

Reference Values for Nuclear Criticality Safety

**Homogeneous and Uniform
UO₂, UNH, PuO₂ and PuNH,
Moderated and Reflected by H₂O**

**A demonstration study by an
Expert Group of the
Working Party on Nuclear Criticality Safety for the
OECD/NEA Nuclear Science Committee.**

**Final evaluation and report prepared by
D. Mennerdahl (EMS, Sweden)**

**Leading participants during the study
W. Weber (GRS, Germany), Y. Naito (NAIS, Japan) and J. Anno (IRSN, France)**

**Major organisations contributing with new calculation results
EMS (Sweden), IPPE (Russia), IRSN (France), ORNL (US), Serco Ass. (UK)**

May 9, 2005

Disclaimer

OECD/NEA, participating organisations and individual participants have contributed to this study for the purpose of cooperation and development. No responsibility is accepted for the application of the values, methods, recommendations and conclusions presented in the report.

FOREWORD

OECD/NEA since 1980 has supported international cooperation with studies on issues related to nuclear criticality safety, in particular comparison of calculation methods and the associated validation. Past expert groups have studied typical transport packages for irradiated fuel, large arrays of units with fissile material, small fissile particles mixed with moderated fissile material and burnup credit, an issue that continues to be studied. To support validation, the OECD/NEA International Criticality Safety Benchmark Evaluation Project (ICSBEP) Handbook has been released and updated with new and revised benchmarks every year since 1995. Almost all the benchmarks are based on critical experiments. The criticality safety expert groups, as well as the ICSBEP, are organised by the OECD/NEA Nuclear Science Committee (NSC), supported by its Working Party on Nuclear Criticality Safety.

In practice, criticality safety control, as well as emergency preparedness and response, often rely on simple systems and handbook data. These data include reference values, such as minimum critical mass, concentration and geometry as well as maximum critical moderation for well-defined systems. Since the systems are well-defined, the reference values are physical constants. The fissile materials in the study were eventually limited to uranium dioxide, uranium nitrate, plutonium dioxide and plutonium nitrate. They are each moderated and reflected by water. Several isotopic distributions of the uranium and plutonium elements were selected.

The accuracy of a reference value influences safety and economy of operations. In perceived and real emergency situations, large uncertainties in the data could result in inappropriate conclusions. Independent safety reviews, such as is required in international transport, could lead to conclusions based on less accurate data. This may be safe in the short term but discourages improvement of the data and methods, preserving large uncertainties in some areas.

The ICSBEP Handbook and other benchmark sources contain more or less complicated systems. They rarely can be used to directly determine the reference values of interest or their accuracies. Large deviations in reference values had been noticed between different criticality safety handbooks and guides. In 1998, some of the members of the Working Party prepared a proposal for a study of reference values (minimum and maximum critical values). It was accepted by the Working Party and the NSC and had its first meeting in 1999.

The present report contains a compilation and evaluation of reference values from various participants. Some of the values are from published handbooks, guides and other literature while other values were calculated mainly for the purpose of this study. As is apparent from the first OECD/NEA study in 1980 and onwards, validation is essential for the credibility of any evaluation or comparison. With proper validation, an accurate estimation of the reference value based on all contributions should be expected. The evaluation takes advantage of the ICSBEP Handbook as well as of recent developments in determination of similarities between benchmarks and applications (reference values). However, the validation process is not complete and does not sufficiently consider other error sources such as nuclide density determinations. A continuation of the study is thus recommended.

Acknowledgements

The collection of reference values was initially made on internet web pages supported primarily by NAIS Co. and for some time also by GRS. These were constructive efforts, showing the participants results continuously as they were being contributed. Dr. Susumu Mitake kindly organised an unofficial meeting by the Expert Group in Tokyo, October 2003. The new OECD/NEA scientific secretary to the Working Party, Dr. Yolanda Rugama, prepared JEFF 3.0 cross sections for use with MCNP to support the final evaluation leading to this report. Code developers and cross-section processing organisations have supported their products and this study by guidance and other services. Various organisations have supported the participants through sponsorship and other activities. The Swedish Nuclear Power Inspectorate (SKI), with short notice, sponsored some of the final evaluation and compilation of the report.

EXECUTIVE SUMMARY

Introduction

A reference value for nuclear criticality safety is a physical constant that corresponds to a parameter value for a well-defined reference system of fissionable and other materials.

Biases and uncertainties in reference values lead to many problems. The safety margins may be large, causing uneconomical operations. Since a single reference value may be used in many thousand operations, even a small extra margin could be costly. Undetected errors could lead to safety hazards. Errors and uncertainties can lead to inappropriate emergency preparedness and response.

Information on various calculation methods is very important to independent reviewers, including authorities, of safety evaluations. Simple reference systems are also useful in the validation of deterministic codes, for which the number of benchmarks is limited. They are also needed before studying other moderators, reflectors, absorbers, mixtures of fissionable materials, etc.

Scope and objectives of the first study

An expert group has completed a first study of reference values used for nuclear criticality safety. A total of 132 reference systems were selected from a wide scope of fissionable materials, moderators, reflectors and reference parameters.

The fissionable materials include only two elements, the actinides uranium and plutonium, and they are not mixed. The uranium isotopes are ^{235}U and ^{238}U and the mass percentages of ^{235}U in the uranium are 100, 20, 5, 4 and 3. The plutonium isotopes are ^{239}Pu , ^{240}Pu , ^{241}Pu and ^{242}Pu and the isotope distributions, with each isotope mass percentage of total plutonium given in that order, are 100/0/0/0, 95/0/0/0, 80/10/10/0, 90/10/0/0, 80/15/5/0 and 71/17/11/1. The four chemical structures are uranium dioxide (UO_2), uranyl nitrate hexahydrate (UNH or $\text{UO}_2(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$), plutonium dioxide (PuO_2) and plutonium nitrate pentahydrate (PuNH or $\text{PuO}_2(\text{NO}_3)_4 \cdot 5\text{H}_2\text{O}$).

All the selected fissionable materials are also fissile materials. Neutron moderation is thus an important issue. Water is the only additional moderating material. Mixing of the water with oxide as well as dissolution of nitrate in water and sometimes mixing of the saturated solution with additional nitrate are required to obtain optimum moderation. The moderated fissionable materials are uniform and homogeneous. The only reflector material is water sufficient for full (saturated) reflection.

The reference parameters are mass, volume, cylinder diameter, slab thickness, fissionable element concentration and moderation atomic ratios H/U and H/Pu. Environmental conditions beyond water reflection include room temperature, normal atmospheric pressure and gravity (not specified exactly). The reference values are selected as those corresponding to optimum moderation under the given system conditions for mass, volume, cylinder diameter and slab thickness. The fissionable element concentration value corresponds to that which makes an infinite system critical. The moderation atomic ratio value H/U or H/Pu corresponds to exactly the same system as that for the element concentration

value. The concentration is a minimum critical value while the atomic ratio is a maximum critical value. The moderation ratio is a more appropriate parameter for criticality safety control since it contains sufficient information in itself.

Results

The scope and objectives were developed after the initialisation of the study. Web sites were developed for collection of reference values and this worked quite well. The major problems and delays in the progress of the study were related to a lack of reported validation of contributed values, to different qualities of the values, to different interests and changed priorities expressed by participants and to differences between participant opinions and the defined scope and objectives.

A reference value that is supported by several methods, each based on appropriate validation, should have a smaller error and uncertainty than most benchmarks. A target uncertainty in k_{eff} of each reference value is a standard deviation of 0.001. It is important to note that the evaluations and the evaluated reference values in this report are for demonstration purposes only. The values are not even preliminary best estimates. The values will often be close to the true values, but further validation, independent verification, improvement of evaluation methods and discussion are needed.

The evaluation clearly shows that a good selection of benchmarks based on critical experiments and associated bias-corrections can be used to reduce the spread of results from direct calculations (raw data). Considering that the bias-corrections are based on linear interpolation, while the relations are non-linear, the agreements between different methods are sometimes remarkable. In other cases, the selection of benchmarks for validation is clearly not adequate for agreement between the results.

Many discrepancies have been identified and most of them have been resolved. Direct errors have been noticed in handbooks and methods. The errors are sometimes non-conservative enough to make “safe” values critical. The methods used to determine nuclide densities need further validation. The limitations when applied to areas outside the solubility ranges need to be better documented and understood. The specifications for nitrate reference values were not sufficiently clear. The material corresponding to the concentration range between the solubility limit and the crystal form was not specified. Critical values for the reference parameters at crystal density are important.

Conclusions

The availability of high-quality products such as the modern calculation methods (codes, cross-sections and utilities), validation sources and validation evaluation tools has made the prospect of obtaining a consensus on reference values more feasible than many participants realised when the study started in 1998. The best estimates of the reference values can easily be converted to benchmarks, after some additional work and confirmation by more evaluators and reviewers.

It is likely that serious errors in methods, new or old, or in the use of the methods can be found. Validation using a limited number of benchmarks, with interpolation between, is not sufficient. Verification of the capabilities of each method, not only at optimum conditions but at all conditions that the method may be applied to, is essential.

The comparison of validated results and the evaluation of discrepancies in contributed reference values have demonstrated that the differences are more often due to inadequate use of methods, inadequate determination of nuclide densities, editorial mistakes, etc. than they are due to cross-section errors. An important reason for this is that the cross-section biases can be corrected for, using appropriate validation against benchmarks based on critical experiments.

INTRODUCTION

Nuclear criticality safety during operations, transport and storage of fissionable materials requires reliable information. Elaborate evaluations of credible systems and sophisticated methods to model the neutron transport in those systems are often justified to assure criticality safety, without causing other unacceptable hazards or side-effects. However, validated reference values for simple systems are valuable for many purposes. Critical values for well-specified, water-moderated and reflected systems are examples of such reference values.

