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Shanahan, J. P., Eckerman, K., Arndt, A., Gold, C., Patton, P. W., Rudin, M., Brey, R., Gesell, T., Rusetski, V., Pagava, S. (2002). An Interdatabase Comparison of Nuclear Decay and Structure Data Utilized in the Calculation of Dose Coefficients for Radionuclides Produced in a Spallation Neutron Source. 1-31.
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AN INTERDATABASE COMPARISON OF NUCLEAR DECAY AND STRUCTURE DATA UTILIZED IN THE CALCULATION OF DOSE COEFFICIENTS FOR RADIONUCLIDES PRODUCED IN A SPALLATION NEUTRON SOURCE

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ABSTRACT

Internal and external dose coefficient values have been calculated for 14 anthropogenic radionuclides which are not currently presented in Federal Guidance Reports Nos. 11, 12, and 13 or Publications 68 and 72 of the International Commission on Radiological Protection. Internal dose coefficient values are reported for inhalation and ingestion of 1 μm and 5 μm AMAD particulates along with the f_1 values and absorption types for the adult worker. Internal dose coefficient values are also reported for inhalation and ingestion of 1 μm AMAD particulates as well as the f_1 values and absorption types for members of the public. Additionally, external dose coefficient values for air submersion, exposure to contaminated ground surface, and exposure to soil contaminated to an infinite depth are also presented. Information obtained from this study will be used to support the siting and permitting of future accelerator-driven nuclear initiatives within the U.S. Department of Energy complex, including the Spallation Neutron Source (SNS) and Accelerator Production of Tritium (APT) Projects.

INTRODUCTION

High intensity proton accelerators have been developed for the production of neutron beams for basic scientific research and development of transmutation technology for long-lived transuranic nuclides. At these facilities several accelerator components are exposed to primary and secondary high energy particles resulting in the production of various spallation products. These radionuclides have the potential to be involved in both internal and external exposure scenarios involving workers and the general public. Quantifying the radiological health risks associated with the production of these anthropogenic radionuclides will be essential for radiation safety and protection.

As part of the University of Nevada, Las Vegas (UNLV) Transmutation Research Program, the Department of Health Physics has been tasked to quantify the radiological health risks to workers during the operation of proposed U.S. Department of Energy (DOE) accelerator facilities. As part of this multi-year study, a research consortium consisting of members from participating universities and national laboratories was established. The primary objective of this research is to calculate internal and external dose coefficients for anthropogenic radionuclides produced at these facilities for workers and members of the public. Information obtained from this study will be used to support the siting and permitting of future accelerator-driven nuclear initiatives within the U.S. DOE complex, including the Spallation Neutron Source (SNS) and Accelerator Production of Tritium (APT) Projects.

Environmental Protection Agency (EPA) Federal Guidance Report No. 11 “Limiting Values of Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion” (EPA 1988), developed two derived guides, Annual Limit on Intake (ALI) and the Derived Air Concentration (DAC), to be used to control radiation exposure in the

workplace. The ALI is the annual intake of a radionuclide which would result in a committed effective dose equivalent of 50 mSv yr^{-1} for stochastic effects, or a committed equivalent dose to an individual organ or tissue of 500 mSv yr^{-1} for non-stochastic effects, to Reference Man (ICRP 1975). A DAC is that concentration of a radionuclide in air which, if breathed by Reference Man for a work-year, would result in an intake corresponding to its ALI. Therefore, ALIs and DACs can be used for assessing radiation doses due to accidental ingestion and inhalation of radionuclides and are used for limiting radionuclide intake through breathing of, or submersion in, contaminated air.

When determining ALIs and DACs, in many situations it is useful to know the committed equivalent dose to an organ or tissue per unit intake ($h_{T,50}$), the committed effective dose per unit intake (e_{50}), the tissue dose equivalent per unit time-integrated exposure to a radionuclide ($h_{T,ext}$) from external exposure, or the effective dose per unit time-integrated exposure to a radionuclide (e_{ext}) from external exposure. These are collectively referred to as dose coefficients, and give either the equivalent dose to a tissue or the effective dose to an individual that is characterized adequately by Reference Man (ICRP 1975). Tabulated dose coefficients for the 825 radionuclides listed in Publication 38 of the ICRP (1983) are found in both Federal Guidance Reports No. 11 (EPA 1988) and 12 (EPA 1993). Federal Guidance Report No. 11 reports dose coefficients (dose conversion factors) for inhalation, ingestion, and submersion in contaminated air scenarios, while Federal Guidance Report No. 12 reports dose coefficients for immersion in contaminated water, exposure to contaminated soil, and updates Federal Guidance Report No. 11 with respect to dose coefficients for submersion in contaminated air.

Internal Dose Coefficients Methodology

The risk of a given biological effect is assumed to relate linearly to the equivalent dose. The risk of an effect is determined by the total equivalent dose averaged throughout an organ or tissue, and is independent of the time in which the equivalent dose is delivered. The intake of certain long-lived radionuclides may result in the continuous deposition of dose to tissues far into the future. To account for this fact in planning work with radioactive materials, the ICRP recommends that the appropriate period for integration of equivalent dose is a working life time of 50 years. The committed equivalent dose, $H_{T,50}$, to a given organ or tissue from a single intake of radioactive material into the body is defined as the integrated equivalent dose accumulated over the next 50 years from that intake, and can be calculated from (EPA 1988):

$$H_{T,50} = K \sum_{S} U_S SEE(T \leftarrow S) \qquad \text{(Sv)}. \tag{1}$$

The constant, K, depends on the units specified for $H_{T,50}$, $SEE(T \leftarrow S)$, and U_S. K is equal to 1.6×10^{-10} Sv g MeV^{-1} when $SEE(T \leftarrow S)$ is expressed in megaelectron volts (MeV) per gram (g) per nuclear transformation, $H_{T,50}$ in Sv, and U_S in nuclear transformations. The specific effective energy, $SEE(T \leftarrow S)$, depends on the details of the nuclear transformations of the radionuclide, including the weighting factors of the emitted radiations (w_r), and the distribution of absorbed energy among body tissues. Computation of U_S reflects the metabolic activity of a radionuclide in the body. Models such as the "Dosimetric Model for the Gastrointestinal Tract" (ICRP 1979) and the "Human Respiratory Tract Model for Radiation Protection" (ICRP 1994) are used to facilitate these calculations and are based on the assumption that the body consists of a number of separate compartments (ICRP 1979). Details of the uptake, distribution, and retention of a

particular radionuclide into the body or body tissues are given in the metabolic data of each element, while various models are used to describe its translocation and clearance (biokinetics) from the body.

