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Practical Use of Whisper During the Performance of a Criticality Safety Evaluation

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1. INTRODUCTION

The purpose of this paper is to present the results of a comparison study of the utilization of a traditionally derived upper subcritical limit (USL) versus an upper subcritical limit derived from the usage of the nuclear data sensitivity/uncertainty-based Whisper method. Further, results from a process-specific criticality safety evaluation are utilized to probe the advantages and challenges of utilizing Whisper (v. 1.1).

For Department of Energy (DOE) facilities, operations with fissionable material shall be determined to remain subcritical under both normal and credible abnormal conditions. One technical practice by which a criticality safety practitioner can satisfy this process analysis requirement is to set limits derived from calculations performed by a method shown by comparison with experimental data to be valid. This validation is typically performed and documented as part of a labor intensive expert-based effort, and is typically performed only as major upgrades to hardware, software, codes, and/or data force the effort. However, there are advanced quantitative calculational techniques, collectively known as Sensitivity/Uncertainty-based methods, by which nuclear criticality safety validation studies may be performed by floor-level criticality safety practitioners during the routine development of a documented criticality safety evaluation.

This has the immediate benefit of allowing the floor-level criticality safety practitioner to utilize the most current hardware, software, codes, or data as the practitioner's organization is able to obtain them. For example, in 2014 the Nuclear Criticality Safety (NCS) Division at Los Alamos National Laboratory (LANL) had been using an outdated version of MCNP (i.e., MCNP5-1.25) with nuclear data libraries that were decades old (i.e., ENDF/B V, ENDF/B VI). At that time, a validation study utilizing Whisper (v. 1.0) code was performed that allowed the Division to update to MCNP6.1 and EDNDF/B-VII.1 nuclear data, the most current at the time [Ref. 1]. A traditional validation study using a non-parametric technique was also developed to support the determination of an appropriate upper-subcritical limit for routine fissionable material operations involving plutonium metal, oxides, and solutions [Ref. 2].

Since that time, Whisper has since been revised for portability, robustness, and user requested features including the simplification of set-up and usage, and is available as version 1.1 [Ref. 3].

2. VALIDATION TECHNIQUES

2.1 Traditional Method Utilized

The Nuclear Criticality Safety Division of Los Alamos National Laboratory has a documented validation report for MCNP6 Version 1.0, on the High-Performance Computing (HPC) platform Moonlight, for operations at Los Alamos National Laboratory (LANL) that involve plutonium metals, oxides, and solutions [Ref. 2]. The validation was conducted using the ENDF/B-VII.1 continuous energy group cross-section library at room temperature (293.6 K). Nuclear criticality safety personnel may use the results during the evaluation of various facility activities involving plutonium materials. The benchmark critical experiments are modeled as reported in the International Criticality Safety Benchmark Experiment Handbook [Ref. 4].

The chosen benchmark critical experiments comprise 261 individual cases, including 68 plutonium metal cases, 35 plutonium oxide cases, and 158 plutonium nitrate solution cases. These benchmarks were chosen to encompass the range of normal and credible abnormal conditions anticipated for systems or processes to which this validation would be applied. The benchmarks were chosen to cover a wide variety of plutonium forms (e.g., Pu metal, PuO_2, $Pu(NO_3)_4$), moderation, homogeneity or heterogeneity, ^{240}Pu content, spectra, and geometry.

A summary of the area of applicability derived from the entire evaluated benchmark critical experiment set is provided in Table 1. For fissionable material configurations outside this area of applicability, an additional margin of subcriticality may be warranted.

Table 1 Area of Applicability

Parameter	Area of Applicability
Fissionable Material	^{239}Pu
Fissionable Material Form	Pu Metal, PuO_2, and $Pu(NO_3)_4$
$H/^{239}Pu$	$0 \leq H/^{239}Pu \leq 2807$
Average Neutron Energy Causing Fission (MeV)	$0.003 \leq ANECF \leq 1.935$
^{240}Pu	0 to 42.9 wt% ^{240}Pu
Moderating Materials	none, water, graphite, polystyrene
Reflecting Materials	none, water, steel, oil, Plexiglas, polyethylene, graphite, W, Cu, U, Th, Al, Ni, Fe, Pb, Cd, Mo, Be, BeO
Other Materials	concrete, PVC, Ga, B, Gd, Ta
Geometry	cylinder array, cylinder, slab, sphere, hemisphere, stacked discs, cuboid, annular

2.1.1 USL Determination

Based on the failure of the data to pass normality tests, including a visual inspection of the results, it was concluded that the set of benchmark critical experiment data utilized for the LANL validation report could not be confirmed to come from a normal distribution. Therefore, a non-normal distribution technique (taken from NUREG/CR-6698) was used to determine the USL. [Ref. 5]

The traditional USL is calculated using the lowest calculated k_{normal} and σ_t from the benchmark evaluation (PU-MET-FAST-039-001):

$$\text{USL} = \text{Smallest } k_{normal} \text{ value in the data set} - \sigma_t - \text{NPM} - \text{MoS} - \text{AoA}$$

$$= 0.9922 - 0.0022 - 0.0 - \text{MoS} - \text{AoA}$$

$$= 0.9900 - \text{MoS} - \text{AoA}$$

Here, NPM is 0 due to the large data set, and an additional Margin of Subcriticality (MoS) of 0.02 is prescribed for the traditional computations performed in support of criticality safety evaluations performed for the LANL NCSD [Ref. 6]. Due to the process models of this report being well within the area of applicability listed in Table 1, an AoA of zero is judged appropriate for this report.

Therefore,

$$\text{USL} = 1.0 - 0.01 - 0.02 - 0 = 0.97$$

2.2 Whisper Method Utilized

Whisper is a computational application designed to assist an analyst with validation studies performed using MCNP. Whisper uses sensitivity/uncertainty (S/U) methods to select relevant benchmarks to a particular process model. Using the selected benchmarks, Whisper computes a calculational margin from an extreme value distribution. This calculational margin may then be used to set a baseline upper subcritical limit, which can be assured to be subcritical [Ref. 7].

Whisper is a controlled software application developed and managed by personnel of the MCNP development team [Ref. 8]. The MCNP development team has made Whisper v. 1.1 available on the Moonlight High Performance Computing platform [Ref. 9]. The computations are conducted using the ENDF/B-VII.1 continuous energy group cross-section library at room temperature (293.6 K). The benchmark critical experiments are modeled as reported in the International Criticality Safety Benchmark Experiment Handbook [Ref. 4].

The set of selected benchmark critical experiments for each process model comprise cases that are most similar, from a neutronic perspective, to the process model (i.e., modeled condition), so each set will be different for each process model.

2.2.1 USL Determination

The USL as determined from a validation using Whisper is calculated as follows:

$$\text{USL} = 1 - [\text{CM} + \text{MOS}_{\text{data}} + \text{MOS}_{\text{software}}] - \text{MOS}_{\text{application}}$$

With regards to $\text{MOS}_{\text{software}}$, MCNP code developers recommend (and is set as default in Whisper) a value of 0.0005. [Ref. 7]. The terms CM and MOS_{data} are computed via the Whisper methodology, and presented to the analyst such that a baseline USL is established for each process model. This baseline USL is the upper subcritical limit below which the analyst can be confident that the model for the application is actually subcritical; at least subcritical by a margin that covers the uncertainties due to nuclear data concerns and calculational technique concerns. There is still an additional margin of subcriticality ($\text{MOS}_{\text{application}}$) that an analyst may select to address any uncertainties in the process condition, manufacturing tolerances, etc.

Currently, there is no prescribed value for $\text{MOS}_{\text{application}}$ as there is with the traditional validation approach. Due to the inherent conservatisms build into the process models of this report (e.g., theoretical density ^{239}Pu, reduced ^{240}Pu content, contiguous water reflection – an $\mathrm{MOS}_{\mathrm{application}}$ of zero is judged appropriate.

3. PRACTICAL APPLICATION

3.1 Glovebox Operations

A well-characterized location is dedicated to the burning of metal and roasting of oxides. This location contains an air-cooled insulated resistance furnace (see Figure 1). The furnace insulation is a low iron content, fired kaolinite [Ref. 10]. The furnace may be sitting upon a tantalum safety tray. This furnace runs a defined temperature profile to convert fissionable material to oxide, as well as calcine oxide to meet customer specifications.

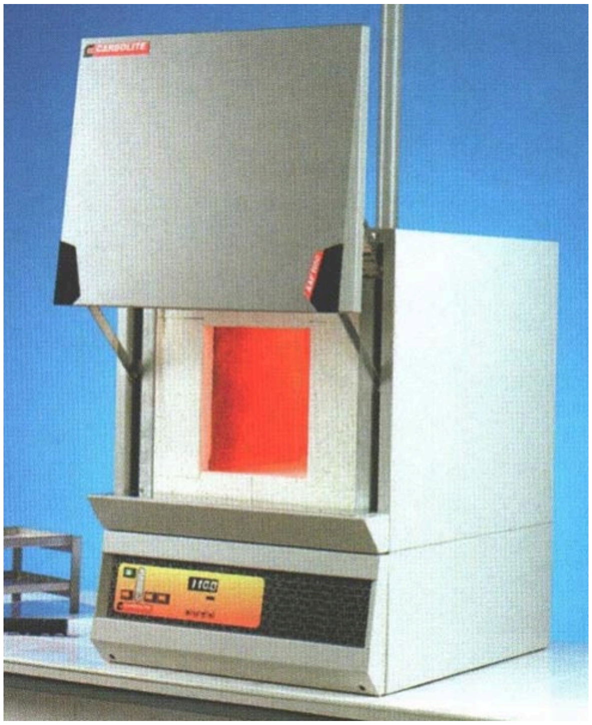

Figure 1. **Resistance Furnace**

3.2 Analysis

3.2.1 Evaluation Method

The computations were performed using MCNP6 v. 1.0 with ENDF/B-VII.1 continuous energy cross-section data on the Moonlight High Performance Computing platform. This is a verified and validated computational method and is approved for use [Refs. 2, 11].

Additional computations were performed using Whisper v. 1.1. Whisper is a controlled software application developed and managed by personnel of the MCNP development team [Ref. 8]. The MCNP development team has made Whisper v. 1.1 available to personnel of LANL NCS organization via the Moonlight High Performance Computing platform [Ref. 9].

For the interested reader, MCNP models and results are given in APPENDIX A.

4. Results

4.1 Comparison of Upper Subcritical Limits for Various Abnormal Conditions

Table 2 presents a side-by-side comparison of the upper subcritical limits from the different validation methodologies.

Table 2 – Comparison of Upper Subcritical Limits

Abnormal Condition	$K_{calc}+2\sigma$	LANL NCSD Validation	Whisper (v. 1.1) baseline USL, (# of BM[*])
Loss of Mass Control (5000-g in a furnace)	0.85977	0.97 (261 BM cases)	0.97888 (46 BM cases)
Loss of Spacing Control (4500-g in a furnace, 4500-kg)	0.8976	0.97 (261 BM cases)	0.97861 (41 BM cases)
Loss of Moderation Control (4500-g material ~3-g/cc)	0.62335	0.97 (261 BM cases)	0.96891 (124 BM cases)
Loss of Moderation Control (1500-g material ~0.25-g/cc)	0.78451	0.97 (261 BM cases)	0.97772 (57 BM cases)

[*] BM means benchmark critical experiment

Due to the degree of subcriticality of the modeled abnormal conditions, the difference between the two different USLs is of minimal practical importance. However, it is interesting to note the number of benchmark critical experiments necessary to support the baseline USL for each process model does vary.

4.2 Comparison of Neutron Spectra

Figure 2 and Table 3 present derived parameters by which the process models' neutron spectrums may be characterized.

