed. Dead-time corrections were applied to count rates before converting to activities.

^cMeasured at a distance of 1 m from the source using a Bicron Micro Rem meter with nominal 40-keV cutoff.

Table 8. Ratio of Dose Equivalent Rate Measured at 1 Meter to Uranium Surface Contamination Measured at Contact

	Point Source (rem/h per dpm)	Distributed Source (rem/h per dpm/100 cm ²)	
Calculated			
Depleted Uranium	1.3×10^{-15}		
Oralloy	5.8×10^{-16}		
Measured ^a : D-38 DOELAP Slab (100 cm ²)	4×10^{-15}	4×10^{-15}	See Note
Measured: Paved Surface Contamination	4×10^{-12}	1×10^{-12}	See Note
Measured: D-38 Plate (25,000 cm ²)		1×10^{-10}	See Note

Note: Contamination distributed over 100 cm² or less (the characteristic dimensions of the D-38 slab and of all but one of the 'distributed' sources) probably approximates a point source to a Micro Rem monitor placed 1 meter away; however, any contamination spread over an area greater than 20 cm² (the active area of a pancake probe) is considered here as a distributed source. The D-38 slab is treated as both a point source and as a distributed source in this analysis.

^aDose-equivalent rate of the standard uranium slab was determined by measurement at 1 m; total activity was calculated from the mass of the slab and its specific activity.

Figure 1

Energy Response of the Bicron Micro Rem Meter

ORNL-DWG 99-04629

Figure 2

Dose Rate at 1 Meter vs. Contamination Level at Contact
(Point Sources)

ORNL-DWG 99-04630

Figure 3

**Dose Rate at 1 Meter vs. Activity at Contact
(Distributed Sources)**

ORNL-DWG 99-04631

APPENDIX A: Photon Emissions and Average Photon Energy in ^{234}U

Average Photon Energy in U-234

Isotope	Emission No.	Probability per decay	E (MeV)	Branch Fraction ¹	Average E per parent U decay (MeV)
U-234	2	0.001180	0.053200	1	0.000063
U-234	3	0.000401	0.121430	1	0.000049
Total Average Photon Energy per ²³⁴ U Disintegration					0.000112

¹Branch fraction - The relative number of atoms of a radioisotope which decay through a given mode.

APPENDIX B: Photon Emissions and Average Photon Energy in Aged ^{235}U

Average Photon Energy in Aged U-235

Isotope	Emission No.	Probability per decay	E (MeV)	Branch Fraction ¹	Average E per decay (MeV)
U-235	1	0.001100	0.072700	1	0.000080
U-235	2	0.027289	0.089953	1	0.002455
U-235	3	0.044590	0.093350	1	0.004162
U-235	4	0.020629	0.105000	1	0.002166
U-235	5	0.015000	0.109140	1	0.001637
U-235	6	0.001500	0.120000	1	0.000180
U-235	7	0.002200	0.140770	1	0.000310
U-235	8	0.105000	0.143760	1	0.015095
U-235	9	0.047000	0.163350	1	0.007677
U-235	10	0.004000	0.182700	1	0.000731
U-235	11	0.540000	0.183720	1	0.099209
U-235	12	0.005900	0.194940	1	0.001150
U-235	13	0.010000	0.202120	1	0.002021
U-235	14	0.047000	0.205310	1	0.009650
U-235	15	0.001000	0.221380	1	0.000221
U-235	16	0.009194	0.190350	1	0.001750
Average Photon Energy per Decay from ²³⁵ U					0.148494
Th-231	1	0.004752	0.058570	1	0.000278
Th-231	2	0.002485	0.072780	1	0.000181
Th-231	3	0.008811	0.081240	1	0.000716
Th-231	4	0.003960	0.082110	1	0.000325
Th-231	5	0.064350	0.084210	1	0.005419
Th-231	6	0.009306	0.089950	1	0.000837
Th-231	7	0.003507	0.092287	1	0.000324
Th-231	8	0.005712	0.095868	1	0.000548
Th-231	9	0.001188	0.099280	1	0.000118
Th-231	10	0.004059	0.102270	1	0.000415
Th-231	11	0.002646	0.108000	1	0.000286
Th-231	12	0.001535	0.163120	1	0.000250
Th-231	13	0.005690	0.114270	1	0.000650
Average Photon Energy from ²³¹ Th per ²³⁵ U Decay					0.010347
Total (²³⁵ U & ²³¹ Th) Average Photon Energy per Parent (²³⁵ U) Disintegration					0.158841

¹Branch fraction - The relative number of atoms of a radioisotope which decay through a given mode.