The committed effective dose, E_{50}, reflects both the distribution of absorbed dose among various tissues of the body and the relative sensitivity of those tissues to the stochastic effects of ionizing radiation (ICRP 1995). The committed effective dose is calculated from:

$$E_{50} = \sum_T w_T H_{T,50} \qquad \text{(Sv)}, \tag{2}$$

where w_T is the tissue weighting factor and equates the risk of cancer induction in a single irradiated tissue or organ to the risk of cancer induction if the whole body were uniformly irradiated.

Dose coefficient calculations, for internal dosimetry applications, require unit activity of a given radionuclide be used in Eq. 1 to calculate the committed equivalent dose per unit intake for a specific organ or tissue. Accordingly, when individual organ and tissue committed equivalent doses are summed after applying the appropriate tissue weighting factors the result is the committed effective dose per unit intake.

External Dose Coefficients Methodology

According to Federal Guidance Report No. 12 (EPA 1993) calculations of external dose coefficients involve three major steps: (1) computation of the energy and angular distributions of the radiation incident on the body for a range of initial energies of monoenergetic sources

distributed in environmental media, (2) evaluation of the transport and energy deposition in organs and tissues of the body by the incident radiations, characterized above in terms of their energy and angular distributions, for each of the initial energies considered, and (3) calculation of the organ or tissue dose for specific radionuclides, considering the energies and intensities of the radiations emitted during nuclear transformations of those nuclides. The result of the first two steps is a set of dose coefficients for monoenergetic sources of photon or electron radiations. The last step simply scales these coefficients to the emissions of the radionuclide of interest.

With respect to steps one and two, Federal Guidance Report No. 12 reports that the estimation of dose to tissues of the body from radiation emitted by an arbitrary distribution of a radionuclide in an environmental medium is an extremely difficult computational task and requires solution to a complex radiation transport problem involving radiations incident on and through the body. As a result, it becomes impractical to solve this problem for the precise spectrum of photons emitted by each radionuclide of interest. Therefore, organ doses for 25 organs in an adult hermaphrodite phantom were computed using various codes for monoenergetic photon sources at 12 energies ranging from 0.1 to 5.0 MeV. The results are tabulated in various tables found in Federal Guidance Report No. 12 for each source, *S*, and are utilized by interpolating photon energy data specific to the radionuclide of interest to obtain the equivalent dose for the organ or tissue of interest. Additionally, the skin dose from environmental electron sources represents a complex radiation transport problem. Skin dose coefficients were calculated for a series of monoenergetic electron emissions that were convoluted to the spectra of the various radionuclides (Eckerman et al 1994) found in ICRP Publication 38 (1983) using the energy and intensity data of the beta and electron emissions. It should be noted that the dose to organs and tissues of the body other than the skin are negligible

for externally emitted electrons, due to the short range of electrons. These results were also tabulated for each source, *S*, and are presented graphically in Federal Guidance Report No. 12. Obtaining the skin dose coefficient for the radionuclide of interest then becomes a matter of integrating energy, *E*, between *E* and *E* + *dE* for a continuous energy spectrum (EPA 1993).

Finally, an external dose coefficient, h_T^S, for any tissue *T* for any exposure mode *S* can be expressed as (EPA 1993):

$$h_T^S = \sum_{j=e,\gamma}\left[\sum_i y_j(E_i)\hat{h}_T^S(E_i) + \int_0^\infty y_j(E)\hat{h}_{Tj}^S(E)dE\right] \qquad \text{(Sv per Bq s m}^{-3}\text{)}, \qquad (3)$$

where $y_j(E_i)$ is the yield of discrete photon radiations of type *j* and energy E_i, and $y_j(E)$ denotes the yield of continuous electron radiations per nuclear transformation with energy between *E* and *E* + *dE*. These summations are performed over all photon and electron radiations. Note that each radiation potentially has two components: (1) the discrete energy emission, and (2) the continuous emissions. The continuous component is only accounted for when calculating the tissue dose equivalent for the skin and can be effectively ignored in all other tissue dose coefficient calculations. The contribution of the radiations to the dose in tissue *T* is defined by the quantity $\hat{h}_T^S(E)$ which is tabulated as a function of energy for tissue *T* for each exposure mode S and obtained from the various tables previously described. The modes of exposure described here are for: (1) submersion in a contaminated atmospheric cloud, (2) immersion in contaminated water, and (3) exposure to contamination on or in the ground (EPA 1993).

METHODS AND MATERIALS

Identification

Five hundred and twenty four radionuclides, based on a mercury spallation neutron source (SNS) target, were given to the Working Group for evaluation. The initial list was provided by SNS personnel at Oak Ridge National Laboratory (ORNL) who examined cooling water and mercury target production rates, and subsequently calculated radionuclide concentrations, radioactivity, and decay heat as a function of buildup and decay times using MCNPX and ORIHET95 computer codes (DeVore, 2002). The identification of radionuclides lacking a published dose coefficient was accomplished by comparing the initial list to three existing radiation safety dose coefficient databases. The databases used in this analysis included: (1) ICRP CD (ICRP 2001), (2) CD supplement to Federal Guidance Report 13 (EPA 2002), and (3) a JAERI report on dose coefficients (Kawai et al. 2002).