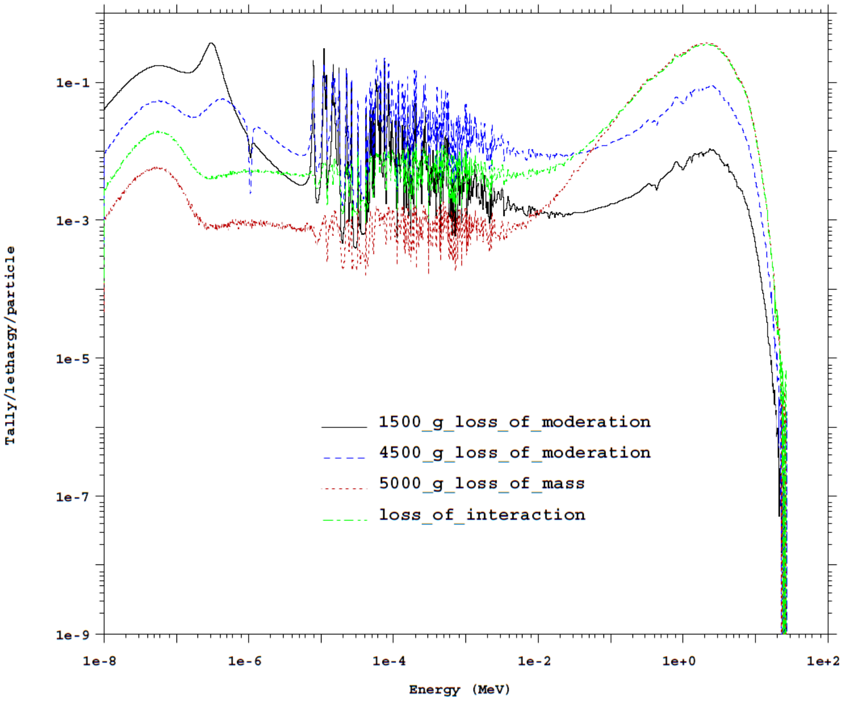

Figure 2. Lethargy profiles for the different abnormal process conditions.

Table 3 – Different Characteristics to Compare

Abnormal Condition	EANCF[1] (Mev)	EALCF[2] (MeV)	% of fissions[3]
Loss of Mass Control (5000-g in a furnace)	1.8524	0.87584	1.5, 3.1, 95.4
Loss of Spacing Control (4500-g in a furnace, 4500-kg)	1.6761	0.30195	4.9, 8.7, 86.4
Loss of Moderation Control (4500-g material ~3-g/cc)	0.54446	2.1822e-4	27.3, 44.0, 28.7
Loss of Moderation Control (1500-g material ~0.25-g/cc)	0.048917	3.2651e-7	82.7, 14.7, 2.6

[1] average neutron energy causing fission.
[2] energy corresponding to the average neutron lethargy causing fission.
[1] The percentages of fissions caused by neutrons in the thermal, intermediate, and fast neutron ranges.

The modeled fast systems (i.e., loss of mass control, loss of spacing control), and modeled thermal system (i.e., loss of moderation control)) have neutronic properties that are readily understood (i.e., the modeled configurations containing copious amounts of water have a more thermal neutron spectrum, as compared to the modeled metal configurations).

4.3 Comparison of Selected Benchmarks

As seen in the results presented in APPENDIX B, both modeled fast systems (i.e., loss of mass control, loss of spacing control), and modeled slow systems (i.e., loss of moderation control, 1500-g, ~0.25-g/cc)) have neutronic properties more similar to models of benchmark critical experiments – hence fewer benchmark critical experiments are needed to satisfy the statistical tests of the Whisper validation technique. The modeled intermediate system (i.e., loss of moderation control, 4500-g, ~3-g/cc) requires more than twice as many benchmark critical experiments to satisfy the statistical tests of the Whisper method such as to obtain an appropriate baseline USL.

As can also be observed, there are sufficiently correlated benchmark critical experiments (as determined by examining the correlation factor (c_k) that Whisper computes for each benchmark critical experiment).

4.3.1 Loss of Mass Control (material in a furnace)

For the 'loss of mass control, (material in the furnace)', 5,000-g of plutonium metal is modeled within a ceramic material, sitting atop stainless steel, surrounded by water. Table 7 presents the benchmark cases Whisper determined are most similar.

As anticipated, models of benchmark critical experiments exhibiting fast neutron spectra of plutonium metal systems are readily selected by Whisper. An interesting note is the selection of the mixed systems. Upon study of these mixed system experiments, it becomes obvious why they were selected by Whisper. MIX-MET-FAST-007 is comprised of a set of experiments that used five distinct spherical masses of alpha-phase plutonium surrounded by varying thicknesses of highly enriched uranium and varying thicknesses of beryllium reflectors. MIX-MET-FAST-005 is a sphere of plutonium surrounded by highly enriched uranium and reflected by aluminum. MIX-MET-FAST-009 is of a δ-phase metal ^{239}Pu(98%) assembly with a 0.75-cm-thick external shell of ^{235}U(90%).

These mixed fissionable material systems may not have been otherwise selected for a validation of a fast plutonium metal system. In addition to this insight, fewer benchmark critical experiments are needed to demonstrate the modeled condition, from a neutronic perspective, is comfortably within the suite of benchmark critical experiment models.

4.3.2 Loss of Spacing Control (material in a furnace)

For the ‘loss of spacing control, (material in a furnace)’ 4,500-g of plutonium metal is modeled within a ceramic material, sitting atop stainless steel, surrounded by water. An additional 4,500-g of plutonium metal is modeled touching the outside of the ceramic material. Table 8 presents the benchmark cases Whisper determined are most similar.

As anticipated, models of benchmark critical experiments exhibiting fast neutron spectra of plutonium metal systems are readily selected by Whisper. Again, it is interesting to note the selection of the MIX-MET-FAST-009-001, MIX-MET-FAST-007-022, and MIX-MET-FAST-007-023 mixed systems.

4.3.3 Loss of Moderation Control (4,500-g Pu(2) material ~3-g/cc)

For the ‘loss of moderation control (4,500-g of Pu(2) material ~3-g/cc)’, 4,500 g of plutonium metal in a Pu-water solution at a concentration of 3 g/cc is modeled within a ceramic material, sitting atop stainless steel, surrounded by water. Table 9 presents the benchmark cases Whisper determined are most similar.

As anticipated, models of benchmark critical experiments exhibiting an ‘intermediate’ neutron spectra of plutonium oxide and solutions systems are readily selected by Whisper. And again, certain mixed systems were selected. The MIX-SOL-THERM-001 series of experiments were performed with mixed plutonium-uranium nitrate solution in annular cylindrical geometry. The ratio of plutonium to total heavy metal (plutonium plus uranium) was 0.22 or 0.97 for all experiments. All measurements were made with a water reflector. The central region of the annular tank could accommodate a concrete or polyethylene annular cylindrical insert. Interior to the inserts for most experiments was a stainless steel bottle containing an additional plutonium-uranium nitrate solution. MIX-SOL-THERM-003 is a critical experiment comprising of cylinders of plutonium and natural uranium nitrate solution that are reflected by water, except on the top face where the reflector was polyethylene. MIX-COMP-THERM-001 has nuclear characteristics similar to the process model under consideration, and it considers plutonium oxide-uranium oxide fuel pins containing 20 wt.% plutonium with light water moderation and reflection.

As is also anticipated, it requires considerably more benchmark critical experiments to satisfy the statistical requirements of the Whisper methodology. This is due to this modeled condition exhibiting an ‘intermediate’ neutron spectrum, for which there are fewer direct benchmark critical experiments.

4.3.4 Loss of Moderation Control (1,500-g Pu(2) material ~0.25-g/cc)

For the ‘loss of moderation control (1,500-g material ~0.25-g/cc)’, 1,500 g of plutonium metal in a Pu-water solution at a concentration of 0.25 g/cc is modeled within a ceramic material, sitting atop stainless steel, surrounded by water reflection. Table 10 presents the benchmark cases Whisper determined are most similar.

As anticipated, models of benchmark critical experiments exhibiting slow neutron spectra of plutonium solutions systems are readily selected by Whisper. Note, no oxide systems were selected. And again, certain mixed systems were selected.

4.4 Process Model Sensitivity Profiles

An additional benefit of utilizing Whisper is the ready availability of sensitivity profiles for each isotope of the modeled configuration to the overall system k. APPENDIX C presents sensitivity profiles based per reaction type that Whisper MCNP calculates for the different process conditions.

Of interest from the sensitivity profiles for each isotope for each reaction type for each process model is the sparseness of data. The elastic scatter, inelastic scatter, (n,gamma), (n,p), (n,alpha), and the various fission cross-section datasets have data from which to glean information. Different summations are presented (Figure 12 through Figure 19) to elucidate what this information may be. Figure 12 through Figure 15 shows the relative sensitivity of k to each isotope as a function of energy. Figure 16 through Figure 19 presents the relative sensitivity of k of each isotope.

This information could be useful in considering if the process model is within a traditional validation's area of applicability, or if additional margin of subcriticality is necessary due to the lack of nuclear data. From a practical criticality safety analysis perspective, these graphs could also be utilized to demonstrate modeling simplifications that could be made (and justified) if an isotope's significance is dwarfed by the other constituents of the process model.

4.5 Challenges

Some challenges of using the Whisper methodology were encountered. Though not a challenge for LANL personnel, it can easily be seen to be a challenge that an organization will necessarily need to have access to personnel with significant computer administrative expertise (e.g., network management, data/file management, etc.) available to install and maintain Whisper. In order to utilize Whisper, it is necessary to install the code, scripts, benchmarks, and related nuclear data. Sensitivity profiles must be generated for each modeled benchmark critical experiment to be made available when Whisper is executed in support of a production calculation. It was also very convenient to have the MCNP-Whisper code developer readily available to answer any questions, or address problems encountered during usage.

Another challenge easily encountered is the time requirements for performing calculations. More time (both wall clock as well as computational) is required to perform Whisper-MCNP computations. Table 1 presents the time required to perform the computations analyzed for the loss of mass control process models. ('Loss of moderation' configurations are not reported due to the different analytical approach taken in the original evaluation (i.e., critical parameter search, versus direct calculation of k_{eff}.).

Though not necessarily a level comparison, as indicated by the number of neutron histories, these numbers present the additional computational needs of Whisper since recommended/default values for various MCNP parameters were utilized for both the traditional as well as the Whisper components of this report.

Table 4 – Reported time for each Process model

Abnormal Condition	Utilizing Traditional USL (min) (# of n histories)	Utilizing Whisper Methodology (# of n histories)
Loss of Mass Control (5000-g in a furnace)	59.9 (2,001,126)	2956.17 (50,002,315)
Loss of Spacing Control (4500-g in a furnace, 4500-kg)	1097.04 (15,004,708)	3848.45 (50,001,734)

Finally, a significant challenge is in the utilization and communication of the results. As even the length of this paper indicates, Whisper-MCNP provides a plethora of information that can obscure and even confound what the basic safety story is even to be for a fissionable material operation under consideration. To elaborate, while documenting the information Whisper-MCNP provides, so much effort may be expended upon understanding the results of the S/U analysis, that understanding the margin of safety of the actual operation suffers.

Conclusion

As was anticipated, there are benefits as well as challenges of using Whisper. The immediate benefit of using Whisper is that the selected critical benchmark critical experiments utilized to establish a process-specific upper subcritical limit are readily known by the evaluation team. It was borne out that the automated Whisper-methodology selected benchmark critical experiments that were also selected by a seasoned NCS-expert. Additionally, Whisper selected certain models of benchmark critical experiments in the support of its recommended USL that would not have otherwise been selected. This should be explored further, in that multi-species fissionable material conditions could easily be validated with minimal effort. With regards to the use of sensitivity profiles, using Whisper-MCNP provided insight as to the relative significance of the various isotopes used in the process models.

The immediate challenge of using Whisper is that it does require additional computational resources (specifically hardware and time) to obtain a process-model specific upper subcritical limit and associated sensitivity profiles. An additional challenge is also that a typical criticality safety evaluation has a number process models, each one addressing a specific credible abnormal condition. Each of these process models would necessarily require a Whisper-MCNP calculation to explicitly demonstrate the necessary validation. This may prove problematic for parametric studies that purposefully transgress AoA regimes.

Whisper is beneficial in that a floor-level criticality safety practitioner can have reasonable assurance that the computational method chosen to demonstrate subcriticality is indeed valid without having to rely upon an expert-based opinion that may not be readily available.

5. References

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8 Artifact artf36407, *Whisper – Software for Sensitivity-Uncertainty-based Nuclear Criticality Safety Validation*, Los Alamos National Laboratory (2015).

9 /usr/projects/mcnp/ncs/WHISPER/bin/whisper_usl.pl, XCP-3 instance of Whisper, v. 1.1, accessed 2016-05-30.

10 **Material Safety Data Sheet,** *26-140, HR 140, RI26.*

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APPENDIX A. MCNP MODELS AND RESULTS

MCNP models, and keff results utilized in this document are provided in this Appendix. Materials are evaluated within the validation report(s). Simple geometries (e.g., sphere, slab, or cylinder) are used to construct the calculational models. For cylinder geometries, the height-to-diameter (H/D) of the fissionable material is varied such that the criticality safety margin is demonstrated for typical process containers.

At least 10,000 neutrons per cycle, and at least 200 active cycles were used for each reported result used when comparing against the traditionally derived USL. The convergence of the fission source was verified via Shannon entropy test and relevant statistical checks.

For comparisons against the USL derived by Whisper, the default neutrons per cycle (i.e., 100,000), and active cycles (i.e., 500) were used.