APPENDIX C: Photon Emissions and Average Photon Energy in Aged ^{238}U

Average Photon Energy in Aged U-238

Isotope	Emission No.	Probability per decay	E (MeV)	Branch Fraction ¹	Average E per decay (MeV)
U-238	1	0.000970	0.066376	1	0.000064385
Average Photon Energy per Decay from ²³⁸ U					0.000064385
Th-234	1	0.038116	0.063290	1	0.002412362
Th-234	2	0.027248	0.092380	1	0.002517170
Th-234	3	0.026884	0.092800	1	0.002494835
Th-234	4	0.002418	0.112810	1	0.000272775
Th-234	5	0.001284	0.076765	1	0.000098566
Average Photon Energy from ²³⁴ Th per ²³⁸ U Decay					0.007795708
Pa-234m	1	0.000136	0.073920	0.9984	0.000010037
Pa-234m	2	0.001157	0.094665	0.9984	0.000109352
Pa-234m	3	0.001875	0.098439	0.9984	0.000184278
Pa-234m	4	0.000873	0.111000	0.9984	0.000096748
Pa-234m	5	0.002067	0.766410	0.9984	0.001581635
Pa-234m	6	0.003740	0.926180	0.9984	0.003458371
Average Photon Energy from ^{234m} Pa per ²³⁸ U Decay					0.005440421
Pa-234	1	0.001224	0.043480	0.0016	0.000000085
Pa-234	2	0.032640	0.063000	0.0016	0.000003290
Pa-234	3	0.002346	0.069900	0.0016	0.000000262
Pa-234	4	0.001224	0.079690	0.0016	0.000000156
Pa-234	5	0.156970	0.094665	0.0016	0.000023775
Pa-234	6	0.254420	0.098439	0.0016	0.000040072
Pa-234	7	0.048960	0.099860	0.0016	0.000007823
Pa-234	8	0.001224	0.103410	0.0016	0.000000203
Pa-234	9	0.118480	0.111000	0.0016	0.000021042
Pa-234	10	0.010200	0.125400	0.0016	0.000002047
Pa-234	11	0.204000	0.131200	0.0016	0.000042824
Pa-234	12	0.002142	0.134370	0.0016	0.000000461
Pa-234	13	0.001530	0.137700	0.0016	0.000000337
Pa-234	14	0.009180	0.140300	0.0016	0.000002061
Pa-234	15	0.003570	0.144000	0.0016	0.000000823
Pa-234	16	0.002040	0.150200	0.0016	0.000000490
Pa-234	17	0.068340	0.152700	0.0016	0.000016697
Pa-234	18	0.007140	0.159100	0.0016	0.000001818
Pa-234	19	0.005100	0.170700	0.0016	0.000001393
Pa-234	20	0.002040	0.174600	0.0016	0.000000570