Dosimetric System

The computation of a dose coefficient begins with an Evaluated Nuclear Structure Data File (ENSDF) (Burrrows 1990) serving as the input data file for the Energy Distribution (EDISTR) code of Dillman (1980). ENSDF data files are maintained by the National Nuclear Data Center (NNDC) at Brookhaven National Laboratory (BNL) and contain evaluated nuclear structure and decay data information for selected radionuclides with mass numbers (A) less than 263. These data files are updated by mass chains with a present cycle time of approximately six years. The primary objective of the EDISTR code is to extract relevant nuclear structure and decay information from the ENSDF file for the purpose of generating a radioactive decay data file. The EDISTR output file contains the necessary dosimetric data needed to perform a dose

coefficient calculation, and is ultimately used by the computational modules within the Dose and Risk Calculation (DCAL) software package. Before the EDISTR output file can be used in the computation of a dose coefficient, it must be properly formatted for use by DCAL. To facilitate this formatting requirement, a series of MS-DOS executables were developed and can be collectively found in the Decay Data (DECDAT) directory. Although the Decay Data Directory is a separate directory, it is usually attached or incorporated into the EDISTR directory for easy of use. Files that have been appropriately formatted are then incorporated into DCAL's Nuclear Decay library (Eckerman et al 1994) for a dose coefficient computation. The DCAL software package contains a series of modules or subroutines necessary for the computation of a dose coefficient calculation as described by the above theory

Prioritization

The list of radionuclides identified as lacking a published dose coefficient value were initially prioritized according to half-life, with the highest priority given to those radionuclides with a half-life greater than or equal to one minute. This prioritization scheme was based on an assumed radiological risk associated with exposure and the computational capabilities of the dosimetry codes. Further refinement of the prioritization scheme evolved from an effort to quantify the accuracy of the data in the ENSDF library compared to another nuclear physics database. The Nubase database (Audi et al. 1997) was used to carry out a direct comparison of relevant nuclear structure and decay data found in an ENSDF data file. The Nubase database was chosen because it is believed to more accurately reflect current scientific literature based on the frequency in which the database is updated. The process developed to cross reference the databases uses Microsoft Excel workbooks, one for each of the radionuclides requiring an

evaluation, with a series of worksheets formatted to carry out the evaluation. There are two types of worksheets found in the workbooks. These include: (1) the data comparison worksheet, used to cross reference the databases for each member of the decay chain, and (2) the classification worksheet, used to tabulate the results from each data comparison worksheet so that a decay chain categorization score can be generated.

Interdatabase Comparison Methodology

Specific variables analyzed in the data comparison worksheets correspond to principal input parameters used by the EDISTR code in compiling a radioactive decay data file. These parameters are: (1) decay mode(s), (2) excitation energy, (3) half-life, (4) Q-value, and (5) spin and parity and are given in Fig. 1. During this work, the excitation energy parameter was used to quantify the energy released, in kiloelectron volts (keV), for the isomeric transition of particular radionuclides. After appropriate information had been transcribed into the data comparison worksheets, the results were analyzed to determine either a percent difference or a binary score. A percent difference was generated for the excitation energy value, half-life value, and Q-value, while a binary score was used to evaluate the decay modes and spin and parity values. Note; that either a binary score of one or a percent difference greater than or equal to one in the data comparison worksheets indicates poor agreement between the databases for the parameter in question. Results from the data comparison worksheets are tabulated and logically tested in a classification worksheet so that the decay chain can be categorized. Logic testing is used to generate a binary score for each parameter after the entire decay chain has been evaluated and these results are then weighted and summed so that a final categorization score is generated. A decay chain can fall into one of three categories based on the results of the logic testing. These

categories are: (1) each member of the decay chain has a corresponding ENSDF data file and shows good agreement between the databases, (2) each member of the decay chain has a corresponding ENSDF data file and one or more members of the decay chain shows poor agreement between the databases, and (3) an ENSDF data file is missing for one or more members of the decay chain. With respect to the category scores, good agreement is defined as having less than one percent difference and the sum of the binary scores equal zero after the entire decay chain has been evaluated and cross referenced.

RESULTS AND DISCUSSION

Radionuclide Identification

One hundred fifty eight of the 524 radionuclides given to the UNLV Transmutation Research Program have been identified as lacking an appropriate reference for a published dose coefficient according to existing radiation safety dose coefficient databases queried as part of this study. The 158 radionuclides identified in this study were categorized according to half-life and the results are presented in Fig. 2. As seen in Fig. 2, the majority of radionuclides, 86, had a half-life less than one minute, 57 had a half-life between one and ten minutes and, 15 had a half-life equal to or greater than ten minutes. Radionuclides identified with a half-life greater than or equal to one minute present the greatest radiological risk to workers and were, therefore, given the highest priority in this study. As a result, 72 radionuclides were identified and included in the interdatabase comparison study as outlined above for a possible dose coefficient calculation. Those radionuclides identified with a half-life of less than one minute were set aside because of concerns regarding the computational capabilities of the dosimetry codes used. These radionuclides may be addressed at a later date.

Interdatabase Comparison Study

Nuclear decay data for the 72 radionuclides identified as lacking a published dose coefficient and their associated decay chain members were established using Nubase and cross referenced with the ENSDF library. A total of 109 decay chains were evaluated as part of this study after secondary and tertiary decay chains were included. The 109 decay chains included 699 radionuclides in their ground and isomeric states with each decay chain having approximately six decay chain members. A quantitative comparison was made of relevant nuclear structure and decay data used by the EDISTR code between the two databases for the 699 radionuclides. Radionuclide results were tabulated for each parameter relative to its associated decay chain so that systemic trends could be identified. The results of this analysis are given in Fig. 3. As shown in Fig. 3, the largest observed discrepancy occurred between reported Q-values with 79 out of the 109 decay chains demonstrating poor agreement. One hundred one of the 105 evaluated decay chains included at least one member with an isomeric state of transition.

When the initial evaluation of the decay chains was completed, the 79 decay chains identified as having a Q-value discrepancy were updated according to the Q-values found in Nubase (Audi et al. 1997). ENSDF cites both a 1993 (Audi and Wapstra 1993) evaluation and the 1995 update to the atomic mass evaluation (Audi and Wapstra 1995) as references for atomic mass excess data, whereas Nubase relies on the latter plus additional updates provided by the authors and is believed to more accurately reflect current scientific literature. As a result, Nubase was used to update ENSDF Q-value records when greater than 1% difference was noted between the databases. Categorical scores were then generated for the 72 radionuclides identified as lacking a published dose coefficient and these scores are presented in Fig. 4.

Agreement was observed in nuclear structure and decay data among relevant databases to allow the calculation of a dose coefficient for 42% (30 out of 72) of the radionuclides evaluated, Category 1. Thirty three percent (24 out of 72) of the radionuclides require further research to resolve observed discrepancies between the databases before a dose coefficient calculation could be performed, Category 2. While 25% (18 out of 72) of the radionuclides had missing ENSDF data files for one or more members of their decay chains and could not be evaluated with respect to a dose coefficient calculations at this time, Category 3. The 30 category one radionuclides identified as lacking a published dose coefficient are presented in Table 1.