To assess the abnormal condition of the introduction of greater than the allowed amount of fissionable material in a glovebox environment, a model representing 5,000-g Pu(0) metal with a density of 19.85-g/cm^3 reflected by 1-in tight fitting water, 0.25-in stainless steel, and 4.5-in neutron shielding, sitting atop 0.25-in stainless steel is investigated, both in the glovebox environment as well as inside the furnace (modeled as 4-in and 5-in of insulating brick ceramic sitting atop a 0.5-in thick tantalum tray).

As shown in Figure 3 and Figure 4, MAGENTA is plutonium, BLUE is water, PINK is insulating brick (furnace model only), ORANGE is the tantalum safety tray (furnace model only), YELLOW is steel, and GREEN is neutron shielding. The modeled environment is judged bounding of credible neutron reflection conditions. Results for this condition are shown to remain subcritical.

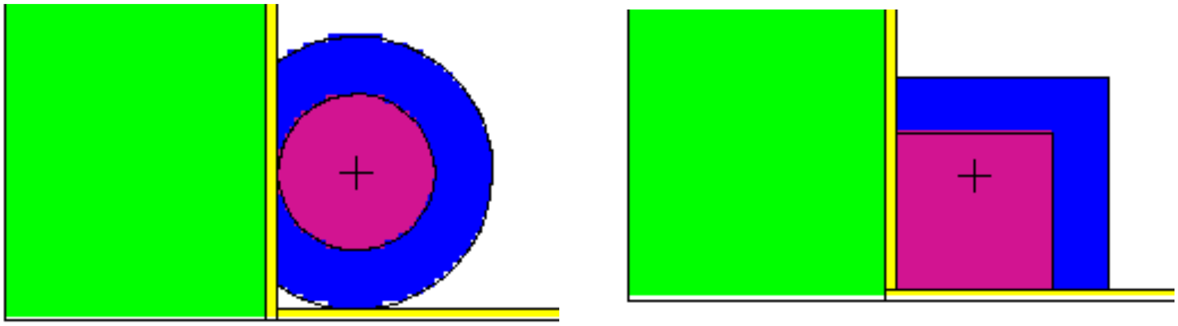

Figure 3. MCNP model for 5,000-g plutonium metal reflected by 1-in water in a glovebox.

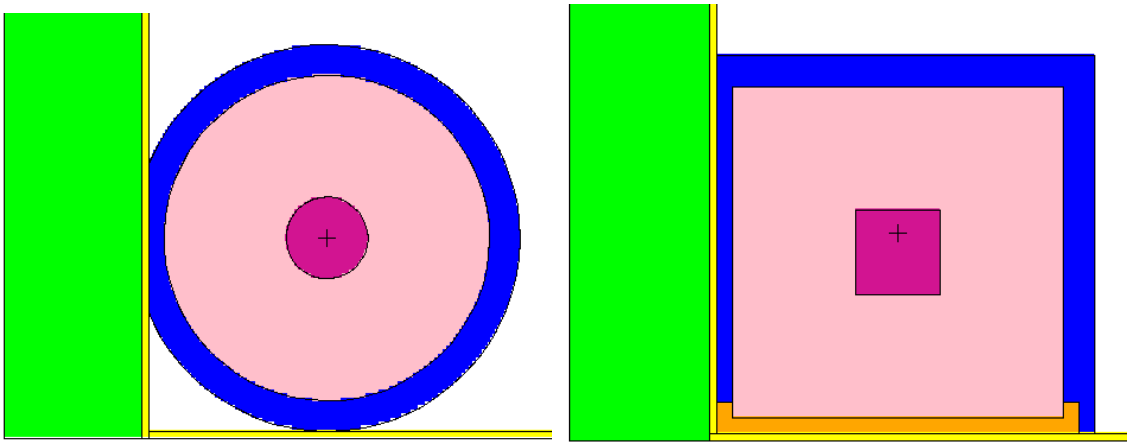

Figure 4. MCNP model for 5,000-g plutonium metal inside the furnace.

Table 5 Typical Result of MCNP Calculations for 5,000-g plutonium metal overmass.

Case ID	H/D Unit 1	H/D Unit 2	k_{calc}	σ	$k_{calc} + 2\sigma$
5000gPu.txt_5000_1.1_in_out	1.1	NA	0.89701	0.00049	0.89799
5000gPuInFurnaceInsulation.txt_4_5000_1_in_out	1.0	NA	0.85963	0.00014	0.85991

5.1.1 Introduction of additional unit

To assess the abnormal condition of an the introduction of an additional item while one is in the furnace, a model representing a 4,500-g plutonium metal unit with a density of 19.85-g/cm^3 surrounded by 4-in thick of insulating brick ceramic, reflected by 1-in tight fitting water, 0.25-in stainless steel, and 4.5-in neutron shielding, sitting atop a 0.5-in thick tantalum tray, and 0.25-in stainless steel is investigated and an additional 4,500-g plutonium metal unit.

As shown in, Figure 5, MAGENTA is plutonium, BLUE is water, PINK is insulating brick, ORANGE is the tantalum safety tray, YELLOW is steel, and GREEN is neutron shielding. The modeled environment is judged bounding of credible reflection conditions. Results are shown to remain subcritical.

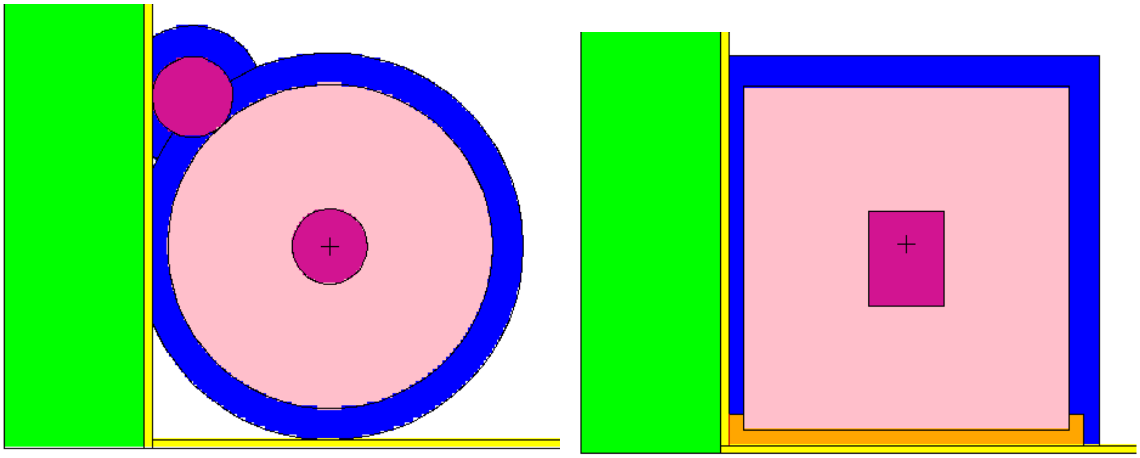

Figure 5. **MCNP model for 4,500-g plutonium metal in furnace, with another 4,500-g plutonium item in a glovebox.**

Table 6 Typical Result of MCNP Calculations for 4,500-g plutonium metal reflected by 4-in thickness of insulating brick in a glovebox.

Case ID	H/D Unit 1	H/D Unit 2	Thickness of insulating brick (in)	k_{calc}	σ	$k_{calc} + 2\sigma$
AddtlUnitNextToFurnaceInsulation.txt_4500_1.25_4500_4_1_in_out	1.25	1.0	4	0.89759	0.00017	0.89793

5.2 Loss of Moderation Control

5.2.1 Water accumulating with un-containerized fissionable material outside the furnace

To assess the abnormal condition of the event of glovebox flooding the following conditions are following assumptions apply,

- The lowest credible bulk density for a collection of small pieces of metal other than turnings is 0.15 times full metal density, ~3-g/cm^3.

- Fissionable material that could be present here under the allowance for plutonium in oxides, dry residues would have a plutonium concentration of over 0.8-g/cm^3 (and greater than 1-g/cm^3 in the case of oxides),

- Moderation upsets involving turnings and a non-violent water ingress could potentially result in a mechanically self-suspended matrix, resembling a metal-water pseudo-solution, with effective plutonium concentrations greater than 0.25-g/cm^3,

To examine the behavior of such a system, results from calculations of a Pu(2) metal-water pseudo-solution was modeled as a hemisphere atop a 0.25-inch thick layer of SS-304, which was directly atop a 6-inch thick layer of concrete. 30-in layer tight-fitting water modeled above the pseudo-solution.

The results of calculations (noted as the 'blue' line corresponding to the 'Mass (30-in water reflection)', with important points relevant to credible process conditions at this location included for ready comparison, is given here as Figure 7. [The 'pink line', corresponding to water saturated fissionable material inside 4.5-in ceramic material.]

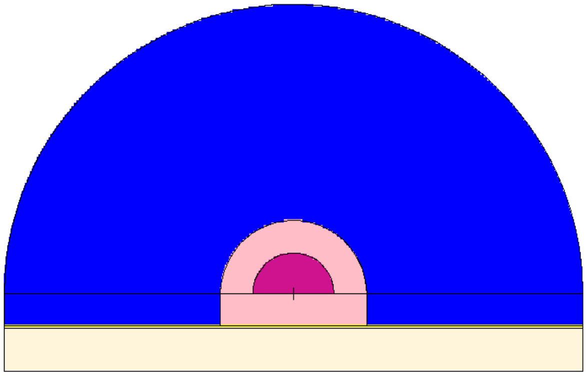

Figure 6. MCNP model for Pu(2) metal-water pseudo-solution. (Note: PINK material representing furnace insulation is not present for plutonium outside of the furnace.)

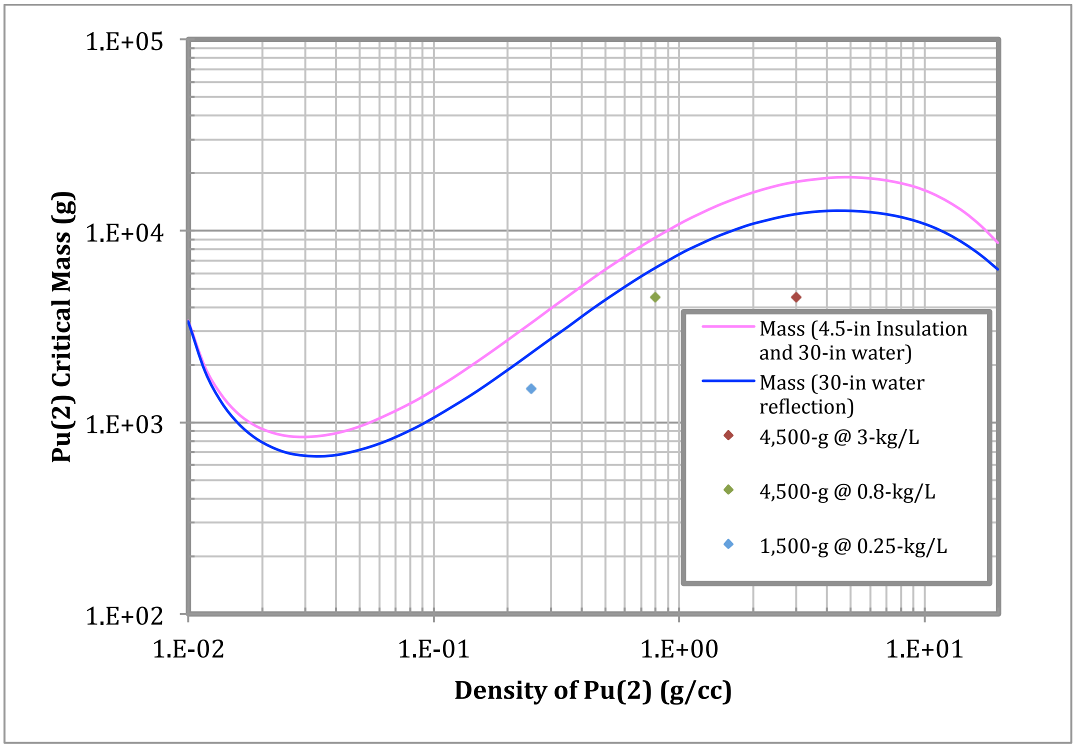

Figure 7. Results of Various Flooded Material Configurations.

APPENDIX B. Benchmark Critical Experiments Selected by Whisper

At the time of this report, there are ~1100 benchmark critical experiments available in the Whisper repository to be distributed with the MCNP code package. The Tables provided in this Appendix present the benchmark critical experiments Whisper determined to be most similar, from a neutronic perspective, to the stated process model. The correlation factor (c_k) and weight, both which are used for the Whisper methodology, are also presented.