Average Photon Energy in Aged U-238

Isotope	Emission No.	Probability per decay	E (MeV)	Branch Fraction ¹	Average E per decay (MeV)
Pa-234	21	0.020400	0.186000	0.0016	0.000006071
Pa-234	22	0.006120	0.193600	0.0016	0.000001896
Pa-234	23	0.004896	0.199700	0.0016	0.000001564
Pa-234	24	0.011220	0.200980	0.0016	0.000003608
Pa-234	25	0.012240	0.203000	0.0016	0.000003976
Pa-234	26	0.002040	0.219800	0.0016	0.000000717
Pa-234	27	0.060180	0.226400	0.0016	0.000021800
Pa-234	28	0.056100	0.227200	0.0016	0.000020393
Pa-234	29	0.009180	0.245200	0.0016	0.000003601
Pa-234	30	0.028560	0.248900	0.0016	0.000011374
Pa-234	31	0.001734	0.267100	0.0016	0.000000741
Pa-234	32	0.010200	0.272100	0.0016	0.000004441
Pa-234	33	0.002652	0.275500	0.0016	0.000001169
Pa-234	34	0.001428	0.286100	0.0016	0.000000654
Pa-234	35	0.001122	0.289600	0.0016	0.000000520
Pa-234	36	0.039780	0.293700	0.0016	0.000018693
Pa-234	37	0.001020	0.309600	0.0016	0.000000505
Pa-234	38	0.003060	0.312500	0.0016	0.000001530
Pa-234	39	0.001224	0.316300	0.0016	0.000000619
Pa-234	40	0.001224	0.320700	0.0016	0.000000628
Pa-234	41	0.003060	0.328000	0.0016	0.000001606
Pa-234	42	0.006120	0.330600	0.0016	0.000003237
Pa-234	43	0.006120	0.351900	0.0016	0.000003446
Pa-234	44	0.029580	0.369800	0.0016	0.000017502
Pa-234	45	0.013260	0.372400	0.0016	0.000007901
Pa-234	46	0.004080	0.409800	0.0016	0.000002675
Pa-234	47	0.001020	0.416300	0.0016	0.000000679
Pa-234	48	0.006120	0.426800	0.0016	0.000004179
Pa-234	49	0.001224	0.446500	0.0016	0.000000874
Pa-234	50	0.015300	0.458800	0.0016	0.000011231
Pa-234	51	0.001632	0.461800	0.0016	0.000001206
Pa-234	52	0.004080	0.467500	0.0016	0.000003052
Pa-234	53	0.002448	0.472100	0.0016	0.000001849
Pa-234	54	0.001836	0.473500	0.0016	0.000001391
Pa-234	55	0.003060	0.478700	0.0016	0.000002344
Pa-234	56	0.004080	0.480400	0.0016	0.000003136
Pa-234	57	0.003060	0.482500	0.0016	0.000002362
Pa-234	58	0.001020	0.498900	0.0016	0.000000814

Average Photon Energy in Aged U-238

Isotope	Emission No.	Probability per decay	E (MeV)	Branch Fraction ¹	Average E per decay (MeV)
Pa-234	59	0.016320	0.506800	0.0016	0.000013234
Pa-234	60	0.013260	0.513700	0.0016	0.000010899
Pa-234	61	0.006120	0.520200	0.0016	0.000005094
Pa-234	62	0.009180	0.521000	0.0016	0.000007652
Pa-234	63	0.006120	0.528000	0.0016	0.000005170
Pa-234	64	0.002040	0.533200	0.0016	0.000001740
Pa-234	65	0.001632	0.537100	0.0016	0.000001402
Pa-234	66	0.002652	0.557000	0.0016	0.000002363
Pa-234	67	0.014280	0.565900	0.0016	0.000012930
Pa-234	68	0.030600	0.568700	0.0016	0.000027844
Pa-234	69	0.109140	0.569500	0.0016	0.000099448
Pa-234	70	0.020400	0.574000	0.0016	0.000018735
Pa-234	71	0.001530	0.585800	0.0016	0.000001434
Pa-234	72	0.005100	0.596600	0.0016	0.000004868
Pa-234	73	0.009180	0.602800	0.0016	0.000008854
Pa-234	74	0.008160	0.611500	0.0016	0.000007984
Pa-234	75	0.002040	0.616200	0.0016	0.000002011
Pa-234	76	0.008160	0.623600	0.0016	0.000008142
Pa-234	77	0.008160	0.627500	0.0016	0.000008193
Pa-234	78	0.004080	0.630600	0.0016	0.000004117
Pa-234	79	0.003060	0.634500	0.0016	0.000003107
Pa-234	80	0.002040	0.639700	0.0016	0.000002088
Pa-234	81	0.002040	0.643200	0.0016	0.000002099
Pa-234	82	0.003060	0.646000	0.0016	0.000003163
Pa-234	83	0.009180	0.653700	0.0016	0.000009602
Pa-234	84	0.006120	0.655000	0.0016	0.000006414
Pa-234	85	0.009180	0.658000	0.0016	0.000009665
Pa-234	86	0.003060	0.660600	0.0016	0.000003234
Pa-234	87	0.013260	0.664800	0.0016	0.000014104
Pa-234	88	0.016320	0.666700	0.0016	0.000017409
Pa-234	89	0.014280	0.669900	0.0016	0.000015306
Pa-234	90	0.002448	0.683300	0.0016	0.000002676
Pa-234	91	0.002856	0.687000	0.0016	0.000003139
Pa-234	92	0.015300	0.692700	0.0016	0.000016957
Pa-234	93	0.046920	0.699000	0.0016	0.000052475
Pa-234	94	0.031620	0.706100	0.0016	0.000035723
Pa-234	95	0.002040	0.711200	0.0016	0.000002321
Pa-234	96	0.001632	0.713800	0.0016	0.000001864