Dose Coefficient Calculations

Beyond the inspection of just the relevant nuclear structure and decay data used by the EDISTR code, a review of the records making up each ENSDF data file was conducted. The records of the ENSDF data file contain specific information that describes measured or deduced nuclear properties for the various levels of the decaying nucleus. Missing or incomplete ENSDF records will affect the output results from EDISTR in the form of intensity and energy balance discrepancies. In addition several radionuclides evaluated as part of this study had their most recent ENSDF evaluations performed prior to 1995 suggesting an evaluation cycle time significantly longer than the stated six years. A more detailed explanation of the ENSDF records and the information they contain is given in the reference by Tuli (Tuli 1987).

An additional problem was identified with 19 of 30 category one radionuclides when one or more decay chain members had missing ENSDF records. Specifically, electron capture and beta minus records were missing for all or various levels of the decaying nucleus for several of these radionuclides. These results indicate a lack of experimental data relative to the

radionuclide and effectively eliminate a decay chain from consideration for a dose coefficient computation.

The output file generated by the EDISTR code contains, among other radioactive decay information, intensity and energy balance data. These data can be used to evaluate a given radionuclide's decay level scheme with respect to the total energy associated with the decay. The percent error associated with the energy balance data should be equal to zero, however, this is not always observed within available data sets. During this work, a percent error of less than or equal to 5% was considered acceptable. The percent errors related to the total energy balance data for the 11 radionuclides and their associated decay chain members identified as having complete ENSDF data sets are given in Table 2. The error in the energy balance data for 38 radionuclides was determined. Five radionuclides had discrepancies greater than 5%. Those radionuclides showing such discrepancies relative to this error included: ^{160}Er (6.82%), ^{201}Pt (44.6%), ^{161}Tm (22.8%), ^{161m}Er (69.5%), and ^{173}W (8.54%). This discrepancy will affect all dose coefficient computations involving these radionuclides, however, the magnitude of this uncertainty in this situation is unclear.

Dose Coefficient Results

The calculated committed equivalent dose coefficients, $h_{T,50}$, and the calculated committed effective dose coefficients, e_{50}, are presented in Tables 3 and 4 for ^{61}Fe. As shown in Table 3, dose coefficients for the inhalation of 1 μm AMAD particles and the ingestion are presented along with the f_1 values and absorption types for the adult worker. Table 4 shows dose coefficients for the inhalation of 5 μm AMAD particulates. Values of f_1 represent the fraction of a stable element reaching the body fluids following ingestion. Absorption types describe the rate

of absorption of a particular radionuclide into the various tissues and compartments of the Human Respiratory Tract Model (ICRP 1994). Absorption types are denoted as: (1) type F (fast) for materials that are readily absorbed into the blood, (2) type M (moderate) for materials with intermediate rates of absorption, and (3) type S (Slow) for relatively insoluble materials. Dose coefficients for air submersion, exposure to contaminated ground surface, and exposure to soil contaminated to an infinite depth are shown in Table 5 for ^{61}Fe. The coefficients are for a soil at a density of 1.6×10^3 kg m^{-3}. Because of the large amount of data associated with the results of this effort, the dose coefficients for the remaining thirteen radionuclides are posted on the ORNL Center for Biokinetic and Dosimetric Research website at http://ordose.ornl.gov/ for the adult worker and members or the public. Table 6 and Table 7 show the committed effective dose per unit intake (e_{50}) and the effective dose per unit time-integrated exposure to a radionuclide (e_{ext}) from an external exposure of an adult worker for all fourteen radionuclides, respectively.

CONCLUSIONS

The 72 radionuclides identified as lacking a published dose coefficient value with a half-life value greater than or equal to one minute were successfully evaluated using the interdatabase comparison methodology developed as part of this study. This methodology emphasized the need to quantify the accuracy of the input data relative to the available physics data prior to performing dose coefficient computations.

Internal and external dose coefficient values were calculated for 14 anthropogenic radionuclides which are not currently presented in Federal Guidance Reports No. 11, 12, and 13 or Publications 68 and 72 of the International Commission on Radiological Protection. Those radionuclides include: (1) ^{157}Er, (2) ^{160}Er, (3) ^{161m}Er, (4) ^{144}Eu, (5) ^{61}Fe, (6) ^{144}Gd, (7) ^{160m}Ho, (8)

^{128}La, (9) ^{153}Pm, (10) ^{201}Pt, (11) ^{113}Sb, (12) ^{161}Tm, (13) ^{173}W, and (14) ^{161}Yb. A detailed report of each of the fourteen radionuclides included in this work can be found on the ORNL Center for Biokinetic and Dosimetric Research website for the adult worker and members of the public. This report includes the committed equivalent dose to an organ or tissue per unit intake ($h_{T,50}$), the committed effective dose per unit intake (e_{50}), the tissue dose equivalent per unit time-integrated exposure to a radionuclide ($h_{T,ext}$) from external exposure, and the effective dose per unit time-integrated exposure to a radionuclide (e_{ext}) from external exposure.

Six of the values reported require further investigation because of discrepancies of energy balance data. Those radionuclides include: (1) ^{160}Er, (2) ^{161m}Er, (3) ^{201}Pt, (4) ^{161}Tm, (5) ^{173}W, and (6) ^{161}Yb. It should also be noted that both internal and external dose coefficient values are reported for three radionuclides whose half-life values are less than one minute. Those radionuclides include: (1) ^{144}Eu, (2) ^{161m}Er, and (3) ^{161m}Ho. Despite the fact that the applicability of compartment modeling for such short-lived radionuclides requires further investigation; external dose coefficient for these nuclides could be utilized in evaluating a dose to an individual.