Previous OECD/NEA studies on nuclear criticality safety demonstrate the importance of validation. These include [103]-[105] involving spent LWR fuel transport, large arrays and dissolution of fuel. Later OECD/NEA studies on burnup credit are not exceptions, but the lack of benchmarks based on public critical experiments has made validation more difficult.

Correctly determined reference values are physical constants, if all specifications are given. The main purpose of this report is to describe initial efforts to establish reference values. Potential applications of such values include establishment of safety limits, validation of calculation methods, emergency preparedness and response. It is important to realise that the selected limiting reference values are not necessarily limiting under other conditions (reflection, moderation, temperature, etc.).

Several criticality safety handbooks have been published [14]-[24] to provide data and safety principles for the design, safety evaluation and licensing of operations, transport and storage of fissionable materials. The data often comprise not only critical values, but also subcritical limits and safe values. The values and limits in each handbook must be used with consideration of the limitations of the handbook, whether they are clearly specified or not. Determination of subcritical limits or safe values is outside the scope of the study. Determination of a reference value that gives a specific k_{eff} value such as 0.95 would not be outside the scope of the study. To call it safe or a recommended limit would be. The Expert Group has clearly expressed that it is not an objective to recommend values; the application of the reference values is left to the user.

Subcritical limits and safe values sometimes differ because the safety criteria and definitions differ in different organisations. However, handbook reference values for well-specified and identical systems should be in agreement, within uncertainties caused by the methods (codes, data and validation) applied. This is of specific importance as safe values often are based on reference values.

The study, see also scope and objectives in APPENDIX A, consists of several steps, each vital for its success. A first step is to select and define the reference systems. A second step is to collect existing and new values for the reference systems. A third step is to use existing or new validation of methods to correct for any remaining biases and to estimate uncertainties. A fourth step is to consider all contributions in an effort to determine a single best estimate reference value for each system. Based on this information, discrepancies in published handbooks and in other contributed results can be identified and, hopefully, explained. Finally, potential future tasks should be discussed and conclusions need to be drawn.

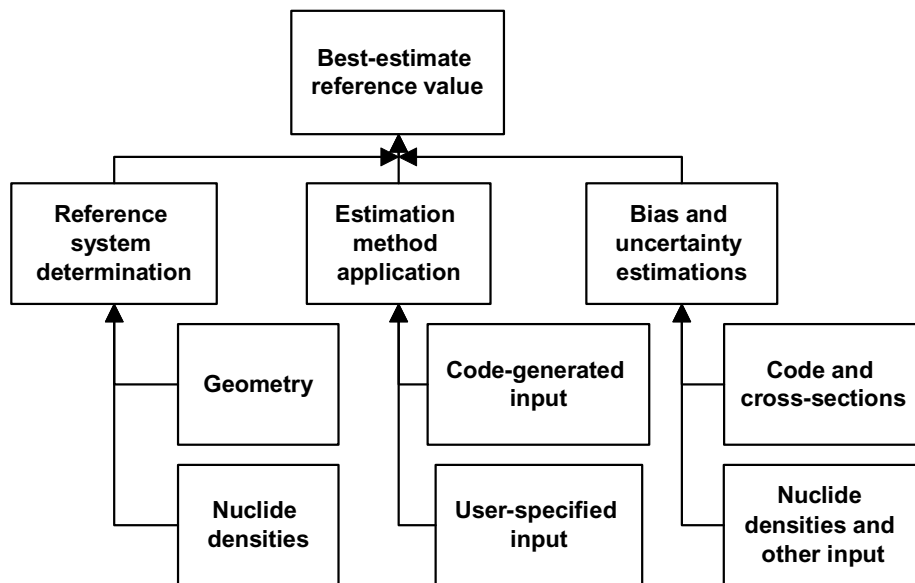
BEST ESTIMATE REFERENCE VALUES

The type of reference value covered by this report is a physical constant for a well-defined reference system containing fissile material. Selected reference systems (applications) include water-moderated and reflected spheres, cylinders and slabs as well as infinite systems of various materials under specified conditions. Other reference systems consist of benchmark specifications. Each unique reference system has a unique reference value associated with a specific reference parameter. The reference parameters for applications include fissile element spherical mass, spherical volume, cylinder diameter, slab thickness, concentration and moderation. For benchmarks, the most common reference parameter is k_{eff} .

The requested reference values refer to mass, geometry or concentration controlled critical systems. The reference parameters for mass and geometry control are minimised with optimum homogeneous and uniform mixtures of the fissile material with water. For concentration control, the systems are infinite and the fissile element concentration or the moderation ratio keeps the system exactly critical. The specifications for soluble materials were not sufficiently clear. They referred to solutions but the intention was probably to cover a mixture of the material with water, whether soluble or not. It should have been solution within the solubility range and a mixture of the crystal form and the saturated solution above the solubility limit.

A reference value is determined from three sources: The determination of the system specifications, the application of a suitable estimation method and finally the bias-correction. Each source contributes to uncertainties in the final value. Figure 1. shows a simplified chart with required input preparation, calculations and bias-correction due to various error sources.

Figure 1. Best estimate reference values, error sources and validation



The system specifications may be given explicitly or implicitly. Explicitly means that materials, geometry and all other system data are fixed and given. Implicitly means that some data need to be derived by the contributor, based on some general specifications. An example is the specification of optimum water-moderation. Optimum conditions determined by different evaluators will vary. The conditions are determined both by the optimisation method and by the input data (including nuclide density correlation “laws” and cross-sections). This process introduces biases and uncertainties.

A benchmark contains simplified geometry and material specifications compared with the experimental configuration. A bias correction and an uncertainty are estimated for the benchmark to account for known and unknown deviations between the benchmark and the experiment. The validation process involves additional material and geometry biases and uncertainties due to the actual modelling of the benchmark. In some cases, there are no such additional biases and uncertainties.

Each code or code system has a number of built-in features and options, including defaults that may be changed by the user. The input data can come from various sources. Whether they come directly from the code system itself or are user-supplied, they need to be tested in various combinations. Further, they need to be tested with the code system to be used for determining the reference value of interest. This is often referred to as verification. Overall validation of the method is treated as a separate issue. Validation of each user’s application of the method is also important.

A bias-correction is necessary to obtain a best estimate reference value, which is the major objective of the study. To obtain a bias-correction, it is necessary to have some benchmarks to validate the method (code and data). Appropriate determination of biases and uncertainties can be complicated but is necessary to get credible results. A bias-correction can be positive, negative or zero. Each benchmark has an associated unique reference value.

Even for a benchmark based on a critical experiment, the reference value is tied to the benchmark model of the experiment and not directly to the experiment itself. There may be several benchmark models of the same experiment. The true reference value for a benchmark may not be known accurately. A best estimate reference value for a benchmark is connected with an uncertainty.

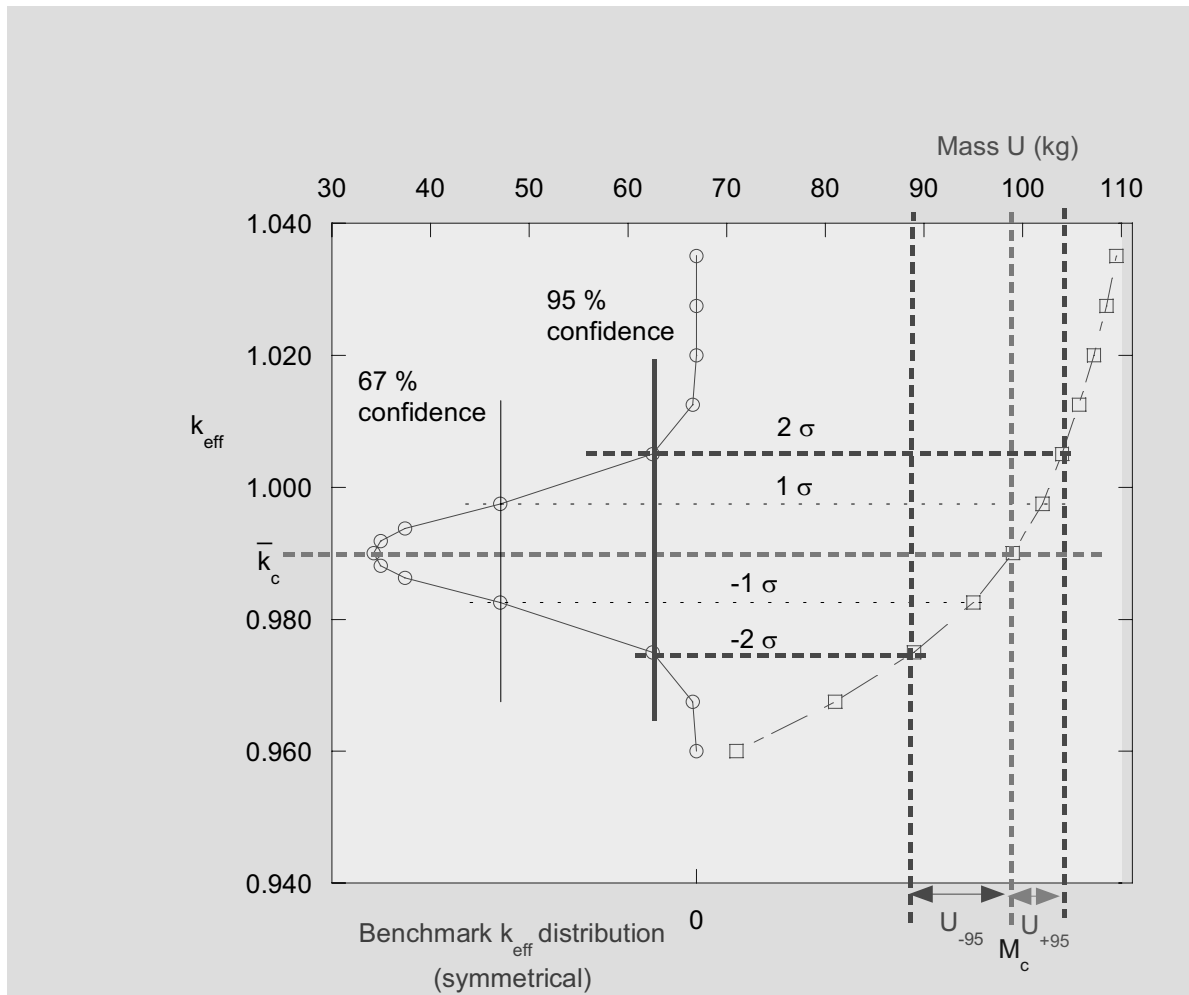
The selection of benchmarks and the evaluation of the results should probably be different for reference value and for safe value determinations. Different weights can be given to each benchmark. Outliers (“odd” results) and complicated systems may be completely left out of the database for reference value determinations. However, all data should be considered in the uncertainty evaluation required to establish safe values. Validation of a method for safety application should be made with typical user input data. Validation for best-estimate purposes should involve more accurate calculations.