Average Photon Energy in Aged U-238

Isotope	Emission No.	Probability per decay	E (MeV)	Branch Fraction ¹	Average E per decay (MeV)
Pa-234	97	0.087720	0.733000	0.0016	0.000102878
Pa-234	98	0.010200	0.738000	0.0016	0.000012044
Pa-234	99	0.024480	0.742810	0.0016	0.000029094
Pa-234	100	0.001326	0.746500	0.0016	0.000001584
Pa-234	101	0.014280	0.755600	0.0016	0.000017264
Pa-234	102	0.001632	0.760000	0.0016	0.000001985
Pa-234	103	0.003060	0.766360	0.0016	0.000003752
Pa-234	104	0.005712	0.768700	0.0016	0.000007025
Pa-234	105	0.002040	0.777900	0.0016	0.000002539
Pa-234	106	0.011220	0.780700	0.0016	0.000014015
Pa-234	107	0.005100	0.783100	0.0016	0.000006390
Pa-234	108	0.014280	0.786270	0.0016	0.000017965
Pa-234	109	0.015300	0.793600	0.0016	0.000019427
Pa-234	110	0.038760	0.796300	0.0016	0.000049383
Pa-234	111	0.004080	0.804300	0.0016	0.000005250
Pa-234	112	0.033660	0.805600	0.0016	0.000043386
Pa-234	113	0.005100	0.812500	0.0016	0.000006630
Pa-234	114	0.026520	0.819600	0.0016	0.000034777
Pa-234	115	0.040800	0.826300	0.0016	0.000053941
Pa-234	116	0.056100	0.831600	0.0016	0.000074644
Pa-234	117	0.001428	0.841900	0.0016	0.000001924
Pa-234	118	0.005100	0.844000	0.0016	0.000006887
Pa-234	119	0.001224	0.851700	0.0016	0.000001668
Pa-234	120	0.001224	0.872900	0.0016	0.000001709
Pa-234	121	0.040800	0.876400	0.0016	0.000057211
Pa-234	122	0.010200	0.880500	0.0016	0.000014370
Pa-234	123	0.122400	0.880510	0.0016	0.000172439
Pa-234	124	0.122400	0.883240	0.0016	0.000172974
Pa-234	125	0.041820	0.899000	0.0016	0.000060154
Pa-234	126	0.005100	0.904370	0.0016	0.000007380
Pa-234	127	0.004080	0.920000	0.0016	0.000006006
Pa-234	128	0.029580	0.925000	0.0016	0.000043778
Pa-234	129	0.112200	0.926000	0.0016	0.000166236
Pa-234	130	0.091800	0.926720	0.0016	0.000136117
Pa-234	131	0.122400	0.946000	0.0016	0.000185265
Pa-234	132	0.081600	0.949000	0.0016	0.000123901
Pa-234	133	0.001020	0.960000	0.0016	0.000001567
Pa-234	134	0.006120	0.966000	0.0016	0.000009459