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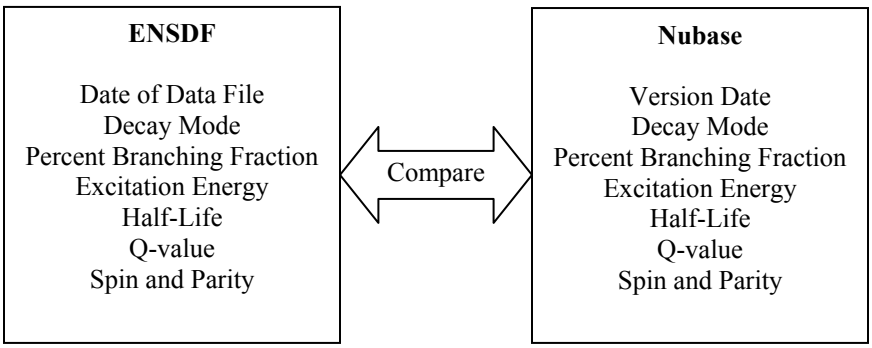
Figure Captions

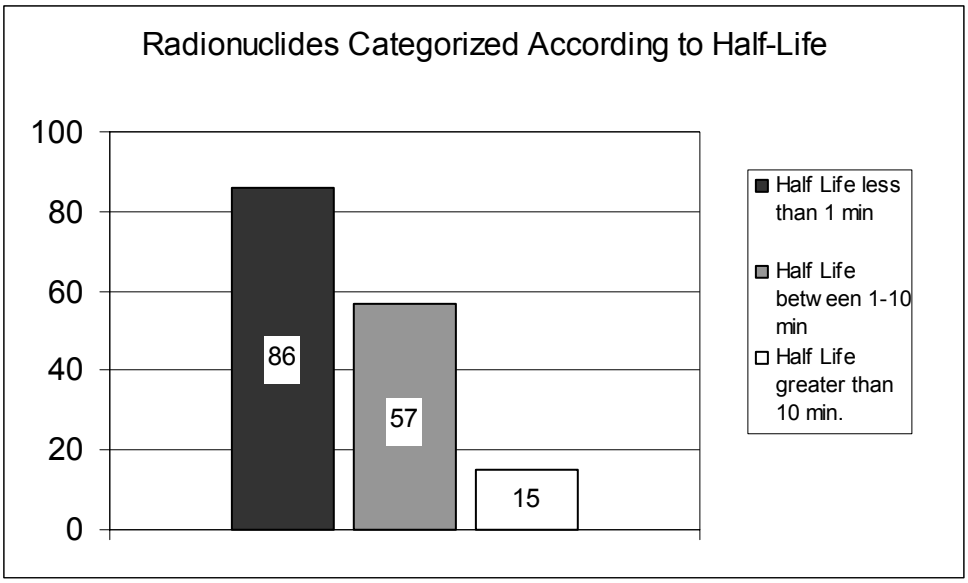
Figure 1. Nuclear structure and decay parameters crossed referenced between ENSDF and Nubase. ENSDF data files showing good agreement between the databases will be utilized in a dose coefficient calculation.

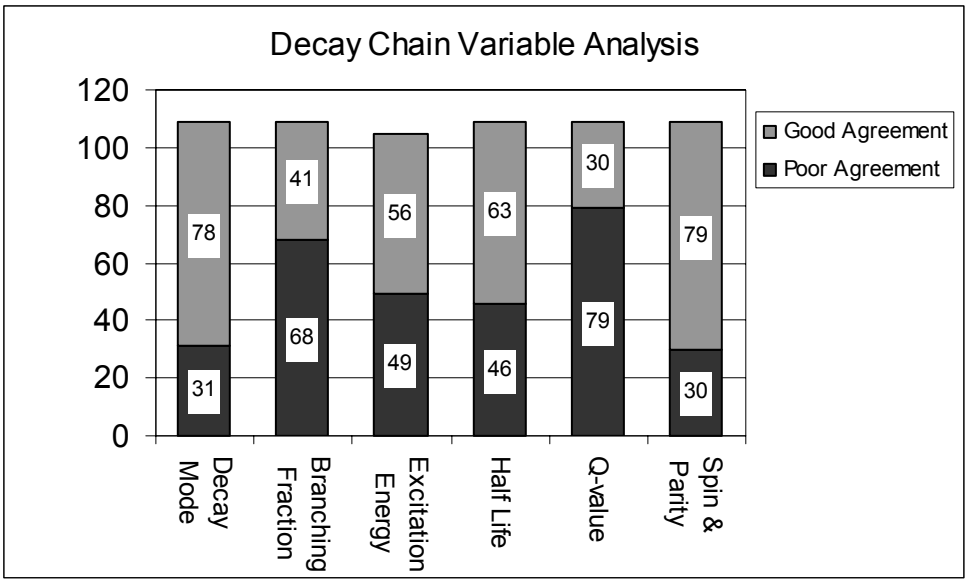
Figure 2. Radionuclides identified as lacking a published dose coefficient according to a query of existing radiation safety dose coefficient databases. Seventy two radionuclides with a half-life of greater than or equal to one minute were selected for a dose coefficient evaluation as part of this study.

Figure 3. Tabulated radionuclidic results for each of the variables evaluated in this work after being crossed-referenced and scored.

Figure 4. Categorical scoring summary for the 72 radionuclides identified as lacking a published dose coefficient.


ENSDF
Date of Data File
Decay Mode
Percent Branching Fraction
Excitation Energy
Half-Life
Q-value
Spin and Parity
Compare
Nubase
Version Date
Decay Mode
Percent Branching Fraction
Excitation Energy
Half-Life
Q-value
Spin and Parity


Radionuclides Categorized According to Half-Life
100
80
60
40
20
0
86
57
15
Half Life less than 1 min
Half Life betw een 1-10 min
Half Life greater than 10 min.


Decay Chain Variable Analysis
120
100
80
60
40
20
0
78
31
41
68
56
49
63
46
30
79
79
30
Good Agreement
Poor Agreement
Decay Mode
Branching Fraction
Excitation Energy
Half Life
Q-value
Spin & Parity

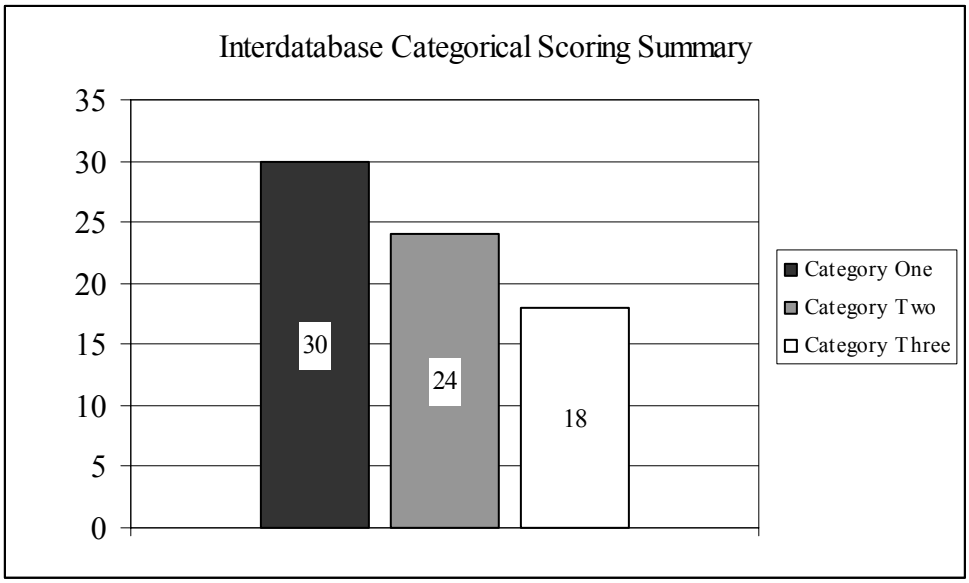

Interdatabase Categorical Scoring Summary
35
30
25
20
15
10
5
0
30
24
18
Category One
Category Two
Category Three

Table 1. Category one radionuclides.