A simplified view of the procedure for determining a reference value (minimum critical mass) is shown in Figure 2. It is based on a compilation of benchmark results on the left side, with the average used as a bias and a standard deviation as a measure of uncertainty. The distribution is assumed to be symmetrical around the mean. On the right, at least three calculations of systems close to the requested reference value (minimum critical mass), are used to generate a curve showing k_{eff} as a function of the actual mass.

The curve is normally curved (!), not a straight line. The bias-corrected estimate of criticality is transferred to the right side, giving the best estimate M_c of the reference value. The uncertainties in the reference value are derived in the same way. The curved line means that the positive and negative reference value uncertainties $U_{.95}$ and $U_{+.95}$ are different when k_{eff} uncertainties are identical. This is seen in APPENDIX G for the method EMS-S4X-238 (original EMS contribution). If k_{eff} complies with a normal distribution, the reference value will not. The reverse is also true; if a reference parameter complies with a normal distribution, k_{eff} will not.

It is easy to see in Figure 2. that a normal (Gaussian) distribution of k_{eff} leads to non-symmetric levels of confidence of the reference value. The figure indicates an uncertainty corresponding to the lower limit of the 95% level of confidence almost twice as large as the upper limit uncertainty. It is not a question of $\pm s_m$. The best-estimate critical mass M_c is 99 kg, the upper limit ($M_c + U_{+.95}$) is 104 kg and the lower limit ($M_c - U_{.95}$) is 89 kg. Other statistical background information is given in APPENDIX B, APPENDIX M and [92].

Figure 2. Estimation of minimum critical mass and its uncertainties



FISSIONABLE REFERENCE SYSTEMS

All the selected fissionable materials are also fissile. The large number of systems selected during the first year of the study was probably more motivated by practical safety interests than by physics and numerical considerations.

The fissionable materials include only two actinide elements, uranium and plutonium, and they are not mixed. The uranium isotopes are ^{235}U and ^{238}U and the mass percentages of ^{235}U in the total uranium are 100, 20, 5, 4 and 3. The plutonium isotopes are ^{239}Pu , ^{240}Pu , ^{241}Pu and ^{242}Pu and the isotope distributions, with each isotope mass percentage of total plutonium given in that order¹, are 100/0/0/0, 95/0/0/0, 80/10/10/0, 90/10/0/0, 80/15/5/0 and 71/17/11/1. The compositions are sorted according to total fissile nuclide (^{239}Pu and ^{241}Pu , with ^{241}Pu weighted higher for equal sums) fractions.

The four chemical structures are uranium dioxide (UO_2), uranyl nitrate hexahydrate (UNH or $\text{UO}_2(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$), plutonium dioxide (PuO_2) and plutonium nitrate pentahydrate (PuNH or $\text{PuO}_2(\text{NO}_3)_4 \cdot 5\text{H}_2\text{O}$).

The fissile materials are not specified completely. Water in optimum fractions has to be added to the small oxide particles and nitrate crystals. The resulting mixtures and solutions are considered homogeneous and uniform (the same concentrations everywhere). Theoretical densities of both oxides and hydrated nitrates must be considered. The issue of realism in the dioxide/water mixtures and in the solution/crystal densities is left to the evaluator but needs to be considered. Mixtures of saturated solutions with nitrate crystals may be realistic under certain conditions. Mixtures of dioxide powder with water at optimum conditions are not always stable, the dioxide powder will settle to the bottom of the system. The evaluator should note if the conditions are not credible; e.g. the solution being above the saturation level or even above the crystal structure density.

The credibility issue must not hide the purpose of the study: to determine physical constants. There must be only one correct value for each reference system. For solutions, the solubility limits and the crystal densities can be considered as physical (or chemical) constants. The range in between was not properly specified at the beginning of the study. A reasonable approach is to assume a mixture of the saturated solution and the crystal (precipitation). IRSN uses this assumption in its extended isopiestic method ([39], [40], [41], [60] and [89]).

The systems are either fully water-reflected or infinite.

¹ Trailing zeros are sometimes skipped, e.g. 100 instead of 100/0/0/0, 90/10 rather than 90/10/0/0, etc.

SOURCES FOR REFERENCE VALUES

The best estimate reference values (physical constants), the major purpose of the study, are obtained by evaluation of validated results from different sources. Some are published in handbooks and in other literature while others have been determined by participants to support the study.

The reported results are not always best estimate values. They may have been calculated using the best available or best validated methods at a certain time but without bias corrections. They may be used safely if the combination of biases and uncertainties are small, compared with the safety margins added before application.

Calculation results without bias corrections are separated from those with corrections. New or revised bias-corrections can be applied later, without recalculations.

Each source of reference values is listed in Table 1. More detailed descriptions are supplied in APPENDIX C. There may be additional methods used for odd cases. The specification of each method may vary slightly in the text, tables and figures but the format should be reasonably consistent.

There may be other handbooks and published results that can be used to determine a single best-estimate value for each reference system.

Table 1. Sources for critical values

Source id.	Reference	Handbook or New calculation	Method (code+data)	Bias correction
ARH-600	[14]	Handbook		
DIN	[15]-[18]	Standards		
EMS-S1K-27	This report	New calculations	SCALE 1, K5 ¹ + 27 lib	
EMS-S4X-238	[29]	New calculations	SCALE 4, XSD ² +238 lib	Yes, rough ³
EMS-M5-E50	This report	New calculations	MCNP5+ENDF/B 5.0	Yes
EMS-M5-E5F	This report	New calculations	MCNP5+ENDF/B 5.F ⁴	Yes
EMS-M5-E62	This report	New calculations	MCNP5+ENDF/B 6.2	Yes
EMS-M5-E66	This report	New calculations	MCNP5+ENDF/B 6.6	Yes
EMS-M5-E68	This report	New calculations	MCNP5+ENDF/B 6.8	Yes
EMS-M5-E7P	This report	New calculations	MCNP5+ENDF/B 7P	Yes
EMS-M5-J32	This report	New calculations	MCNP5+JEF 2.2	Yes
EMS-M5-J33	This report	New calculations	MCNP5+JEFF 3.0	Yes
EMS-M5-F22	This report	New calculations	MCNP5+JENDL 3.2	Yes
EMS-M5-F30	This report	New calculations	MCNP5+ JENDL 3.3	Yes
EMS-S5X-238	This report	New calculations	SCALE 5, XSD ² + 238 lib	Yes
EMS-S5X-27	This report	New calculations	SCALE 5, XSD ² + 27 lib	Yes
EMS-S5X-44	This report	New calculations	SCALE 5, XSD ² + 44 lib	Yes
EMS-S5K-238	This report	New calculations	SCALE 5, K5a ² + 238 lib	Yes
EMS-S5K-27	This report	New calculations	SCALE 5, K5a ² + 27 lib	Yes
EMS-S5K-44	This report	New calculations	SCALE 5, K5a ² + 44 lib	Yes
GRS-HzK-98	[19]	Handbook		
GRS-M4-E50	[31]	New calculations	MCNP – E5 Lib	
GRS-S4X-44	[31]	New calculations	SCALE – 44 Lib	
IPPE-84	[20]	Handbook	KRAB-1+ABBN-78	
IPPE-ABBN93	[35] New	New calculations	XSD or K5A+ABBN93a	Yes
IRSN-CrV0-20	[39]-[41]	New calculations	CRISTAL V0	
IRSN-CrV1-172	[43]	New calculations	CRISTAL V1	
IRSN-DTF-7 8	[21]	Handbook	DTF-IV, literature?	
IRSN-DTF-9 6	SEC/DI/96.16	Internal report	DTF-IV, literature?	
JAERI-H-88	[22]	Handbook (transl)	JACS	Yes, rough ³
JAERI-H-99	[23], [24]	Handbook (transl)	JACS	Yes, rough ³
NUPEC	[51]	New calculations	SCALE 44 Lib	
ORNL-S4X-238	[52]	New calculations	SCALE 238 Lib	
Serco-Mk8-F22	[55], [56]	New calculations	MONK 8A, -B, JEF 2.2	Yes ⁵

-
1. SCALE 1 with KENOV (not Va), Modified 1985 for IBM PC AT (Intel 80286) with 640 kb RAM.
 2. XSD stands for XSDRNPM while K5a stands for KENOVa.
 3. EMS-S4X-238 and JAERI validations are not focused on the current applications, based on “old” validation.
 4. As E50 except that the .55c set is used for ²³⁹Pu. “F” stands for Final.
 5. SERCO validation and to some extent all EMS validations are also quite rough, not being very focused.