Average Photon Energy in Aged U-238

Isotope	Emission No.	Probability per decay	E (MeV)	Branch Fraction ¹	Average E per decay (MeV)
Pa-234	135	0.014280	0.978800	0.0016	0.000022364
Pa-234	136	0.030600	0.980500	0.0016	0.000048005
Pa-234	137	0.020400	0.980500	0.0016	0.000032004
Pa-234	138	0.019380	0.984000	0.0016	0.000030512
Pa-234	139	0.005100	0.044900	0.0016	0.000000366
Pa-234	140	0.002550	0.074600	0.0016	0.000000304
Pa-234	141	0.007650	0.083200	0.0016	0.000001018
Pa-234	142	0.003060	0.108500	0.0016	0.000000531
Pa-234	143	0.005100	0.122300	0.0016	0.000000998
Pa-234	144	0.008160	0.126000	0.0016	0.000001645
Pa-234	145	0.003060	0.153100	0.0016	0.000000750
Pa-234	146	0.002448	0.171300	0.0016	0.000000671
Pa-234	147	0.003060	0.208000	0.0016	0.000001018
Pa-234	148	0.003774	0.217500	0.0016	0.000001313
Pa-234	149	0.003060	0.229000	0.0016	0.000001121
Pa-234	150	0.005100	0.240500	0.0016	0.000001963
Pa-234	151	0.003060	0.251000	0.0016	0.000001229
Pa-234	152	0.002040	0.277400	0.0016	0.000000905
Pa-234	153	0.006120	0.292700	0.0016	0.000002866
Pa-234	154	0.017340	0.353300	0.0016	0.000009802
Pa-234	155	0.001224	0.358500	0.0016	0.000000702
Pa-234	156	0.030600	0.394100	0.0016	0.000019295
Pa-234	157	0.002346	0.399700	0.0016	0.000001500
Pa-234	158	0.002040	0.427500	0.0016	0.000001395
Pa-234	159	0.004080	0.446000	0.0016	0.000002912
Pa-234	160	0.010200	0.452700	0.0016	0.000007388
Pa-234	161	0.003060	0.460000	0.0016	0.000002252
Pa-234	162	0.002040	0.493700	0.0016	0.000001612
Pa-234	163	0.004080	0.516000	0.0016	0.000003369
Pa-234	164	0.001020	0.549400	0.0016	0.000000897
Pa-234	165	0.001734	0.579700	0.0016	0.000001608
Pa-234	166	0.002550	0.585400	0.0016	0.000002389
Pa-234	167	0.006120	0.593800	0.0016	0.000005815
Pa-234	168	0.001530	0.627900	0.0016	0.000001537
Pa-234	169	0.004080	0.638000	0.0016	0.000004165
Pa-234	170	0.001530	0.656000	0.0016	0.000001606
Pa-234	171	0.012240	0.668500	0.0016	0.000013092
Pa-234	172	0.005100	0.686200	0.0016	0.000005600

Average Photon Energy in Aged U-238

Isotope	Emission No.	Probability per decay	E (MeV)	Branch Fraction ¹	Average E per decay (MeV)
Pa-234	173	0.012240	0.694600	0.0016	0.000013603
Pa-234	174	0.001530	0.699800	0.0016	0.000001713
Pa-234	175	0.001020	0.737600	0.0016	0.000001204
Pa-234	176	0.001020	0.741700	0.0016	0.000001211
Pa-234	177	0.002550	0.756000	0.0016	0.000003085
Pa-234	178	0.001020	0.772300	0.0016	0.000001261
Pa-234	179	0.003060	0.797300	0.0016	0.000003904
Pa-234	180	0.001938	0.890100	0.0016	0.000002760
Pa-234	181	0.001530	0.897100	0.0016	0.000002196
Pa-234	182	0.002856	0.905000	0.0016	0.000004136
Pa-234	183	0.005100	0.926000	0.0016	0.000007556
Pa-234	184	0.010099	0.955590	0.0016	0.000015441
Average Photon Energy from ²³⁴ Pa per ²³⁸ U Decay					0.002761280

Total (²³⁸U, ²³⁴Th, ^{234m}Pa, & ²³⁴Pa) Average Photon Energy per Parent (²³⁸U) Decay 0.016062

¹Branch fraction - The relative number of atoms of a radioisotope which decay through a given mode.

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