Radionuclide	Radionuclide	Radionuclide
^{157}Er	^{178}Os	^{193}Tl
^{160}Er	^{195}Pb	^{157}Tm
^{61}Fe	^{153}Pm	^{160}Tm
^{144}Gd	^{133}Pr	^{161}Tm
^{171}Hf	^{201}Pt	^{171}W
^{197}Ir	^{176}Re	^{172}W
^{127}La	^{113}Sb	^{173}W
^{128}La	^{167}Ta	^{174}W
^{168}Lu	^{171}Ta	^{119}Xe
^{176}Os	^{192}Tl	^{161}Yb

Table 2. The percent error results for the EDISTR total energy balance data.

Chain	Radionuclide	Energy Balance Data (Percent Error)
^{157}Er	^{157}Er	2.36
	^{157}Ho	1.51
	^{157m}Dy	2.67
	^{157}Dy	1.42
	^{157}Tb	0.00
^{160}Er	^{160}Er	6.82
	^{160m}Ho	0.33
	^{160}Ho	0.16
^{61}Fe	^{61}Fe	3.07
	^{61}Co	0.00
^{144}Gd	^{144}Gd	0.11
	^{144}Eu	0.00
^{128}La	^{128}La	3.30
	^{128}Ba	0.01
	^{128}Cs	0.00
^{153}Pm	^{153}Pm	0.99
	^{153}Sm	0.13
^{201}Pt	^{201}Pt	44.64
	^{201}Au	0.19
^{113}Sb	^{113}Sb	0.77
	^{113m}Sn	0.21
	^{113}Sn	0.43
	^{113m}In	0.00
^{161}Tm	^{161}Tm	22.77
	^{161}mEr	69.48
	^{161}Er	3.48
	^{161m}Ho	0.00
	^{161}Ho	0.08
^{173}W	^{173}W	8.54
	^{173}Ta	0.09
	^{173}Hf	0.15
	^{173}Lu	0.33
^{161}Yb	^{161}Yb	0.51
	^{161}Tm	22.77
	^{161m}Er	69.48
	^{161}Er	3.48
	^{161m}Ho	0.00
	^{161}Ho	0.08

Table 3. Internal dose coefficients for the adult worker 1.0 μm particles (AMAD).

Nuclide: ^{61}Fe Physical Half-life: 5.98 m

Adult Worker

Committed Equivalent Dose Coefficients (Sv/Bq)

	Inhalation			Ingestion
	Type F	Type M	Type S	
f_1	1.0×10^{-01}	1.0×10^{-01}	1.0×10^{-01}	1.0×10^{-01}
Adrenals	5.00×10^{-13}	3.10×10^{-13}	2.89×10^{-13}	1.28×10^{-12}
Bladder Wall	3.37×10^{-13}	6.99×10^{-14}	4.04×10^{-14}	3.26×10^{-13}
Bone Surfaces	1.81×10^{-12}	4.54×10^{-13}	3.05×10^{-13}	4.87×10^{-13}
Brain	4.84×10^{-13}	2.68×10^{-13}	2.44×10^{-13}	2.26×10^{-14}
Breast	4.49×10^{-13}	2.90×10^{-13}	2.72×10^{-13}	3.55×10^{-13}
GI-Tract				
St Wall	1.32×10^{-11}	1.86×10^{-11}	1.92×10^{-11}	2.04×10^{-10}
SI Wall	3.46×10^{-12}	5.40×10^{-12}	5.61×10^{-12}	3.79×10^{-11}
ULI Wall	2.56×10^{-12}	4.12×10^{-12}	4.29×10^{-12}	2.35×10^{-11}
LLI Wall	9.08×10^{-13}	1.12×10^{-12}	1.15×10^{-12}	6.27×10^{-12}
Kidneys	4.23×10^{-13}	2.06×10^{-13}	1.82×10^{-13}	1.26×10^{-12}
Liver	8.81×10^{-13}	2.99×10^{-13}	2.35×10^{-13}	7.97×10^{-13}
Resp. Tract				
ET Region	1.60×10^{-10}	2.06×10^{-10}	2.11×10^{-10}	5.42×10^{-14}
Lung	1.32×10^{-11}	2.99×10^{-11}	3.18×10^{-11}	5.32×10^{-13}
Muscle	5.14×10^{-13}	3.18×10^{-13}	2.97×10^{-13}	5.58×10^{-13}
Ovaries	3.91×10^{-13}	1.61×10^{-13}	1.35×10^{-13}	1.10×10^{-12}
Pancreas	6.83×10^{-13}	5.60×10^{-13}	5.46×10^{-13}	4.85×10^{-12}
Red Marrow	3.05×10^{-12}	5.87×10^{-13}	3.15×10^{-13}	8.08×10^{-13}
Skin	3.72×10^{-13}	1.67×10^{-13}	1.45×10^{-13}	2.47×10^{-13}
Spleen	5.61×10^{-13}	4.08×10^{-13}	3.92×10^{-13}	3.02×10^{-12}
Testes	2.86×10^{-13}	3.94×10^{-14}	1.23×10^{-14}	9.11×10^{-14}
Thymus	6.54×10^{-13}	5.04×10^{-13}	4.88×10^{-13}	2.75×10^{-13}
Thyroid	5.30×10^{-13}	3.23×10^{-13}	3.00×10^{-13}	5.42×10^{-14}
Uterus	3.75×10^{-13}	1.38×10^{-13}	1.12×10^{-13}	9.41×10^{-13}
Remainder	8.05×10^{-11}	1.03×10^{-10}	1.06×10^{-10}	1.35×10^{-12}

Committed Effective Dose Coefficients (Sv/Bq)

	Inhalation			Ingestion
	Type F	Type M	Type S	
f_1	1.0×10^{-01}	1.0×10^{-01}	1.0×10^{-01}	1.0×10^{-01}
Effective Dose	8.02×10^{-12}	1.15×10^{-11}	1.19×10^{-11}	2.69×10^{-11}

Table 4. Internal dose coefficients for the adult worker of 5.0 μm particles (AMAD).