EVALUATION OF BEST ESTIMATE VALUES AND UNCERTAINTIES

During the final evaluation, it was decided to add more methods. MCNP5 and a wide selection of continuous energy cross-sections (ENDF/B releases 5.0, 6.2, 6.6 and 6.8, JEF 2.2 as well as JENDL3.2 and 3.3) were used (even more were available but not used). Release 1.30 was obtained late November 2004 together with preliminary ENDF/B-VII cross-sections. JEFF 3.0 cross-sections were contributed in December 2004 by OECD/NEA (Dr. Yolanda Rugama).

SCALE 5 was released recently, unfortunately without new cross-sections. Revised calculations with the 238-group library as well as new calculations with the 27- and 44-group libraries were carried out. Reference values were calculated using both KENOv and XSDRNPM/S for all applications and for the three mentioned cross-section libraries. This simplifies validation of XSDRNPM results.

IPPE originally had contributed results from a 1984 handbook. During the final evaluation, IPPE added results using a more recent method based on XSDRNPM and ABBN93a cross-sections.

The contributions from the participants are summarized in APPENDIX G. The methods used by each participant to calculate critical values as well as validation and, in some cases, bias corrections and uncertainties are described in APPENDIX C and for EMS and IPPE also in APPENDIX I. The validation methods vary between the participants, as does the quality of the bias corrections.

APPENDIX D contains calculated sensitivities for changes in k_{eff} (Dk) due to a small change in each of the selected parameters mass, volume, cylinder diameter, slab thickness and concentration. They can be used to obtain the Dk values corresponding to different calculated or best estimate critical values. The small k_{eff} changes used to derive the sensitivities are usually less than 0.005, but there is no consistency. The sensitivities are not linear. There is no single value that could be used to get accurate corrections for the different biases found for different methods. An appropriately determined curve would be the best way to handle this problem.

Reported results that are not corrected for biases can be very useful if they are supported by separate validation reports or conclusions. Calculation results from different contributors based on identical or almost identical methods are also valuable. They reduce the potential for human error and indicate the sensitivity of the method to users.

Often, the variations of the calculation results can be attributed mainly to the basic evaluated nuclear cross section library. Such observations simplify comparisons of calculated values, e.g. during independent verification of safety evaluations, and may support improvements of the basic cross sections.

An effort has been made during the evaluation of the contributed values to select suitable benchmarks for validation (APPENDIX E). Typical criteria are simple systems, preferably with water moderation and reflection, and low uncertainties in the benchmarks. Later, APPENDIX H, the similarities between applications and benchmarks are evaluated using more sophisticated methods (SCALE 5 TSUNAMI-IP). EALF values for all applications are shown in Table II.

The selected benchmarks were calculated with all the EMS methods as well as with the recent IPPE-ABBN93 method. The results, as well as some preliminary trends, are given in APPENDIX F.

IPPE benchmark results were obtained using the same cross-sections as in the applications. XSDRNPM has been reported to give essentially the same results as the Monte Carlo code KENOvA when the same cross-sections and appropriate convergence, mesh and angular quadrature input are applied.

SCALE 5 and the new TSUNAMI sequences were used to calculate the similarity indices c_k , E_{sum} and G related to the applications and the benchmarks. In addition, an index R_{en} was defined to display EALF ratios for benchmarks related to applications. The results are summarised in APPENDIX H. Mathematical calculations, unrelated to benchmarks, of R_{en} were inserted for information. The lack of benchmark EALF values near the application EALF is sometimes very obvious.

Comparisons of the TSUNAMI-IP indices to R_{en} show that EALF is indeed a useful trending parameter for these systems.

The benchmark uncertainties and the TSUNAMI indices were used to select sub-sets of benchmarks for validation of different applications. APPENDIX I contains bias determinations for the EMS and IPPE methods applied to the different applications.

Serco has also submitted bias-corrected results based on MONK calculations and large sets of benchmarks. The JAERI handbook results are validated as well, but the validation range appears to be too wide to be reliable when the reference values are to be determined. There are not so many reference values. The benchmarks are also quite old, lacking the bias and uncertainty information available in the ICSBEP Handbook. The “raw” data were not directly available (though the biases are published in the Handbook). A decision was made to base the best-estimate values on averages of bias-corrected Serco MONK, IPPE ABBN93, EMS-SCALE5+238, EMS-MCNP5+ENDF/B-7P (or -68), EMS-MCNP5+JEFF3.0 and EMS-MCNP5+JENDL-3.3 results.

These best estimate reference values are intended for demonstration only. They are dominated by EMS methods. The associated EMS evaluation and validation results are correlated since they are based on identical geometry and nuclide density input data. However, the demonstration is considered valuable since any detected biases can be corrected easily for all the methods. It is apparent from some comparisons of bias-corrected reference values that the bias-correction has not worked out very well. However, often the opposite is true; the bias-corrections have been successful in reducing the spread of results, indicating some quality.

It is repeated that total bias-corrections and uncertainties need to cover not only cross-section and code-related biases and uncertainties but also those from nuclide density determinations. Very late during the evaluation (March 2005) a comparison of nuclide density methods was carried out with very interesting results for solutions (APPENDIX K). Some of the previously selected base methods for best-estimate determination now had to be completely removed; the density methods were not adequate. The IRSN extended isopiestic method turned out to be the only credible source for some values, while the IPPE ABBN93 method also is credible near the crystal density values.

The best-estimates are included in Tables 2 to 5. The precision corresponds to a k_{eff} precision between 0.0001 and 0.001. The uncertainties are very subjective and no effort has been made to separate upper and lower limits of confidence. Even so, at this time, this compilation of reference values may be the best source available anywhere.

Table 2. Demonstration reference values for UO₂

Fissile material	Parameter	Reference value	Expanded standard uncertainty (95)¹	Comments
U(100)O ₂	Mass (kg U)	0.798	0.010	
	Volume (litre)	4.38 ²	0.10	
	Cylinder diam. (cm)	12.47 ²	0.06	
	Slab thickness (cm)	3.45 ²	0.10	
	Concentr. (g U/l)	12.18	0.20	
	Moderation H/U	2137	34	
U(20)O ₂	Mass (kg U)	5.22	0.10	
	Volume (litre)	10.78	0.40	
	Cylinder diam. (cm)	17.97	0.20	
	Slab thickness (cm)	7.24	0.30	
	Concentr. (g U/l)	64.0	0.7	
	Moderation H/U	409.0	5.0	
U(5)O ₂	Mass (kg U)	37.0	1.0	
	Volume (litre)	27.91	1.00	
	Cylinder diam. (cm)	25.68	0.35	
	Slab thickness (cm)	12.17	0.30	
	Concentr. (g U/l)	285.6	2.0	
	Moderation H/U	89.6	0.7	
U(4)O ₂	Mass (kg U)	55.1	1.2	
	Volume (litre)	35.7	0.9	
	Cylinder diam. (cm)	28.25	0.50	
	Slab thickness (cm)	13.77	0.20	
	Concentr. (g U/l)	369.3	3.0	
	Moderation H/U	68.7	0.6	
U(3)O ₂	Mass (kg U)	99.0	1.5	
	Volume (litre)	53.5	1.0	
	Cylinder diam. (cm)	32.79	0.55	
	Slab thickness (cm)	16.69	0.30	
	Concentr. (g U/l)	522	5	
	Moderation H/U	47.8	0.5	

1. Subjective and simplified. Upper and lower limits could be quite different.

2. A correction has been made since the theoretical density for U(100)O₂ is 10.84 and not 10.96 g/cm³.

Table 3. Demonstration reference values for UNH

Fissile material	Parameter	Reference value	Expanded standard uncertainty (95)¹	Comments
U(100)NH	Mass (kg U)	0.826	0.012	
	Volume (litre)	6.70	0.40	
	Cylinder diam. (cm)	14.95	0.50	
	Slab thickness (cm)	5.46	0.35	
	Concentr. (g U/l)	12.23	0.50	
	Moderation H/U	2109	83	
U(20)NH	Mass (kg U)	6.13	0.10	
	Volume (litre)	16.30	1.20	
	Cylinder diam. (cm)	21.00	0.40	
	Slab thickness (cm)	9.29	0.25	
	Concentr. (g U/l)	64.8	1.0	
	Moderation H/U	397.1	6.2	
U(5)NH	Mass (kg U)	75.4	3.0	
	Volume (litre)	80.7	8.0	
	Cylinder diam. (cm)	37.9	1.6	
	Slab thickness (cm)	20.04	0.70	
	Concentr. (g U/l)	311.4	5.3	
	Moderation H/U	76.2	1.4	
U(4)NH	Mass (kg U)	144	7	
	Volume (litre)	136	15	
	Cylinder diam. (cm)	45.4	1.7	
	Slab thickness (cm)	25.05	0.85	
	Concentr. (g U/l)	416	10	
	Moderation H/U	55.1	1.5	
U(3)NH	Mass (kg U)	469	40	
	Volume (litre)	370	50	
	Cylinder diam. (cm)	64.8	3.5	
	Slab thickness (cm)	37.5	2.2	
	Concentr. (g U/l)	629	7	
	Moderation H/U	33.6	1.3	