Table 7 – Benchmark Models Selected for Loss of Mass Process Model

Benchmark	c_k	Weight
pu-met-fast-022-001*	0.9961	1
pu-met-fast-023-001*	0.9948	0.9621
pu-met-fast-039-001*	0.9947	0.9589
pu-met-fast-001-001*	0.9946	0.9586
pu-met-fast-036-001*	0.994	0.9396
mix-met-fast-009-001	0.9937	0.9302
pu-met-fast-024-001*	0.9933	0.92
pu-met-fast-035-001*	0.9925	0.8979
pu-met-fast-009-001*	0.9914	0.8644
pu-met-fast-025-001*	0.9907	0.8447
pu-met-fast-044-005*	0.9889	0.7925
pu-met-fast-021-002*	0.9888	0.7907
pu-met-fast-044-003*	0.9877	0.7569
pu-met-fast-029-001*	0.9876	0.7554
pu-met-fast-044-002*	0.9863	0.7177
pu-met-fast-030-001*	0.9861	0.7124
pu-met-fast-044-004*	0.986	0.7083
pu-met-fast-021-001*	0.9821	0.5961
pu-met-fast-011-001*	0.9815	0.5783
pu-met-fast-031-001*	0.9803	0.545
pu-met-fast-042-006*	0.9782	0.4837
pu-met-fast-042-007*	0.9778	0.4713
pu-met-fast-042-004*	0.9777	0.4702
pu-met-fast-042-009*	0.9775	0.4638
pu-met-fast-042-008*	0.9772	0.4542
pu-met-fast-042-012*	0.9771	0.4507
pu-met-fast-042-005*	0.977	0.4492
pu-met-fast-042-010*	0.9769	0.4467
pu-met-fast-042-011*	0.9768	0.4436
pu-met-fast-042-015*	0.9765	0.4357
pu-met-fast-042-003*	0.9765	0.4348
pu-met-fast-042-013*	0.9763	0.4298
pu-met-fast-042-014*	0.9762	0.4265
pu-met-fast-003-103*	0.9752	0.3972
mix-met-fast-007-022	0.9748	0.3861
pu-met-fast-042-002*	0.9745	0.3766
pu-met-fast-018-001*	0.9744	0.3751
mix-met-fast-007-023	0.9729	0.3303
pu-met-fast-044-001*	0.9726	0.3215
pu-met-fast-045-005*	0.9707	0.267
mix-met-fast-001-001*	0.97	0.2474
pu-met-fast-027-001*	0.9693	0.2266
pu-met-fast-042-001*	0.9683	0.1981
pu-met-fast-032-001*	0.9657	0.1226
pu-met-fast-008-001*	0.963	0.0435
mix-met-fast-005-001	0.9619	0.0123

[*] Denotes the benchmark is present in Reference 2.

Table 8 – Benchmark Models Selected for Loss of Spacing Process Model

Benchmark	c_k	Weight
pu-met-fast-036-001*	0.9955	1
pu-met-fast-024-001*	0.994	0.9515
pu-met-fast-044-005*	0.9937	0.9387
pu-met-fast-011-001*	0.9935	0.9342
pu-met-fast-044-004*	0.993	0.9146
pu-met-fast-044-003*	0.9904	0.8277
pu-met-fast-023-001*	0.9898	0.8049
pu-met-fast-039-001*	0.9892	0.7847
pu-met-fast-044-002*	0.9891	0.7814
pu-met-fast-022-001*	0.9886	0.7636
pu-met-fast-021-002*	0.9885	0.7621
pu-met-fast-042-004*	0.9878	0.739
pu-met-fast-031-001*	0.9878	0.7378
pu-met-fast-042-003*	0.9877	0.7333
pu-met-fast-042-002*	0.9875	0.7281
pu-met-fast-042-006*	0.9862	0.682
pu-met-fast-042-005*	0.9858	0.6704
pu-met-fast-001-001*	0.9858	0.6701
mix-met-fast-009-001	0.9857	0.665
pu-met-fast-035-001*	0.9856	0.6608
pu-met-fast-009-001*	0.9856	0.6608
pu-met-fast-042-007*	0.9853	0.6513
pu-met-fast-042-008*	0.9845	0.6248
pu-met-fast-042-001*	0.9841	0.6114
pu-met-fast-042-009*	0.9841	0.61
pu-met-fast-025-001*	0.9838	0.5989
pu-met-fast-042-010*	0.9836	0.5919
pu-met-fast-042-011*	0.9831	0.5769
pu-met-fast-027-001*	0.9831	0.5755
pu-met-fast-042-012*	0.9828	0.5647
pu-met-fast-042-013*	0.982	0.5394
pu-met-fast-042-014*	0.9819	0.5363
pu-met-fast-042-015*	0.9819	0.5336
pu-met-fast-021-001*	0.9794	0.4485
pu-met-fast-030-001*	0.9791	0.4388
pu-met-fast-029-001*	0.9777	0.3913
pu-met-fast-044-001*	0.975	0.2984
pu-met-fast-018-001*	0.9733	0.2388
mix-met-fast-007-022	0.9701	0.1291
pu-met-fast-045-005*	0.9687	0.0822
mix-met-fast-007-023	0.9664	0.0021

* Denotes the benchmark is present in Reference 2.

Table 9 – Benchmark Models Selected for Loss of Moderation Control (~3-g/cc) Process Model

Benchmark	c_k	Weight
pu-comp-mixed-002-006*	0.9495	1
pu-comp-mixed-002-007*	0.9464	0.9746
pu-comp-mixed-002-008*	0.9404	0.9268
pu-comp-mixed-001-002*	0.94	0.9234
pu-comp-mixed-001-003*	0.9388	0.9143
pu-comp-mixed-002-009*	0.9334	0.8713
pu-comp-mixed-001-004*	0.9324	0.8627
pu-comp-mixed-002-015*	0.9239	0.795
pu-comp-mixed-002-014*	0.9226	0.7847
pu-comp-mixed-002-013*	0.9224	0.7833
pu-comp-mixed-002-012*	0.9196	0.7603
pu-comp-mixed-002-016*	0.9188	0.754
pu-comp-mixed-002-020*	0.9149	0.7232
pu-comp-mixed-002-021*	0.9144	0.7187
pu-comp-mixed-002-011*	0.9137	0.7134
pu-comp-mixed-002-019*	0.9133	0.7103
pu-comp-mixed-002-018*	0.9117	0.6976
pu-comp-mixed-002-022*	0.9114	0.6946
pu-comp-mixed-002-010*	0.9065	0.6557
pu-comp-mixed-002-017*	0.8976	0.5843
pu-sol-therm-001-006*	0.8789	0.4346
pu-sol-therm-007-003*	0.8763	0.4141
pu-sol-therm-007-002*	0.8758	0.4098
pu-sol-therm-001-005*	0.8662	0.3332
pu-sol-therm-001-004*	0.8652	0.3253
pu-sol-therm-034-007*	0.8631	0.3082
pu-sol-therm-001-003*	0.863	0.308
pu-sol-therm-034-008*	0.8611	0.2923
pu-sol-therm-007-006*	0.8608	0.2903
pu-sol-therm-007-009*	0.8608	0.29
pu-sol-therm-007-008*	0.8606	0.2881
pu-sol-therm-007-007*	0.8605	0.2876
pu-sol-therm-007-010*	0.86	0.2837
pu-sol-therm-007-005*	0.8599	0.2828
pu-sol-therm-001-002*	0.8597	0.2815
pu-sol-therm-010-001*	0.8591	0.2764
pu-sol-therm-034-009*	0.8573	0.2618
pu-sol-therm-002-007*	0.8571	0.2604
pu-sol-therm-002-006*	0.8561	0.2528
pu-sol-therm-001-001*	0.8545	0.2394
pu-sol-therm-010-002*	0.8534	0.2305
pu-sol-therm-002-005*	0.8525	0.2238
mix-sol-therm-001-007	0.8518	0.2183
pu-sol-therm-034-010*	0.8515	0.2161
pu-sol-therm-002-004*	0.8515	0.2155
pu-sol-therm-010-009*	0.8504	0.2071
pu-sol-therm-002-003*	0.8501	0.2048
pu-sol-therm-034-001*	0.85	0.2037
mix-sol-therm-003-002	0.8493	0.1983
mix-sol-therm-003-001	0.8475	0.1841
pu-sol-therm-002-002*	0.8475	0.1839
pu-sol-therm-010-004*	0.8468	0.178
pu-sol-therm-011-165*	0.846	0.1719
pu-sol-therm-002-001*	0.8459	0.1705
pu-sol-therm-010-003*	0.8457	0.1691
mix-sol-therm-003-003	0.8452	0.1654
pu-sol-therm-010-010*	0.8447	0.161
pu-sol-therm-034-011*	0.8444	0.1592
pu-sol-therm-010-011*	0.8438	0.1543
pu-sol-therm-010-006*	0.8426	0.1448
pu-sol-therm-010-005*	0.8425	0.144
pu-sol-therm-003-006*	0.8422	0.1411
mix-sol-therm-001-008	0.8415	0.1358
pu-sol-therm-028-001*	0.8406	0.1285
pu-sol-therm-011-164*	0.8405	0.128
pu-comp-mixed-001-005*	0.8398	0.1223
mix-sol-therm-003-004	0.8398	0.1218
pu-sol-therm-011-163*	0.8397	0.1213
pu-sol-therm-010-012*	0.8396	0.1207
mix-comp-therm-001-002	0.8396	0.1206
pu-sol-therm-010-007*	0.8396	0.1203
pu-sol-therm-022-001*	0.8395	0.1195
pu-sol-therm-003-005*	0.8394	0.1188
pu-sol-therm-011-162*	0.8389	0.1147
pu-sol-therm-034-002*	0.8384	0.1107
pu-sol-therm-011-161*	0.838	0.1073

Benchmark	c_k	Weight
pu-sol-therm-004-011*	0.8378	0.1057
pu-sol-therm-005-007*	0.8377	0.1053
pu-sol-therm-003-004*	0.8369	0.0992
pu-sol-therm-003-008*	0.8365	0.0959
pu-sol-therm-028-002*	0.836	0.0917
pu-sol-therm-003-003*	0.836	0.0916
pu-sol-therm-032-001*	0.8354	0.0869
pu-sol-therm-034-012*	0.8354	0.0868
pu-sol-therm-005-006*	0.8352	0.0855
pu-sol-therm-003-007*	0.835	0.0837
mix-sol-therm-001-006	0.8349	0.0829
pu-sol-therm-003-002*	0.8346	0.0804
pu-sol-therm-003-001*	0.8337	0.0734
pu-comp-mixed-002-029*	0.8332	0.0692
pu-sol-therm-010-008*	0.8331	0.0688
pu-sol-therm-004-010*	0.8331	0.0686
pu-sol-therm-022-002*	0.833	0.0678
pu-sol-therm-010-013*	0.8329	0.0667
pu-sol-therm-005-005*	0.8321	0.0608
mix-comp-therm-001-001	0.8321	0.0601
pu-sol-therm-032-002*	0.8318	0.0584
pu-comp-mixed-002-028*	0.8317	0.0571
mix-comp-therm-001-003	0.8315	0.0555
pu-sol-therm-028-003*	0.8315	0.0554
mix-sol-therm-001-003	0.831	0.0518
pu-comp-mixed-002-027*	0.8303	0.0463
pu-sol-therm-005-004*	0.83	0.0434
pu-sol-therm-004-009*	0.8283	0.0301
pu-sol-therm-028-007*	0.8282	0.0292
pu-sol-therm-032-003*	0.8278	0.0259
pu-sol-therm-005-009*	0.8276	0.0248
pu-sol-therm-005-003*	0.8276	0.0244
pu-comp-mixed-002-025*	0.8275	0.024
pu-comp-mixed-002-024*	0.8274	0.023
pu-sol-therm-034-013*	0.8273	0.0219
pu-comp-mixed-002-026*	0.8268	0.0183
pu-sol-therm-004-008*	0.8268	0.0183
mix-sol-therm-001-009	0.8268	0.0182
pu-sol-therm-004-004*	0.8266	0.0168
pu-sol-therm-012-006*	0.8265	0.0156
pu-sol-therm-005-008*	0.826	0.0117
pu-sol-therm-004-007*	0.8258	0.0101
pu-sol-therm-004-012*	0.8254	0.0072
pu-sol-therm-005-002*	0.8253	0.0063
pu-sol-therm-010-014*	0.8253	0.0058
pu-sol-therm-004-003*	0.8252	0.0056
pu-sol-therm-004-013*	0.8251	0.0048
pu-sol-therm-005-001*	0.8248	0.0019

* Denotes the benchmark is present in Reference 2.