Nuclide: ^{61}Fe Physical Half-life: 5.98 m

Adult Worker

Committed Equivalent Dose Coefficients (Sv/Bq)

	Inhalation		
	Type F	Type M	Type S
f_1	1.0×10^{-01}	1.0×10^{-01}	1.0×10^{-01}
Adrenals	6.33×10^{-13}	3.76×10^{-13}	3.47×10^{-13}
Bladder Wall	4.36×10^{-13}	1.07×10^{-13}	7.14×10^{-14}
Bone Surfaces	2.30×10^{-12}	6.77×10^{-13}	4.99×10^{-13}
Brain	7.52×10^{-13}	4.94×10^{-13}	4.66×10^{-13}
Breast	5.59×10^{-13}	3.26×10^{-13}	3.01×10^{-13}
GI-Tract			
St Wall	2.47×10^{-11}	3.49×10^{-11}	3.61×10^{-11}
SI Wall	6.33×10^{-12}	1.01×10^{-11}	1.06×10^{-11}
ULI Wall	4.63×10^{-12}	7.72×10^{-12}	8.06×10^{-12}
LLI Wall	1.52×10^{-12}	2.09×10^{-12}	2.16×10^{-12}
Kidneys	5.67×10^{-13}	3.03×10^{-13}	2.73×10^{-13}
Liver	1.08×10^{-12}	3.51×10^{-13}	2.71×10^{-13}
Resp. Tract			
ET Region	3.09×10^{-10}	3.96×10^{-10}	4.05×10^{-10}
Lung	1.25×10^{-11}	2.83×10^{-11}	3.01×10^{-11}
Muscle	7.58×10^{-13}	5.17×10^{-13}	4.91×10^{-13}
Ovaries	5.38×10^{-13}	2.74×10^{-13}	2.44×10^{-13}
Pancreas	1.01×10^{-12}	9.01×10^{-13}	8.89×10^{-13}
Red Marrow	3.77×10^{-12}	8.22×10^{-13}	4.98×10^{-13}
Skin	5.18×10^{-13}	2.63×10^{-13}	2.35×10^{-13}
Spleen	7.88×10^{-13}	6.12×10^{-13}	5.93×10^{-13}
Testes	3.63×10^{-13}	5.48×10^{-14}	2.09×10^{-14}
Thymus	9.31×10^{-13}	7.16×10^{-13}	6.92×10^{-13}
Thyroid	7.91×10^{-13}	5.32×10^{-13}	5.03×10^{-13}
Uterus	5.11×10^{-13}	2.33×10^{-13}	2.02×10^{-13}
Remainder	1.55×10^{-10}	1.98×10^{-10}	2.03×10^{-10}

Committed Effective Dose Coefficients (Sv/Bq)

	Inhalation		
	Type F	Type M	Type S
f_1	1.0×10^{-01}	1.0×10^{-01}	1.0×10^{-01}
Effective Dose	1.34×10^{-11}	1.84×10^{-11}	1.90×10^{-11}

Table 5. External dose coefficients for ^{61}Fe.

	Air Submersion	Contaminated Ground Surface	Soil to an Infinite Depth
Units = Sv per Bq-s m^{-3}	Adult	Adult	Adult
Description	$h_{T,ext}$	$h_{T,ext}$	$h_{T,ext}$
Red Marrow	6.77×10^{-14}	1.29×10^{-15}	4.60×10^{-17}
Adrenals	5.74×10^{-14}	1.13×10^{-15}	4.10×10^{-17}
Bone Surface	1.02×10^{-13}	1.76×10^{-15}	6.67×10^{-17}
Brain	7.37×10^{-14}	1.19×10^{-15}	4.59×10^{-17}
Breasts	7.72×10^{-14}	1.30×10^{-15}	5.07×10^{-17}
GB Wall	5.77×10^{-14}	1.13×10^{-15}	4.05×10^{-17}
Esophagus	5.91×10^{-14}	1.09×10^{-15}	3.88×10^{-17}
St Wall	6.16×10^{-14}	1.21×10^{-15}	4.18×10^{-17}
SI Wall	5.67×10^{-14}	1.20×10^{-15}	3.96×10^{-17}
ULI Wall	5.82×10^{-14}	1.21×10^{-15}	4.04×10^{-17}
LLI Wall	5.76×10^{-14}	1.24×10^{-15}	4.05×10^{-17}
Ht Wall	6.14×10^{-14}	1.19×10^{-15}	4.15×10^{-17}
Kidneys	6.19×10^{-14}	1.23×10^{-15}	4.26×10^{-17}
Liver	6.25×10^{-14}	1.21×10^{-15}	4.24×10^{-17}
Lung	6.86×10^{-14}	1.26×10^{-15}	4.59×10^{-17}
Ovaries	5.86×10^{-14}	1.14×10^{-15}	3.99×10^{-17}
Pancreas	5.59×10^{-14}	1.13×10^{-15}	3.83×10^{-17}
Skin	1.58×10^{-13}	1.38×10^{-14}	6.86×10^{-17}
Spleen	6.27×10^{-14}	1.21×10^{-15}	4.27×10^{-17}
Testes	6.83×10^{-14}	1.36×10^{-15}	4.99×10^{-17}
Thymus	6.49×10^{-14}	1.17×10^{-15}	4.42×10^{-17}
Thyroid	7.03×10^{-14}	1.25×10^{-15}	4.29×10^{-17}
UB Wall	5.74×10^{-14}	1.23×10^{-15}	4.20×10^{-17}
Uterus	5.53×10^{-14}	1.18×10^{-15}	3.93×10^{-17}
Muscle	6.69×10^{-14}	1.36×10^{-15}	4.66×10^{-17}
h_remainder	2.08×10^{-12}	4.17×10^{-14}	1.44×10^{-15}
e_{ext}	1.67×10^{-13}	3.42×10^{-15}	1.15×10^{-16}

Table 6. Committed Effective Dose Coefficients per Unit Intake, e_{50} , for the Adult Worker (Sv/Bq).