1. Subjective and simplified. Upper and lower limits could be quite different.

Table 4. Demonstration reference values for PuO₂

Fissile material	Parameter	Reference value	Expanded standard uncertainty (95) ¹	Comments
Pu(100/0/0/0)O ₂	Mass (kg Pu)	0.510	0.018	
	Volume (litre)	1.151	0.033	
	Cylinder diam. (cm)	7.68	0.10	
	Slab thickness (cm)	1.721	0.060	
	Concentr. (g Pu/l)	7.28	0.30	
	Moderation H/Pu	3636	190	
Pu(95/5/0/0)O ₂	Mass (kg Pu)	0.621	0.018	
	Volume (litre)	1.236	0.040	
	Cylinder diam. (cm)	7.95	0.11	
	Slab thickness (cm)	1.934	0.070	
	Concentr. (g Pu/l)	7.88	0.09	
	Moderation H/Pu	3360	123	
Pu(80/10/10/0)O ₂	Mass (kg Pu)	0.686	0.036	
	Volume (litre)	1.288 ²	0.042	
	Cylinder diam. (cm)	8.04 ²	0.12	
	Slab thickness (cm)	1.912 ²	0.070	
	Concentr. (g Pu/l)	8.16	0.09	
	Moderation H/Pu	3250	115	
Pu(90/10/0/0)O ₂	Mass (kg Pu)	0.754	0.027	
	Volume (litre)	1.307	0.040	
	Cylinder diam. (cm)	8.15	0.10	
	Slab thickness (cm)	2.066	0.025	
	Concentr. (g Pu/l)	8.56	0.25	
	Moderation H/Pu	3094	88	
Pu(80/15/5/0)O ₂	Mass (kg Pu)	0.874	0.042	
	Volume (litre)	1.367 ²	0.042	
	Cylinder diam. (cm)	8.27 ²	0.12	
	Slab thickness (cm)	2.096 ²	0.090	
	Concentr. (g Pu/l)	9.09	0.25	
	Moderation H/Pu	2914	78	
Pu(71/17/11/1)O ₂	Mass (kg Pu)	0.907	0.050	
	Volume (litre)	1.413 ²	0.054	
	Cylinder diam. (cm)	8.37 ²	0.13	
	Slab thickness (cm)	2.104 ²	0.080	
	Concentr. (g Pu/l)	9.28	0.35	
	Moderation H/Pu	2859	104	

1. Subjective and simplified. Upper and lower limits could be quite different.

2. Includes a correction. The theoretical density for PuO₂ with this isotope distribution is not 11.46 g/cm³.

Table 5. Demonstration reference values for PuNH

Fissile material	Parameter	Reference value	Expanded standard uncertainty (95)¹	Comments
Pu(100/0/0/0)NH	Mass (kg Pu)	0.524	0.020	
	Volume (litre)	7.36	0.50	
	Cylinder diam. (cm)	15.56	0.40	
	Slab thickness (cm)	5.67	0.30	
	Concentr. (g Pu/l)	7.33	0.20	
	Moderation H/Pu	3598	96	
Pu(95/5/0/0)NH	Mass (kg Pu)	0.639	0.030	
	Volume (litre)	10.78	0.50	
	Cylinder diam. (cm)	17.94	0.40	
	Slab thickness (cm)	7.18	0.30	
	Concentr. (g Pu/l)	7.93	0.20	
	Moderation H/Pu	3325	82	
Pu(80/10/10/0)NH	Mass (kg Pu)	0.707	0.040	
	Volume (litre)	12.18	0.50	
	Cylinder diam. (cm)	18.74	0.40	
	Slab thickness (cm)	7.61	0.30	
	Concentr. (g Pu/l)	8.19	0.20	
	Moderation H/Pu	3221	97	
Pu(90/10/0/0)NH	Mass (kg Pu)	0.777	0.040	
	Volume (litre)	13.42	0.50	
	Cylinder diam. (cm)	19.48	0.40	
	Slab thickness (cm)	8.11	0.30	
	Concentr. (g Pu/l)	8.59	0.20	
	Moderation H/Pu	3068	70	
Pu(80/15/5/0)NH	Mass (kg Pu)	0.905	0.040	
	Volume (litre)	15.42	0.50	
	Cylinder diam. (cm)	20.54	0.40	
	Slab thickness (cm)	8.75	0.30	
	Concentr. (g Pu/l)	9.15	0.20	
	Moderation H/Pu	2881	62	
Pu(71/17/11/1)NH	Mass (kg Pu)	0.948	0.040	
	Volume (litre)	15.83	0.50	
	Cylinder diam. (cm)	20.72	0.40	
	Slab thickness (cm)	8.89	0.30	
	Concentr. (g Pu/l)	9.31	0.25	
	Moderation H/Pu	2833	74	

1. Subjective and simplified. Upper and lower limits could be quite different.

COMPARISON OF CONTRIBUTED VALUES WITH BEST ESTIMATE VALUES

The data in criticality safety handbooks, standards and guides are derived not only to support safe systems but also to allow efficient and fast evaluations. A non-conservative (non-pessimistic) value could be a safety problem if not used properly, taking the bias into account. On the other hand, a conservative value could lead to inefficient operations and designs. A conservative value applied by the regulator in one country could also lead to problems in transport licensing (multilateral approval is required). It is valuable for a reviewer to understand the causes of differences in the calculation results for the same system.

In an emergency situation, correct information may be more valuable than ever. Non-conservative values without known biases could cause a criticality accident due to bad decisions. On the other hand, conservative values could lead to unnecessary worries, alarms, evacuations, stopped industrial operations, bad publicity, etc. e. g. during the JCO accident in Japan 1999 it was essential for the safety specialists at JAERI to have correct and not conservative information and calculation methods.

This study also makes it clear that deterministic codes need to be better validated. Some critical experiment specifications can be used to create benchmarks for deterministic codes but in most cases it is not meaningful. It is better to use the validated Monte Carlo results to create simple benchmarks like the reference values in this report. The total uncertainty can be made smaller than for most experimental benchmarks.

Conclusions from comparisons between handbook and calculated results with appropriately determined best estimate values for a limited set of fissile systems may be extended to more complicated systems containing similar fissile materials.

The best estimate reference values and uncertainties reported in the previous chapter are for demonstration only. Many values and uncertainties will be good, others not so good. They are based on subjective selections and evaluations of benchmarks, correlated inputs for benchmarks and reference system calculations, linear interpolation and extrapolation of non-linear relations, work carried out under time-pressure, insufficient time for review, etc.

The following charts (Figures 3 to 15) show total biases for the used methods compared with the best estimate reference values given in the previous section. The points are connected with lines to easier identify the method and are not intended to show any trend between different reference systems. There are three charts for each material type. The first covers all values, the second is focusing on smaller biases while the third is limited to methods that are reasonably “modern”.

Each bias is calculated as the difference between the (bias-corrected when available) value in APPENDIX G and the value in Tables 2 to 5. The sum of the biases for the “major 6” bias-corrected values (cross-sections only!) used to determine the first best-estimate values are not always close to zero. The reason is that additional bias-corrections due to density issues have been added to some reference values (APPENDIX L).