Table 10 – Benchmark Models Selected for Loss of Moderation Control (~0.25-g/cc) Process Model

Benchmark	c_k	Weight
pu-sol-therm-007-003*	0.9917	1
pu-sol-therm-007-002*	0.9904	0.9503
pu-sol-therm-001-006*	0.99	0.9318
pu-sol-therm-001-005*	0.9899	0.9308
pu-sol-therm-001-004*	0.9896	0.9173
pu-sol-therm-001-003*	0.9889	0.8893
pu-sol-therm-007-009*	0.9883	0.8675
pu-sol-therm-007-008*	0.9882	0.8644
pu-sol-therm-007-006*	0.9881	0.8592
pu-sol-therm-007-007*	0.988	0.8577
pu-sol-therm-007-010*	0.9877	0.8438
pu-sol-therm-007-005*	0.9875	0.8365
pu-sol-therm-001-002*	0.9874	0.8346
pu-sol-therm-010-001*	0.9869	0.8156
pu-sol-therm-002-007*	0.9856	0.7652
pu-sol-therm-002-006*	0.9848	0.7324
pu-sol-therm-001-001*	0.9841	0.7048
pu-sol-therm-010-002*	0.9829	0.6619
pu-sol-therm-002-005*	0.9823	0.6389
pu-sol-therm-002-004*	0.9813	0.5994
pu-sol-therm-010-009*	0.9811	0.5904
pu-sol-therm-002-003*	0.9806	0.5725
pu-sol-therm-002-002*	0.9781	0.4769
pu-sol-therm-010-004*	0.9775	0.4537
pu-sol-therm-011-165*	0.9775	0.4526
pu-sol-therm-002-001*	0.977	0.4322
pu-sol-therm-034-001*	0.9769	0.428
pu-sol-therm-010-003*	0.9768	0.425
mix-sol-therm-003-002	0.9761	0.3965
pu-sol-therm-010-010*	0.9758	0.3877
pu-sol-therm-010-011*	0.9752	0.3629
mix-sol-therm-003-001*	0.9745	0.3376
pu-sol-therm-010-006*	0.9743	0.331
pu-sol-therm-010-005*	0.974	0.3161
pu-sol-therm-003-006*	0.9734	0.2946
pu-sol-therm-011-164*	0.973	0.2799
mix-sol-therm-003-003	0.9728	0.2712
pu-sol-therm-011-163*	0.9723	0.2512
pu-sol-therm-011-162*	0.9713	0.2155
pu-sol-therm-010-012*	0.9713	0.2142
pu-sol-therm-010-007*	0.9709	0.1984
pu-sol-therm-003-005*	0.9707	0.19
pu-sol-therm-028-001*	0.9706	0.1874
pu-sol-therm-011-161*	0.9706	0.1858
pu-sol-therm-004-011*	0.969	0.125
pu-sol-therm-003-004*	0.9688	0.1176
mix-sol-therm-001-008	0.9688	0.1171
mix-sol-therm-001-007	0.9688	0.116
pu-sol-therm-003-008*	0.9687	0.1144
pu-sol-therm-005-007*	0.9686	0.1097
pu-sol-therm-003-003*	0.968	0.0849
mix-sol-therm-003-004	0.9677	0.0741
pu-sol-therm-028-002*	0.9672	0.0545
pu-sol-therm-003-007*	0.9671	0.0517
pu-sol-therm-032-001*	0.9668	0.04
pu-sol-therm-005-006*	0.9668	0.0388
pu-sol-therm-003-002*	0.9665	0.0307

* Denotes the benchmark is present in Reference 2.

APPENDIX C. Sensitivity Information as Provided by Whisper-MCNP

Sensitivity profiles, and various summations of the sensitivity profiles are provided in this Appendix.

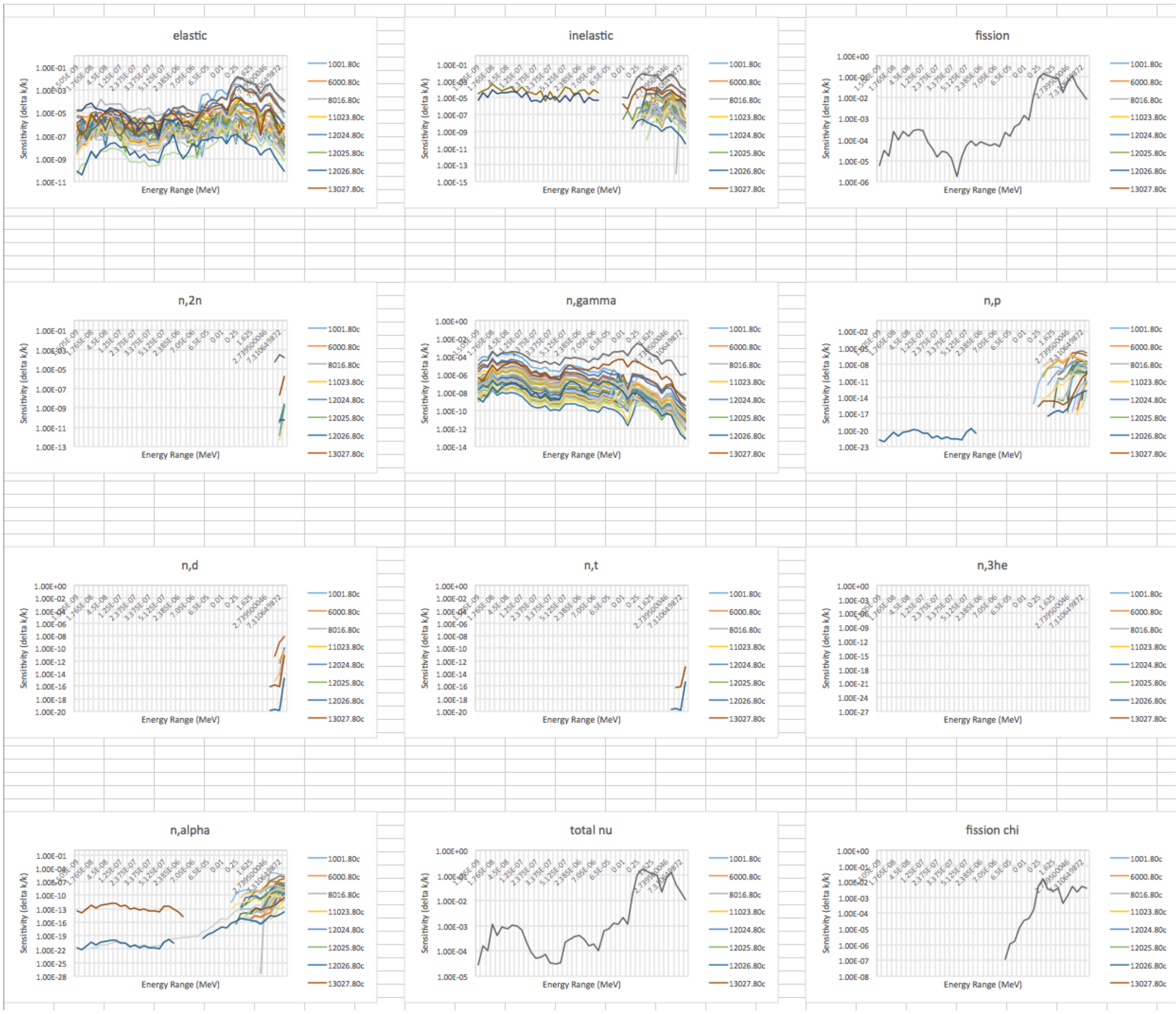

Figure 8. Sensitivity profiles for each isotope for each reaction type for the loss of mass condition.

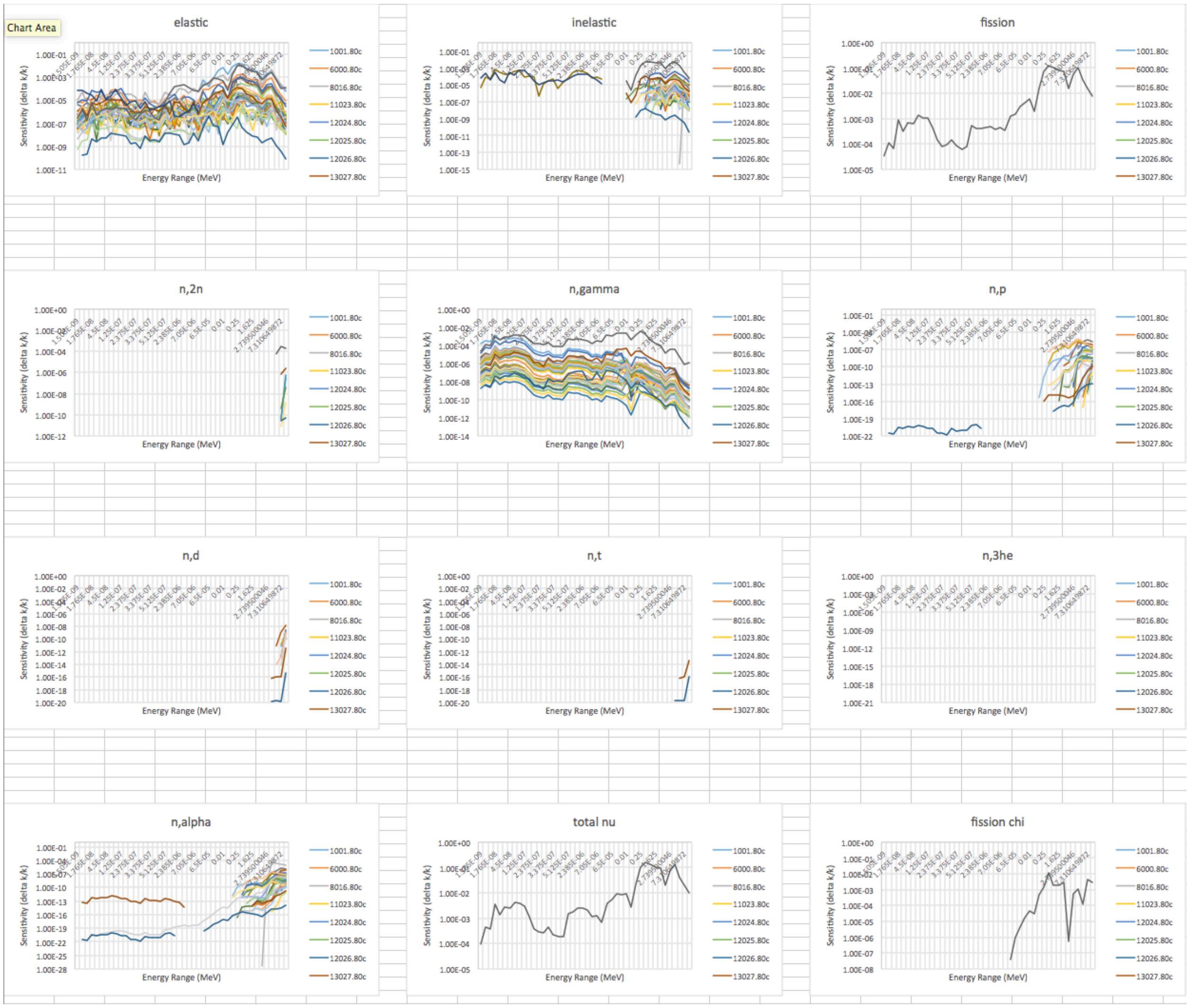
Chart Area

elastic

inelastic

fission

n,2n

n,gamma

n,p

n,d

n,t

n,3he

n,alpha

total nu

fission chi

Figure 9. **Sensitivity profiles for each isotope for each reaction type for the loss of spacing condition.**