Nuclide	AMAD	f_1	type F	type M	type S	Ingestion
^{157}Er	1 μm	5.0×10^{-04}	9.84×10^{-12}	1.55×10^{-11}	1.61×10^{-11}	2.72×10^{-11}
	5 μm	5.0×10^{-04}	1.72×10^{-11}	2.53×10^{-11}	2.62×10^{-11}	2.72×10^{-11}
^{160}Er	1 μm	5.0×10^{-04}	2.85×10^{-10}	5.12×10^{-10}	5.38×10^{-10}	7.81×10^{-10}
	5 μm	5.0×10^{-04}	4.94×10^{-10}	7.24×10^{-10}	7.51×10^{-10}	7.81×10^{-10}
^{161m}Er	1 μm	5.0×10^{-04}	5.11×10^{-18}	5.12×10^{-18}	5.12×10^{-18}	4.50×10^{-18}
	5 μm	5.0×10^{-04}	8.37×10^{-18}	8.39×10^{-18}	8.39×10^{-18}	4.50×10^{-18}
^{144}Eu	1 μm	5.0×10^{-04}	2.60×10^{-13}	2.64×10^{-13}	2.64×10^{-13}	1.22×10^{-12}
	5 μm	5.0×10^{-04}	4.00×10^{-13}	4.04×10^{-13}	4.05×10^{-13}	1.22×10^{-12}
^{61}Fe	1 μm	1.0×10^{-01}	8.02×10^{-12}	1.15×10^{-11}	1.19×10^{-11}	2.69×10^{-11}
	5 μm	1.0×10^{-01}	1.34×10^{-11}	1.84×10^{-11}	1.90×10^{-11}	2.69×10^{-11}
^{144}Gd	1 μm	5.0×10^{-04}	6.37×10^{-12}	7.94×10^{-12}	8.11×10^{-12}	3.00×10^{-11}
	5 μm	5.0×10^{-04}	1.02×10^{-11}	1.25×10^{-11}	1.28×10^{-11}	3.00×10^{-11}
^{160m}Ho	1 μm	5.0×10^{-04}	1.36×10^{-10}	2.21×10^{-10}	2.31×10^{-10}	3.45×10^{-10}
	5 μm	5.0×10^{-04}	2.48×10^{-10}	3.48×10^{-10}	3.59×10^{-10}	3.45×10^{-10}
^{128}La	1 μm	5.0×10^{-04}	8.42×10^{-12}	1.12×10^{-11}	1.15×10^{-11}	2.87×10^{-11}
	5 μm	5.0×10^{-04}	1.42×10^{-11}	1.79×10^{-11}	1.83×10^{-11}	2.87×10^{-11}
^{153}Pm	1 μm	5.0×10^{-04}	4.77×10^{-12}	7.07×10^{-12}	7.33×10^{-12}	1.23×10^{-11}
	5 μm	5.0×10^{-04}	7.94×10^{-12}	1.10×10^{-11}	1.14×10^{-11}	1.23×10^{-11}
^{201}Pt	1 μm	1.0×10^{-02}	3.11×10^{-12}	4.33×10^{-12}	4.47×10^{-12}	7.59×10^{-12}
	5 μm	1.0×10^{-02}	5.22×10^{-12}	7.09×10^{-12}	7.29×10^{-12}	7.59×10^{-12}
^{113}Sb	1 μm	1.0×10^{-02}	5.62×10^{-12}	7.41×10^{-12}	7.65×10^{-12}	1.68×10^{-11}
	5 μm	1.0×10^{-02}	9.54×10^{-12}	1.22×10^{-11}	1.26×10^{-11}	1.68×10^{-11}
^{161}Tm	1 μm	5.0×10^{-04}	1.40×10^{-11}	2.16×10^{-11}	2.25×10^{-11}	2.99×10^{-11}
	5 μm	5.0×10^{-04}	2.53×10^{-11}	3.54×10^{-11}	3.65×10^{-11}	2.99×10^{-11}
^{173}W	1 μm	3.0×10^{-01}	1.05×10^{-11}	1.53×10^{-11}	1.58×10^{-11}	1.62×10^{-11}
	5 μm	3.0×10^{-01}	1.79×10^{-11}	2.48×10^{-11}	2.56×10^{-11}	1.62×10^{-11}
^{161}Yb	1 μm	5.0×10^{-04}	4.70×10^{-12}	6.38×10^{-12}	6.56×10^{-12}	1.17×10^{-11}
	5 μm	5.0×10^{-04}	8.18×10^{-12}	1.06×10^{-11}	1.08×10^{-11}	1.17×10^{-11}

Table 7. Effective Dose per Unit Time-Integrated Exposure, e_{ext} , for an Adult (Sv per Bq s m^{-3}).

Nuclide	Air Submersion	Ground Surface	Soil to an Infinite Depth
^{157}Er	6.98×10^{-14}	1.58×10^{-15}	4.44×10^{-17}
^{160}Er	2.28×10^{-15}	8.33×10^{-17}	5.70×10^{-19}
^{161m}Er	1.42×10^{-12}	3.77×10^{-14}	6.28×10^{-16}
^{144}Eu	1.26×10^{-13}	1.04×10^{-15}	8.38×10^{-17}
^{61}Fe	1.67×10^{-13}	3.42×10^{-15}	1.15×10^{-16}
^{144}Gd	5.46×10^{-14}	1.04×10^{-15}	3.72×10^{-17}
^{160m}Ho	2.14×10^{-13}	4.34×10^{-15}	1.45×10^{-16}
^{128}La	3.25×10^{-13}	6.94×10^{-15}	2.18×10^{-16}
^{153}Pm	7.75×10^{-15}	2.55×10^{-16}	3.72×10^{-18}
^{201}Pt	4.40×10^{-16}	6.82×10^{-17}	6.23×10^{-20}
^{113}Sb	1.43×10^{-13}	3.18×10^{-15}	9.43×10^{-17}
^{161}Tm	1.33×10^{-13}	2.68×10^{-15}	8.71×10^{-17}
^{173}W	1.13×10^{-13}	2.58×10^{-15}	6.96×10^{-17}
^{161}Yb	1.21×10^{-13}	2.70×10^{-15}	7.88×10^{-17}