Figure 3. UO_2 reference values – Estimated total biases for each method

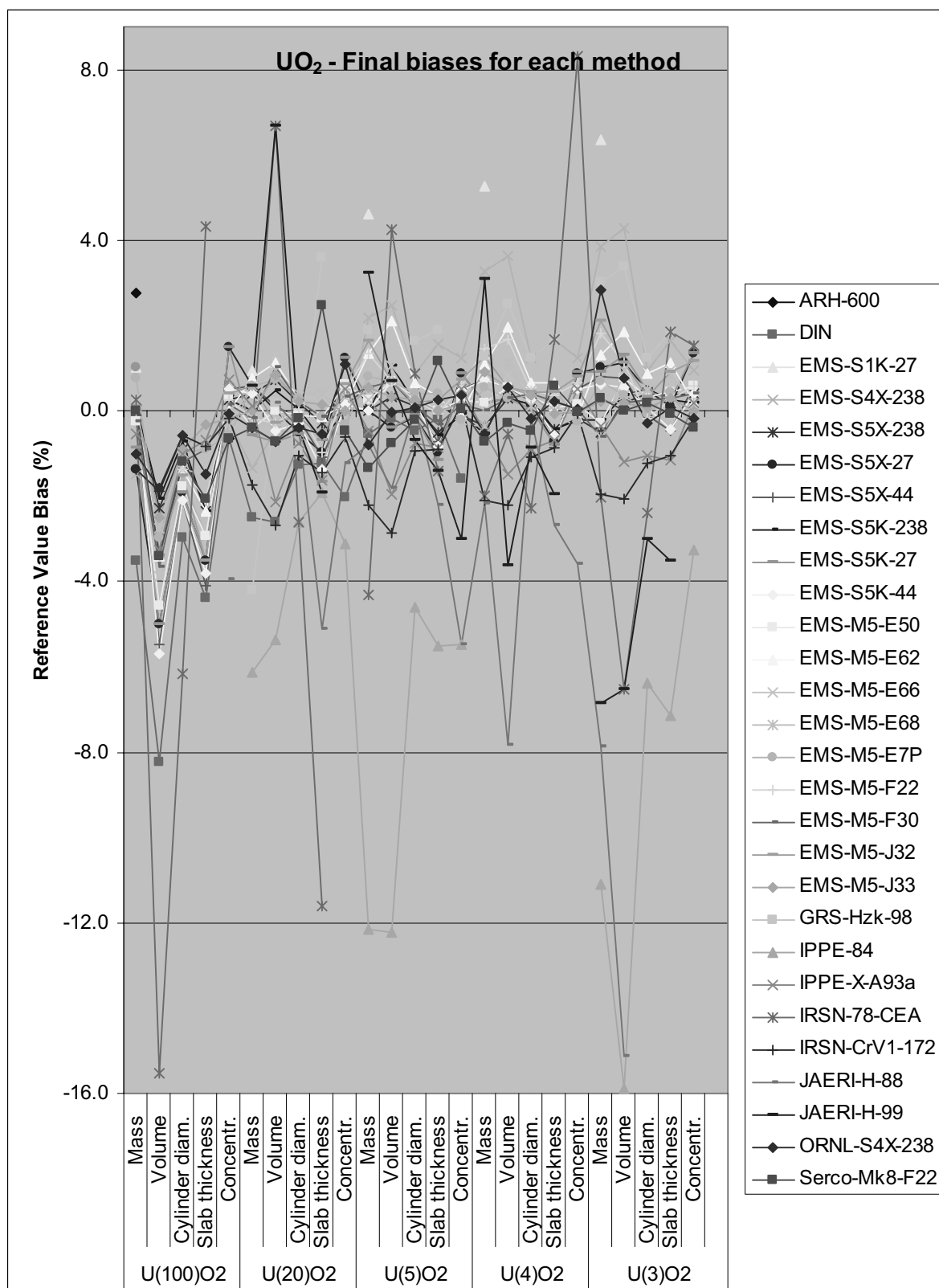


Figure 4. UO_2 reference values – Estimated total biases for each method (enlarged)

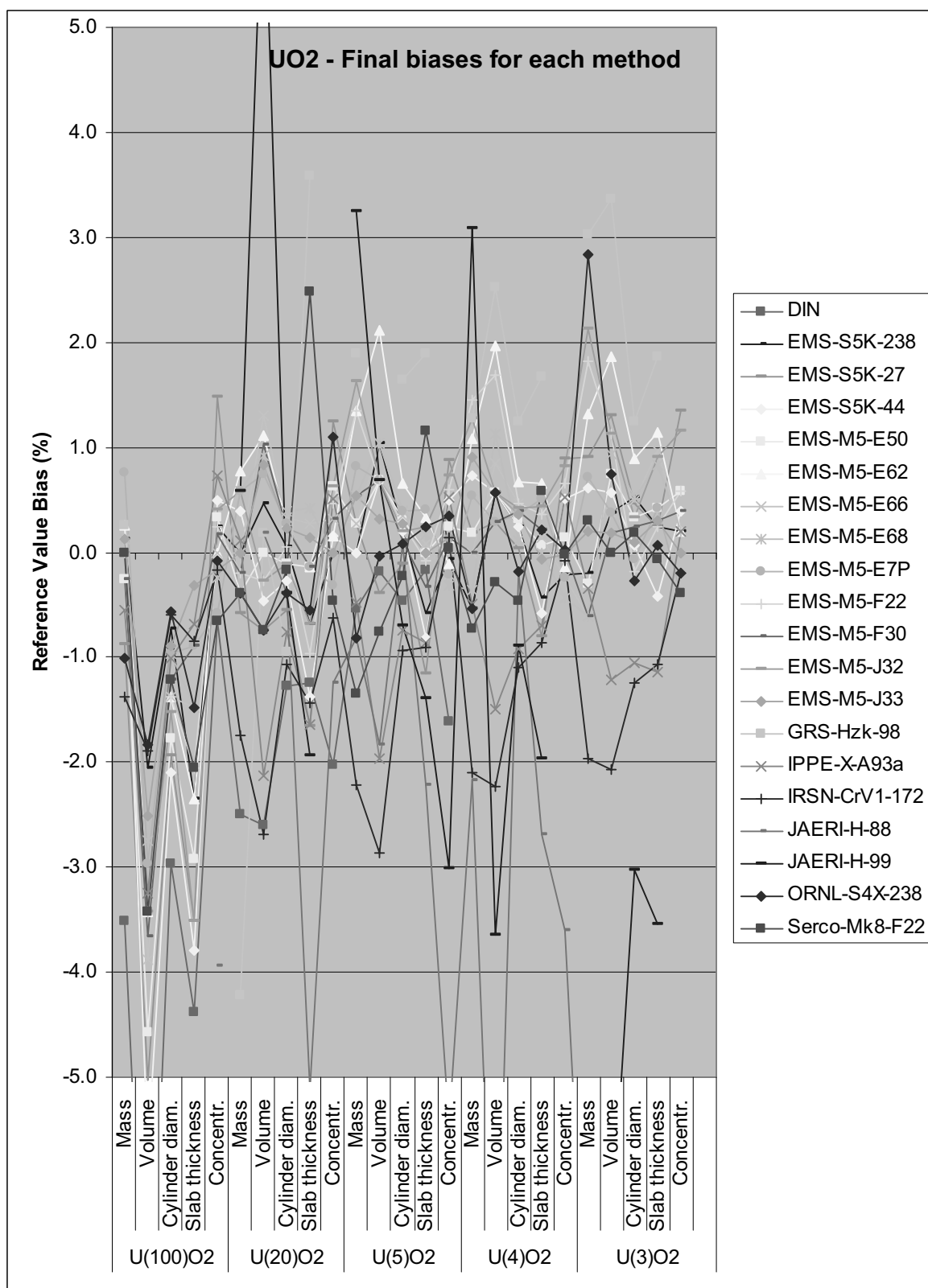


Figure 5. UO_2 reference values – Estimated total biases for “modern” method (enlarged)