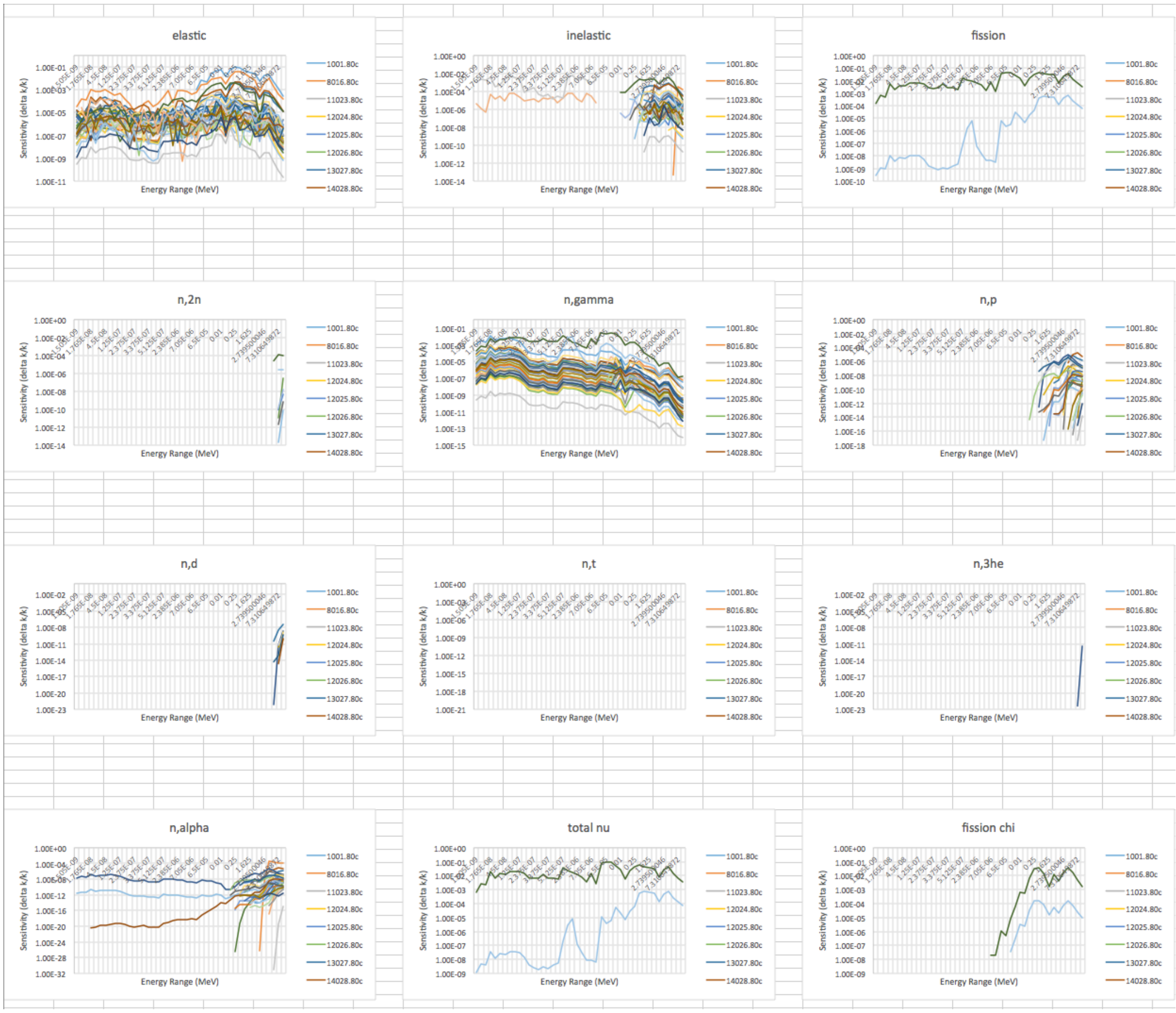

Figure 10. Sensitivity profiles for each isotope for each reaction type for the loss of moderation control of 4,500-g Pu(2).

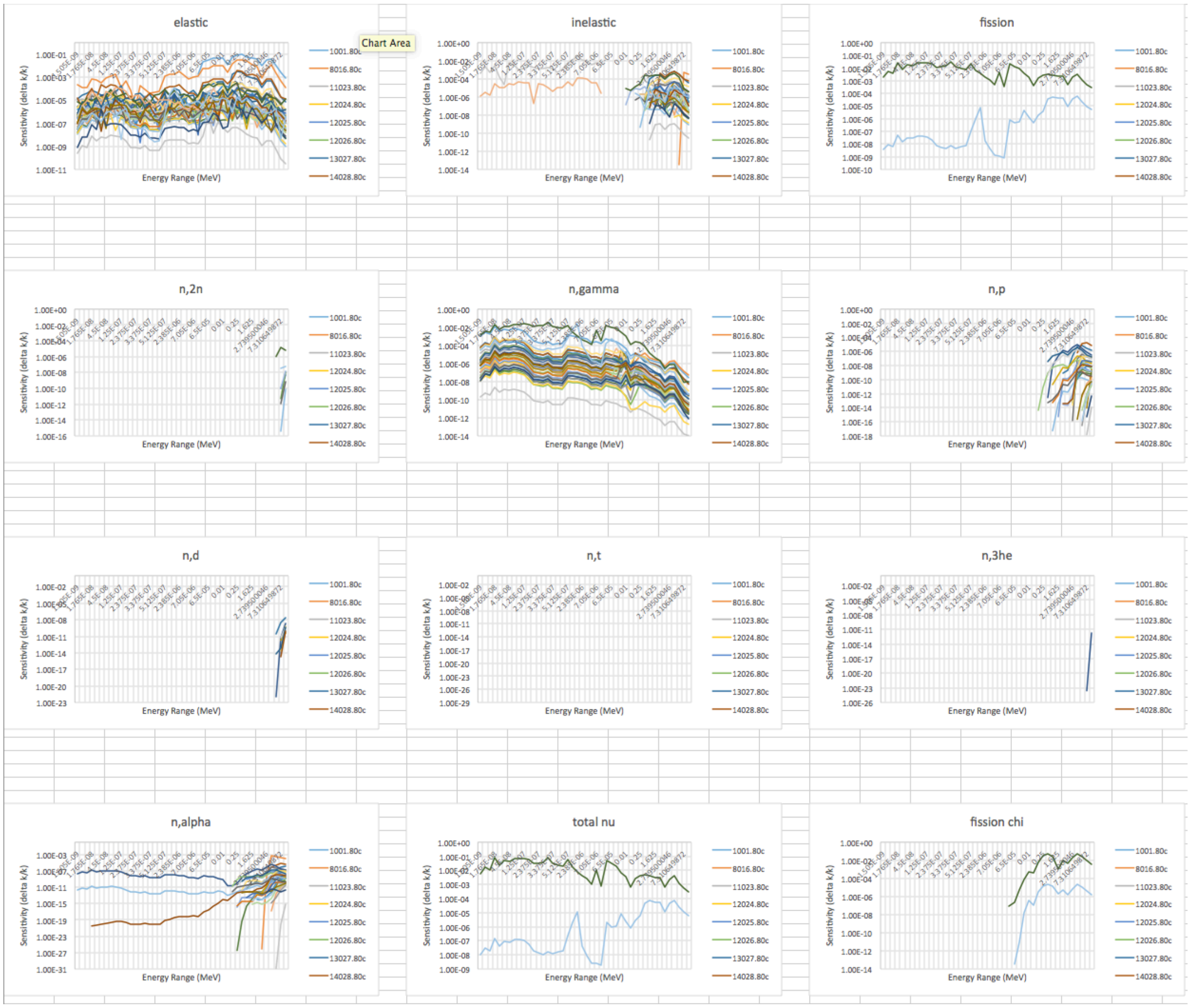

Figure 11. Sensitivity profiles for each isotope for each reaction type for the loss of moderation control of 1,500-g Pu(2).

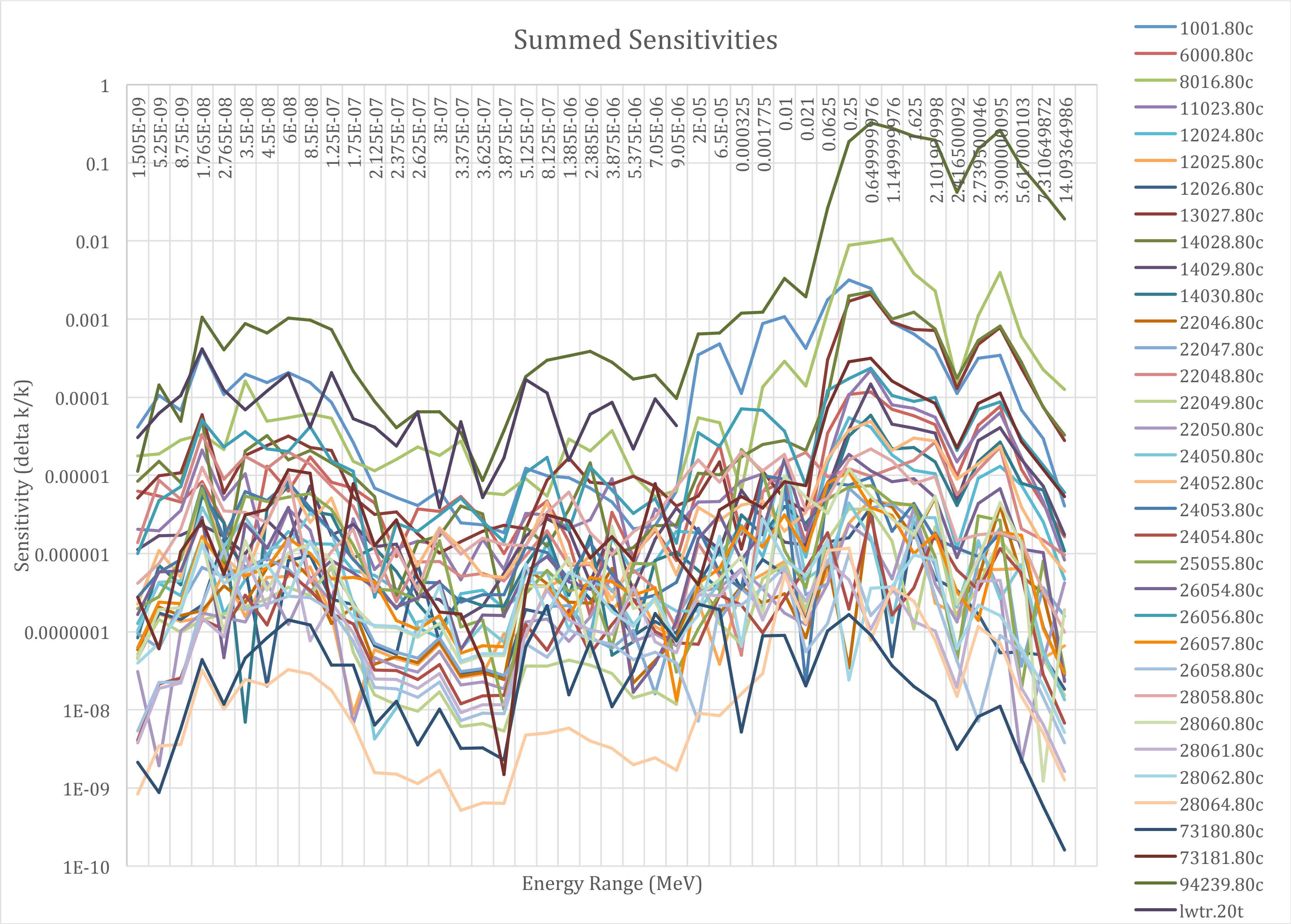

Figure 12. Summed sensitivity profiles for each isotope for the loss of mass control of 5,000-g plutonium.

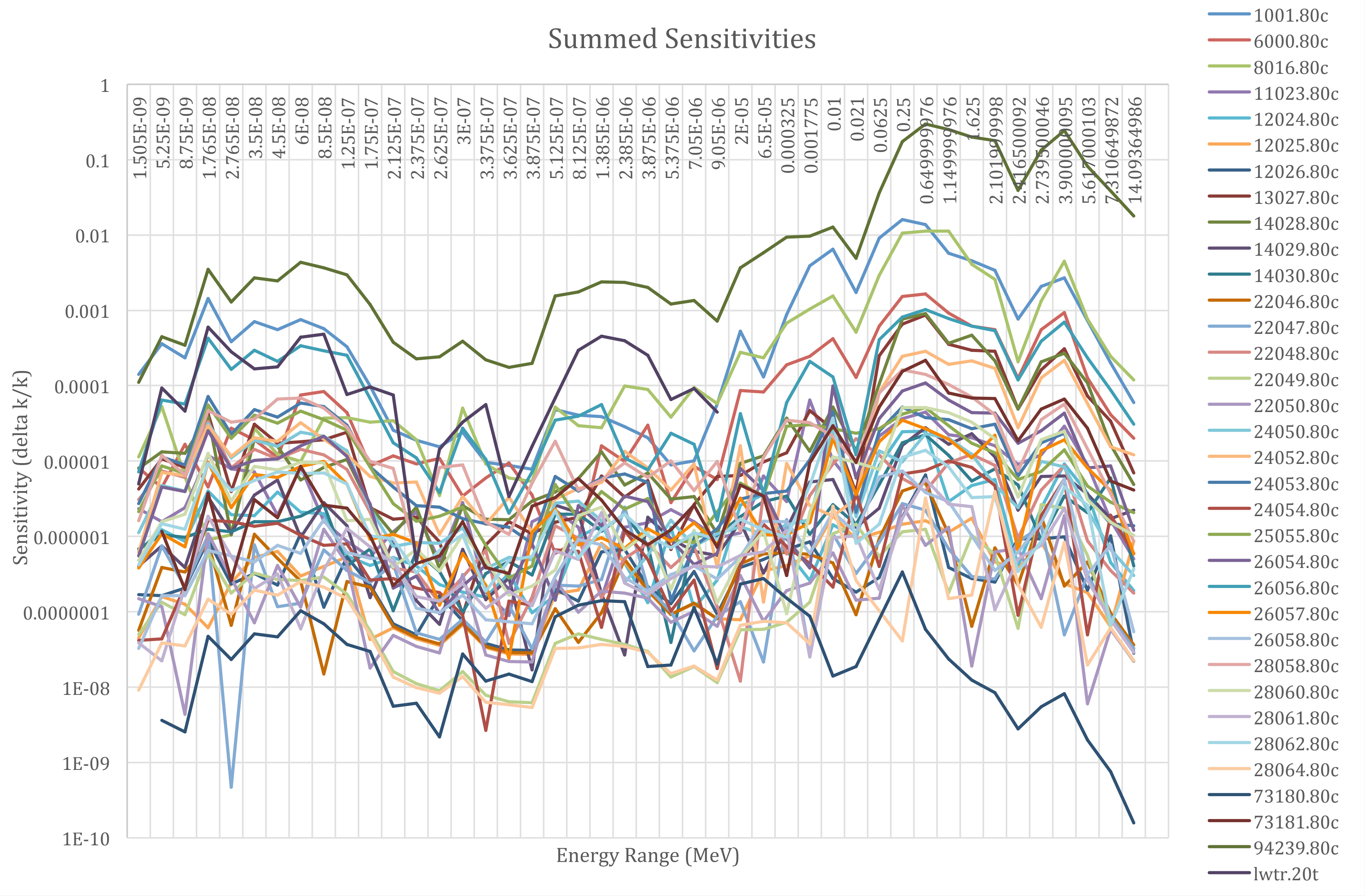

Figure 13. **Summed sensitivity profiles for each isotope for the loss of spacing control.**