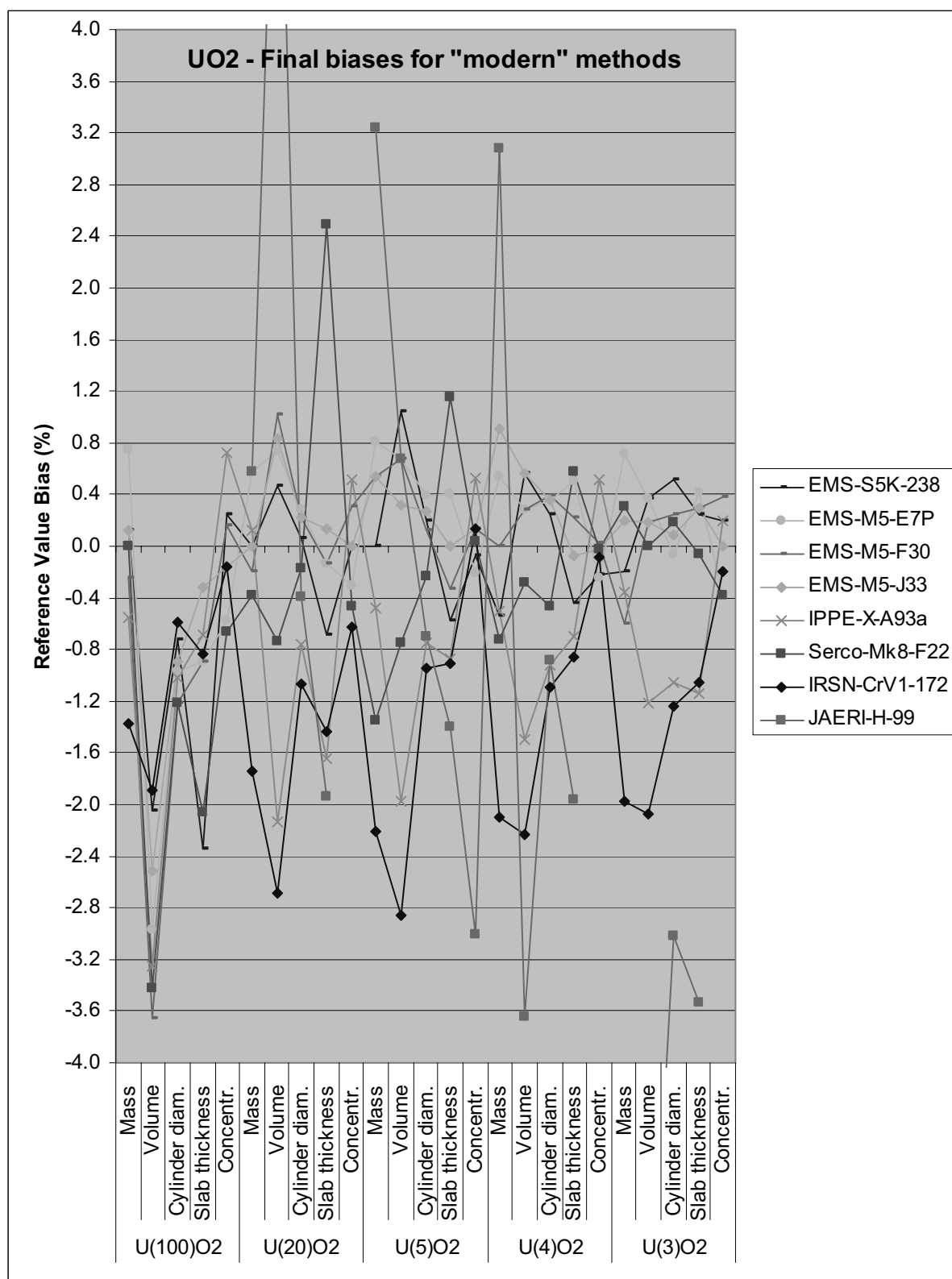


Figure 6. UNH reference values – Estimated total biases for each method

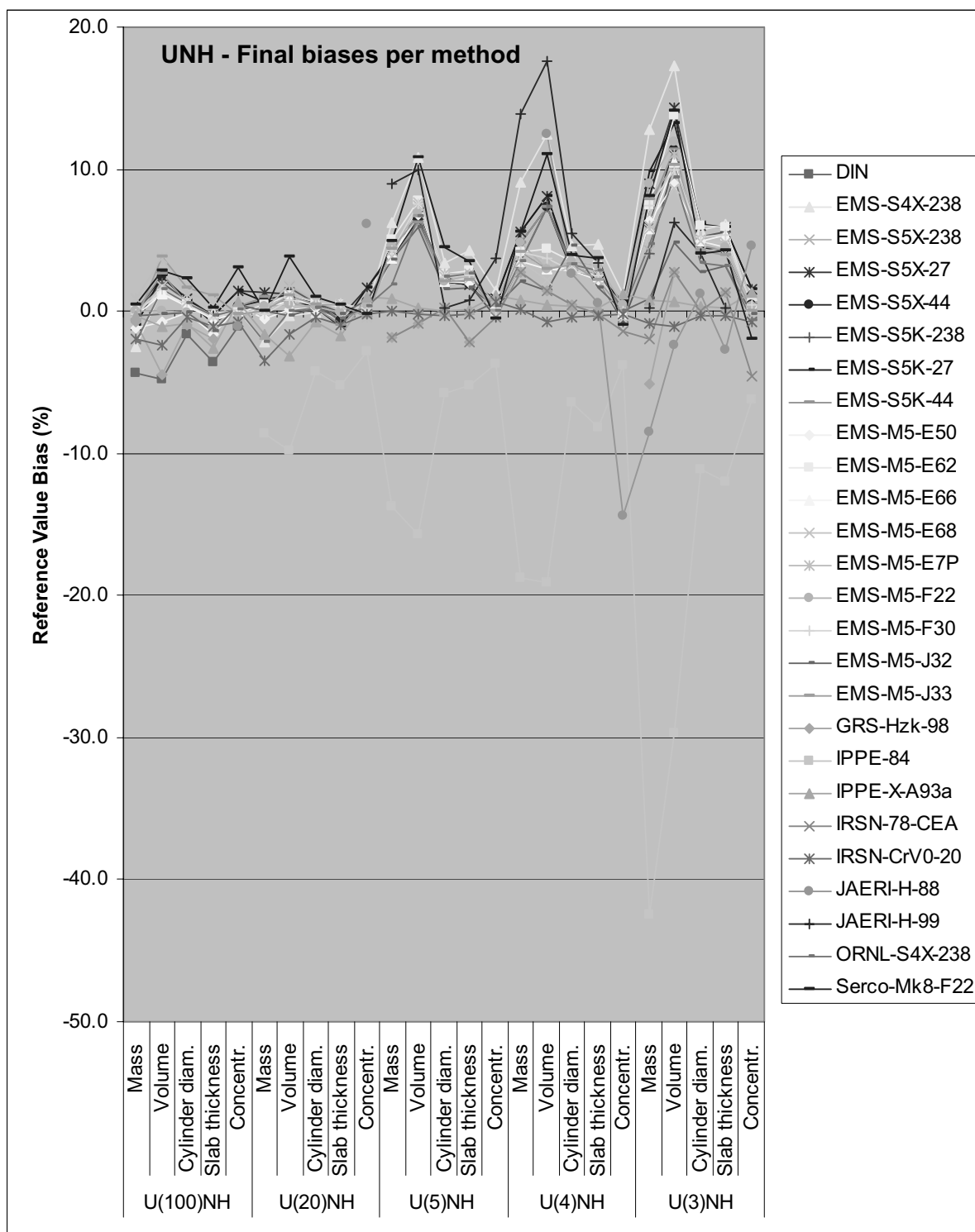


Figure 7. UNH reference values – Estimated total biases for each method (enlarged)

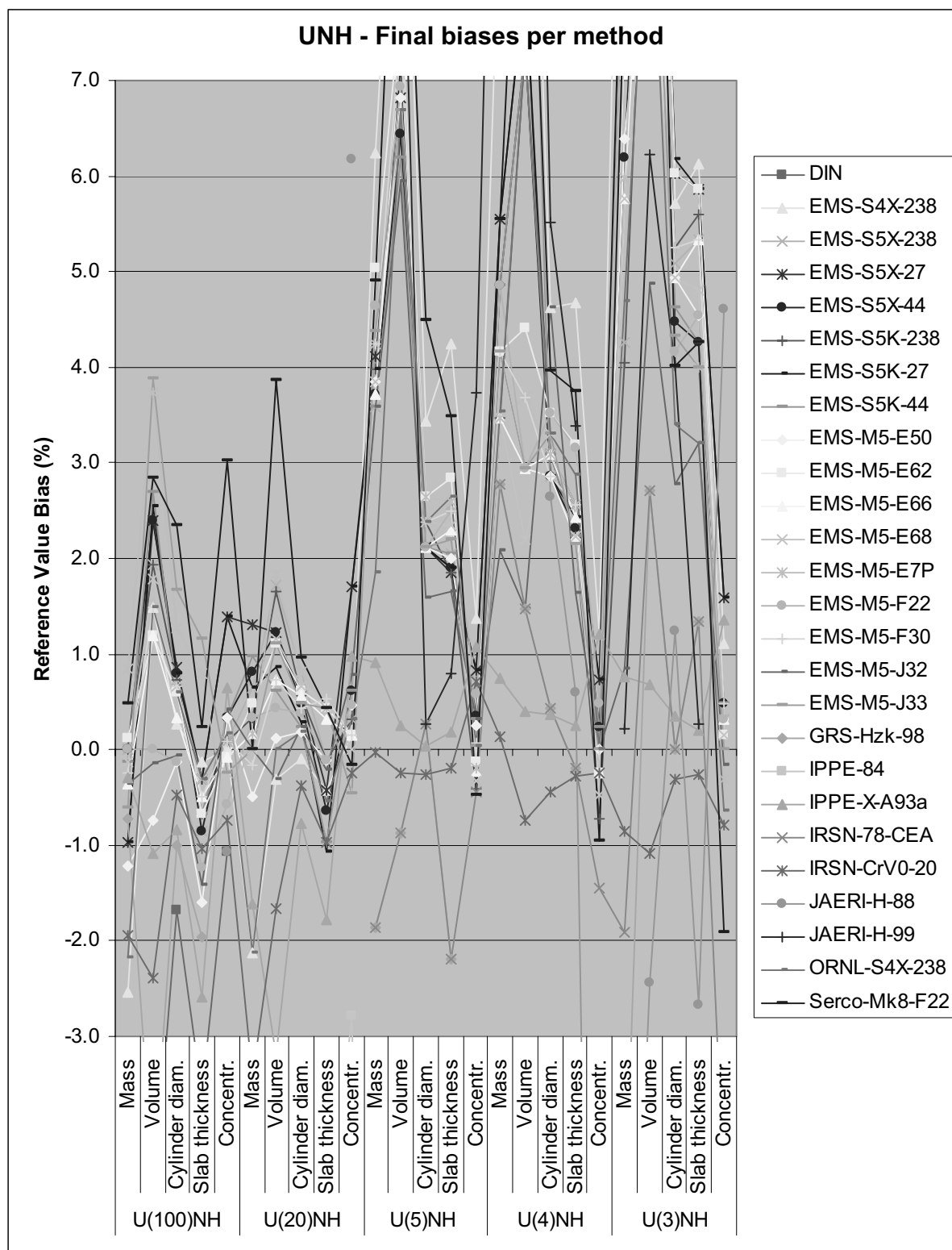


Figure 8. UNH reference values – Estimated total biases for “modern” method (enlarged)