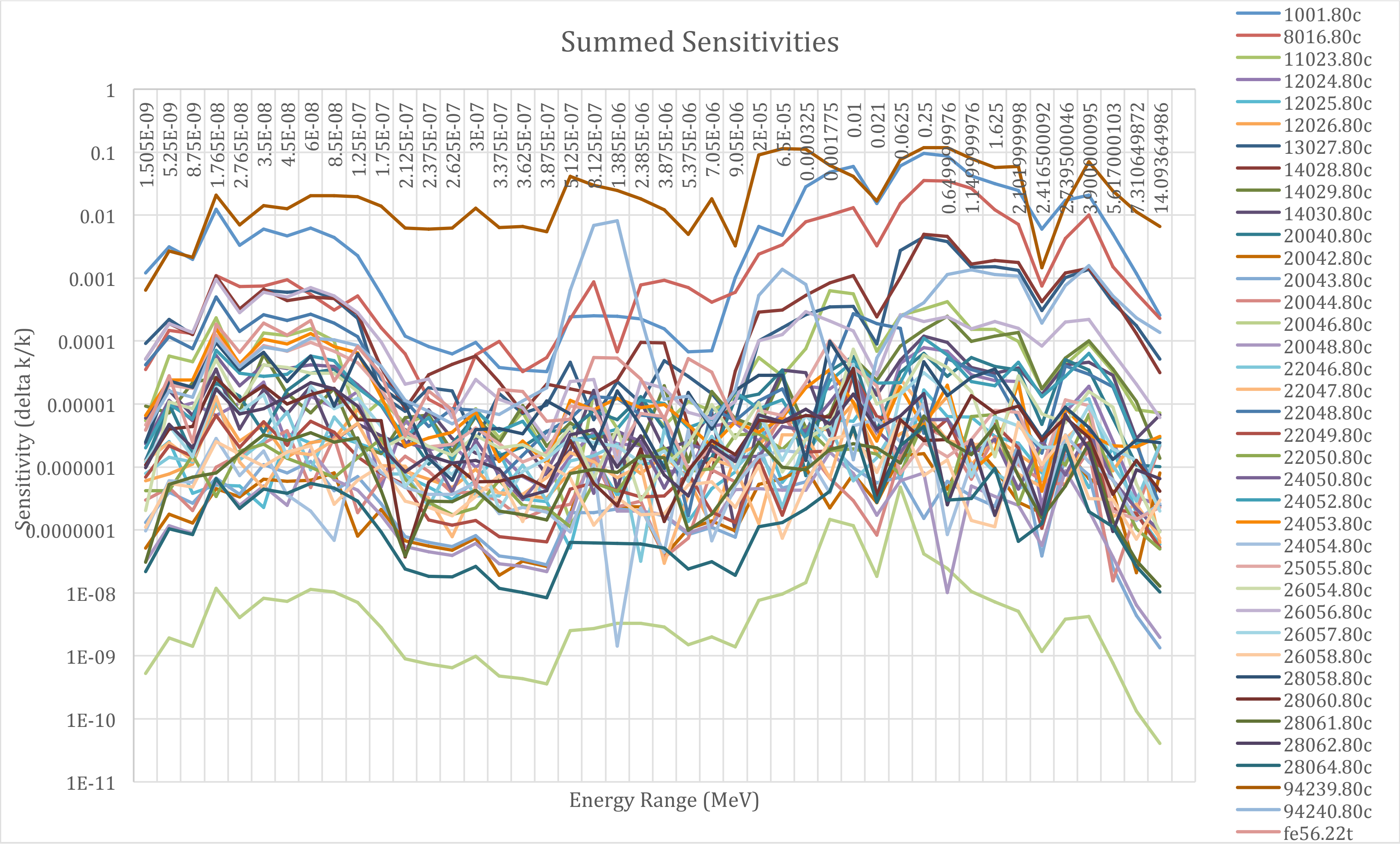

Figure 14. **Summed sensitivity profiles for each isotope for the loss of moderation control of 4,500-g Pu(2).**

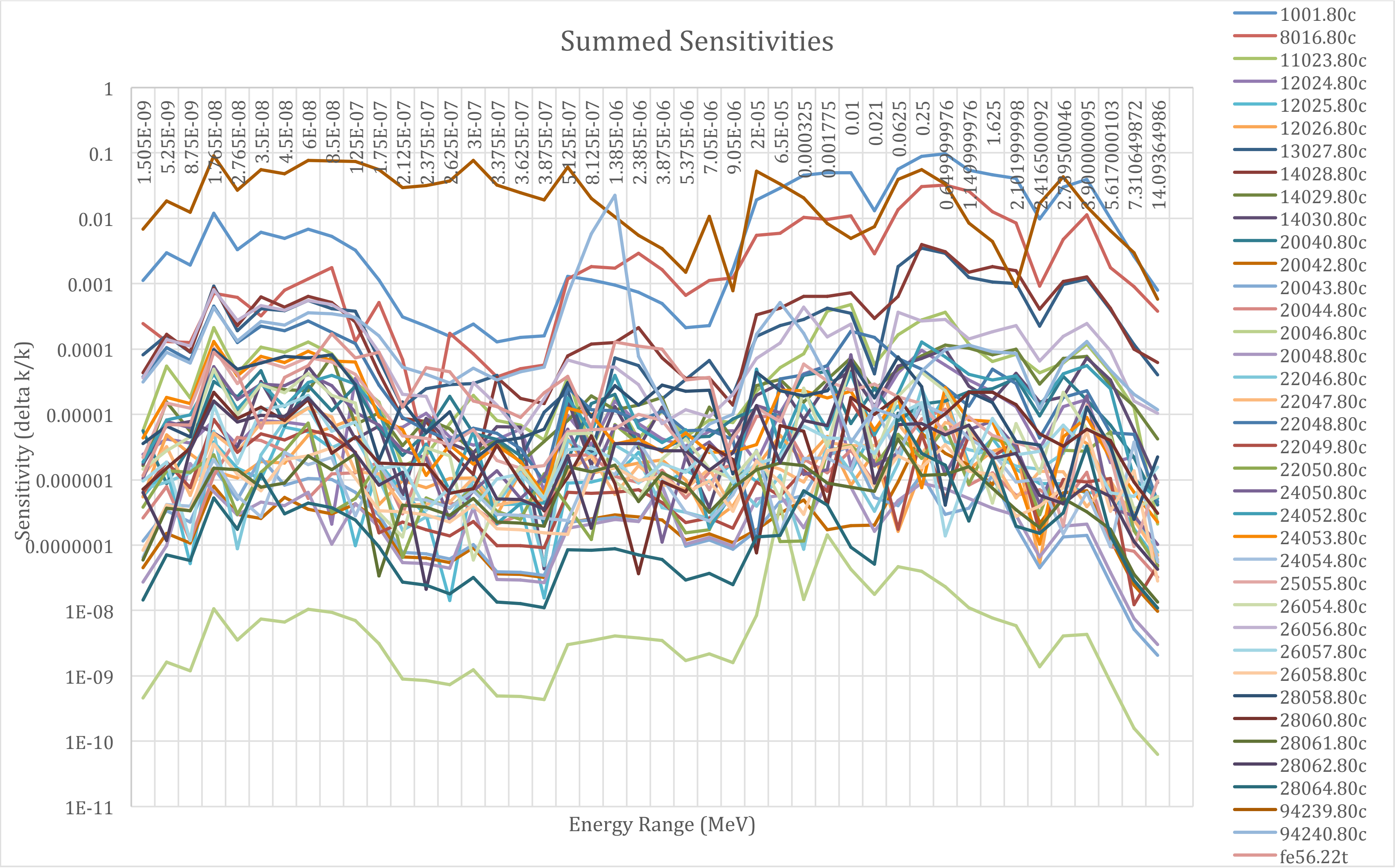

Figure 15. Summed sensitivity profiles for each isotope for the loss of moderation control of 1,500-g Pu(2).

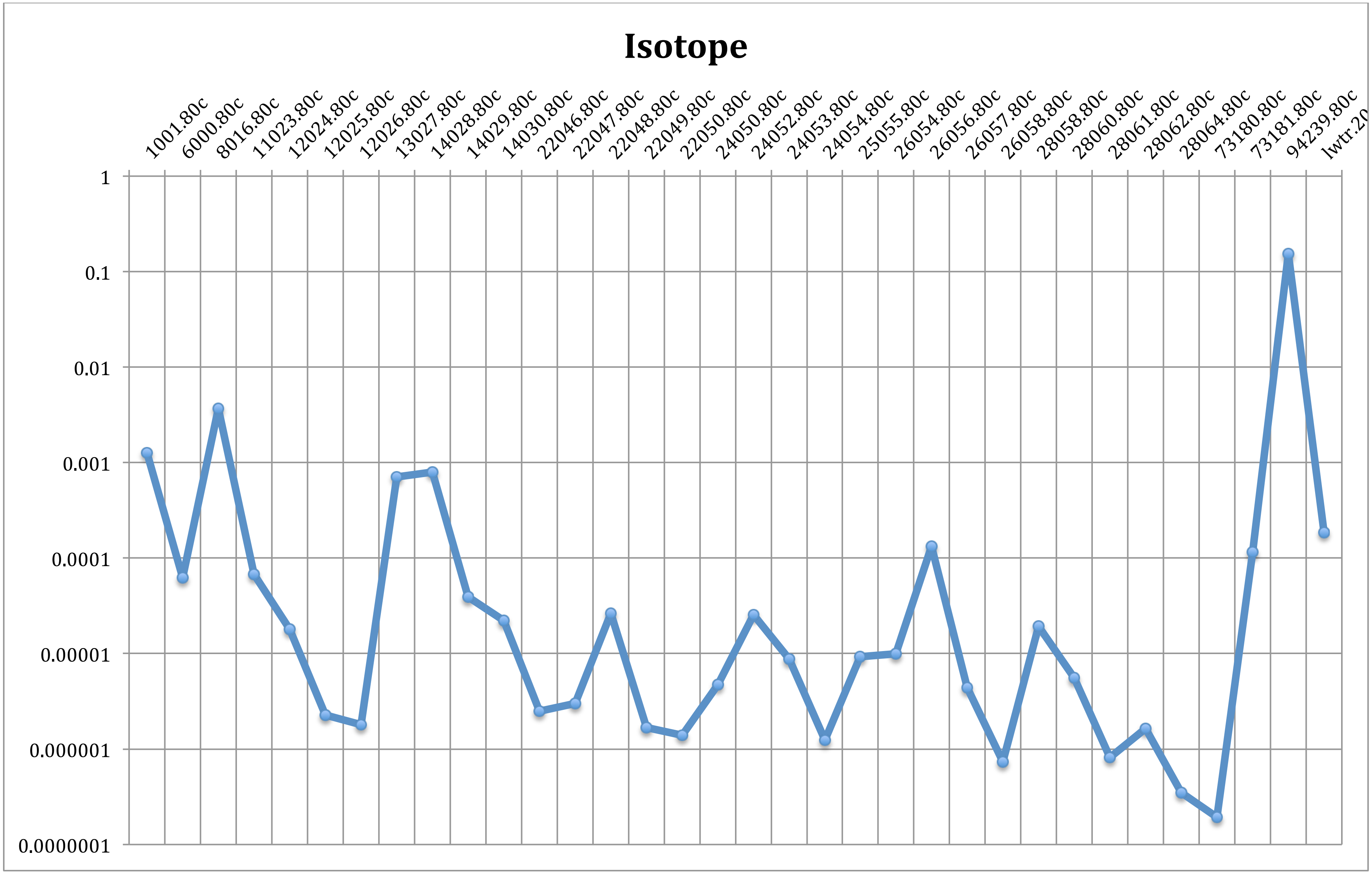

Figure 16. **Summed sensitivity for each isotope for the loss of mass control of 5,000-g plutonium condition.**

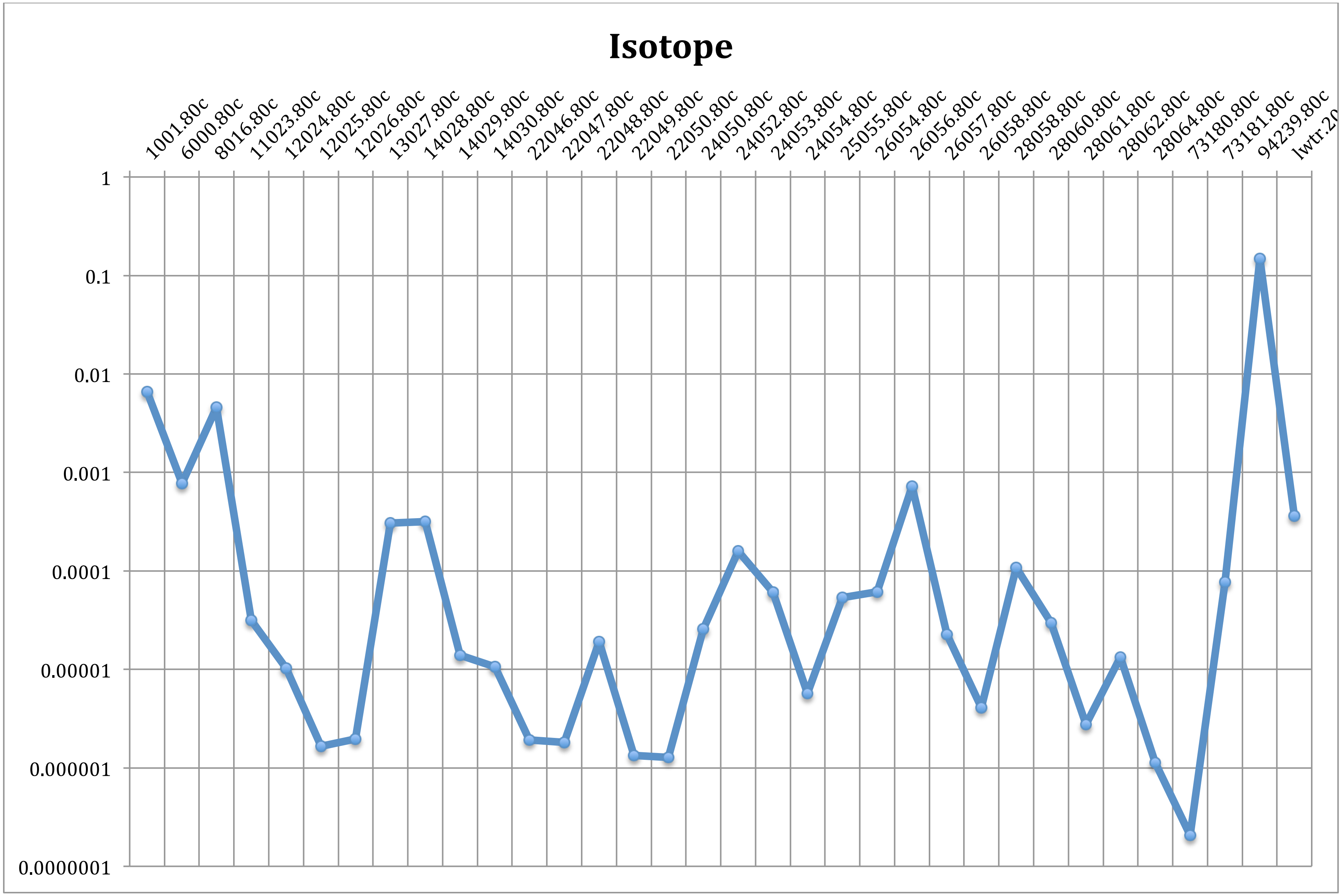

Figure 17. **Summed sensitivity for each isotope for the loss of spacing control condition.**

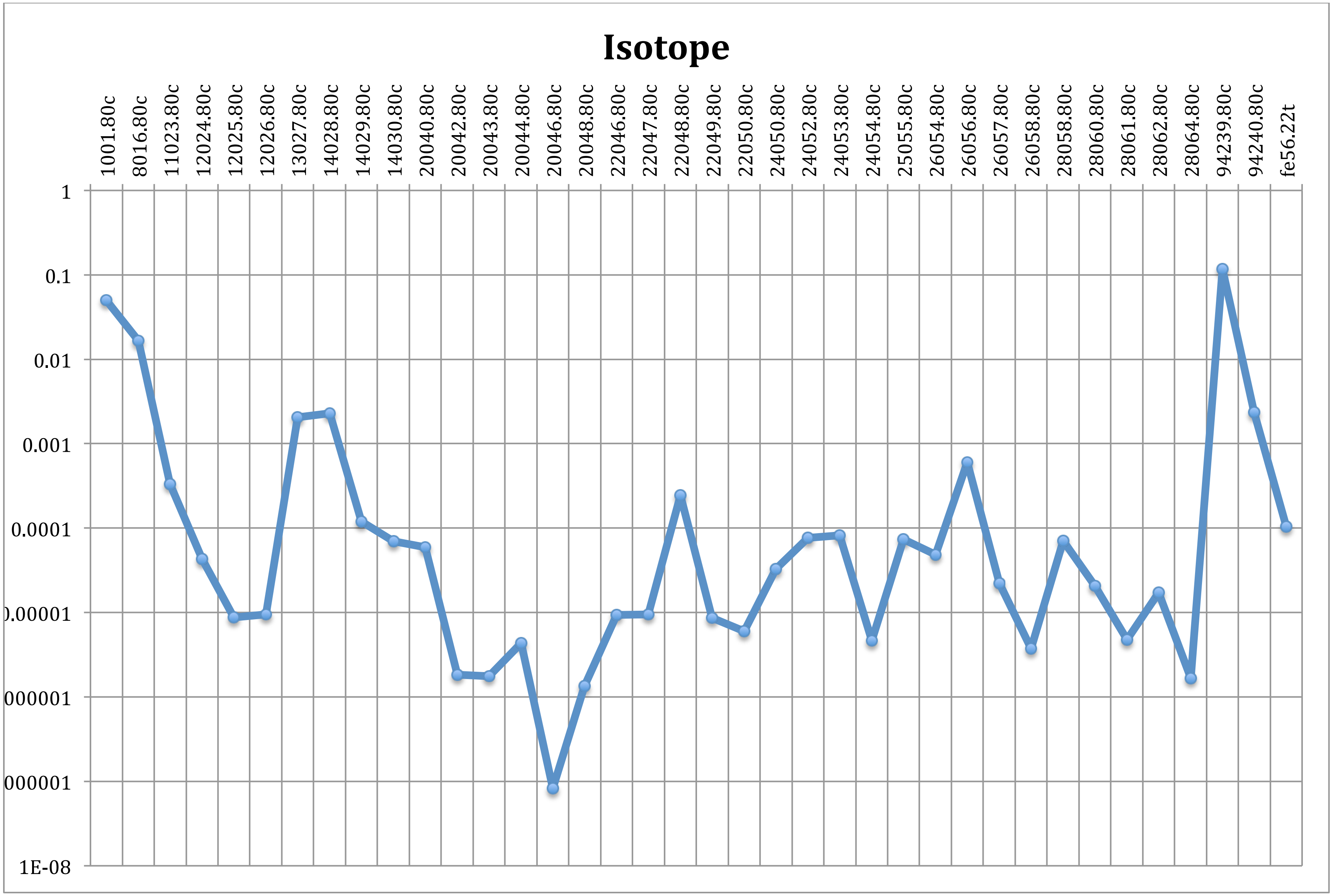

Figure 18. **Summed sensitivity for each isotope for the loss of moderation control condition (4,500-g).**

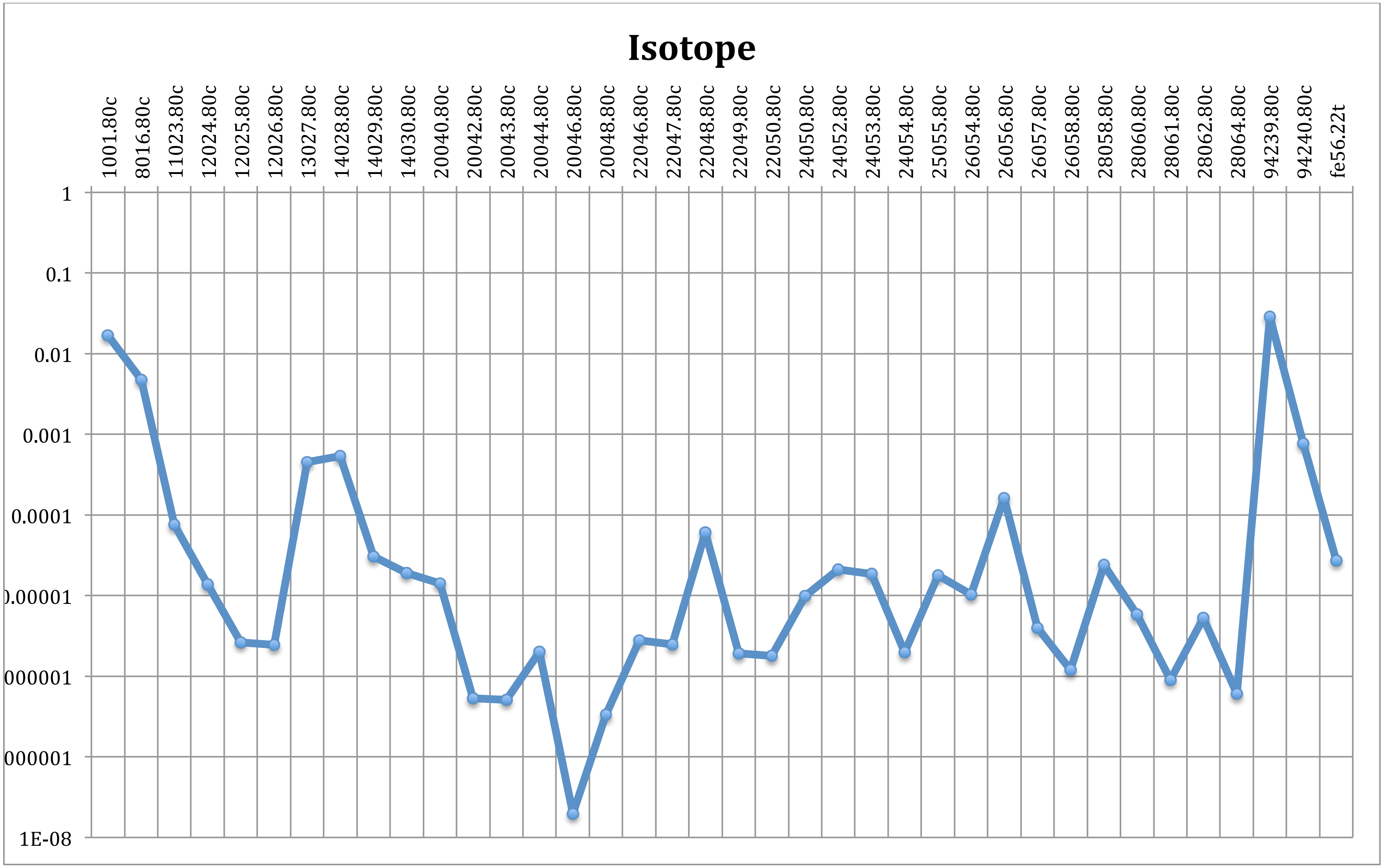

Figure 19. **Summed sensitivity for each isotope for the loss of moderation control condition (1,500-g).**

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