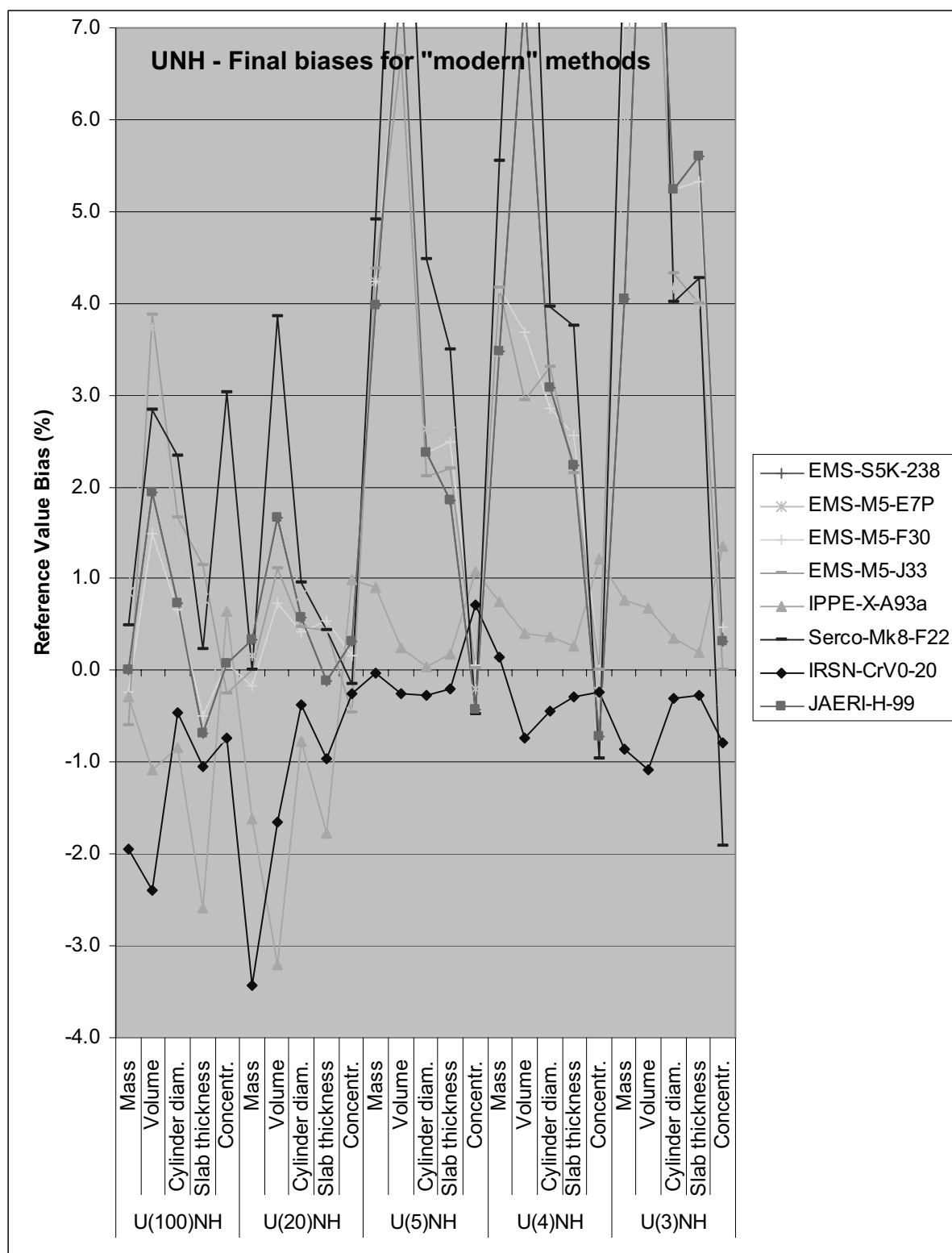


Figure 9. PuO₂ reference values – Estimated total biases for each method

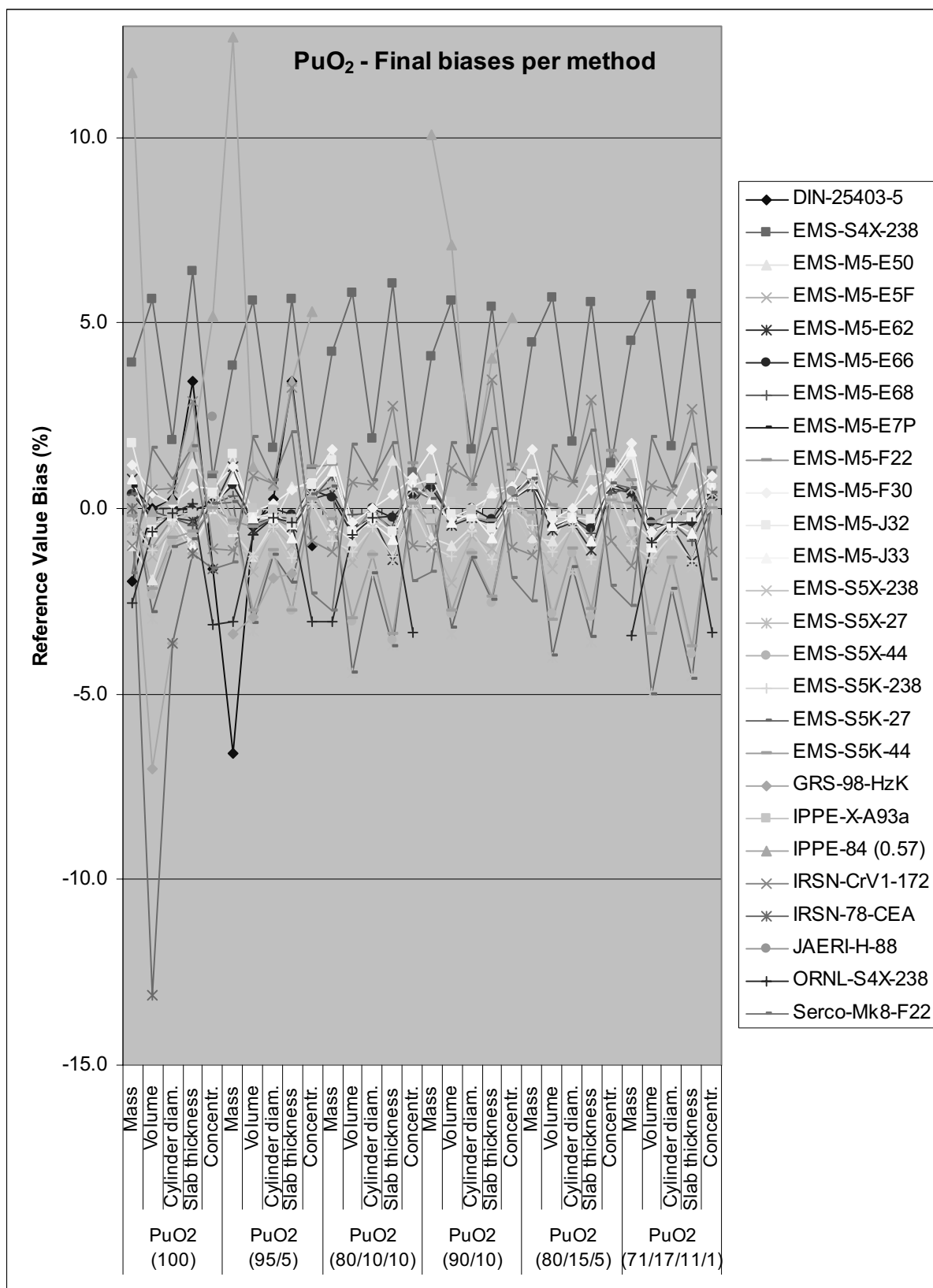


Figure 10. PuO₂ reference values – Estimated total biases for each method (enlarged)

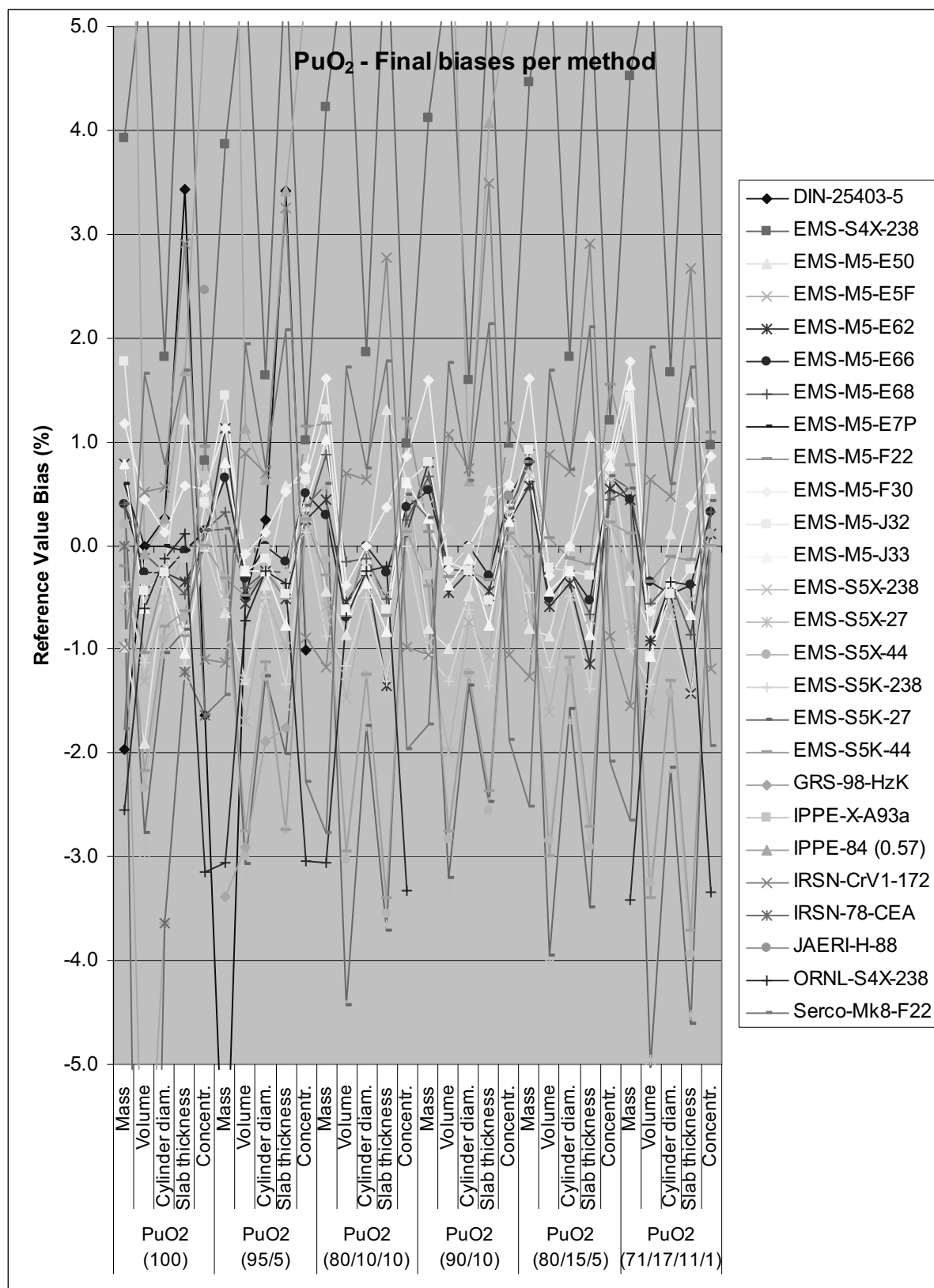


Figure 11. PuO₂ reference values – Estimated total biases for “modern” method (enlarged)

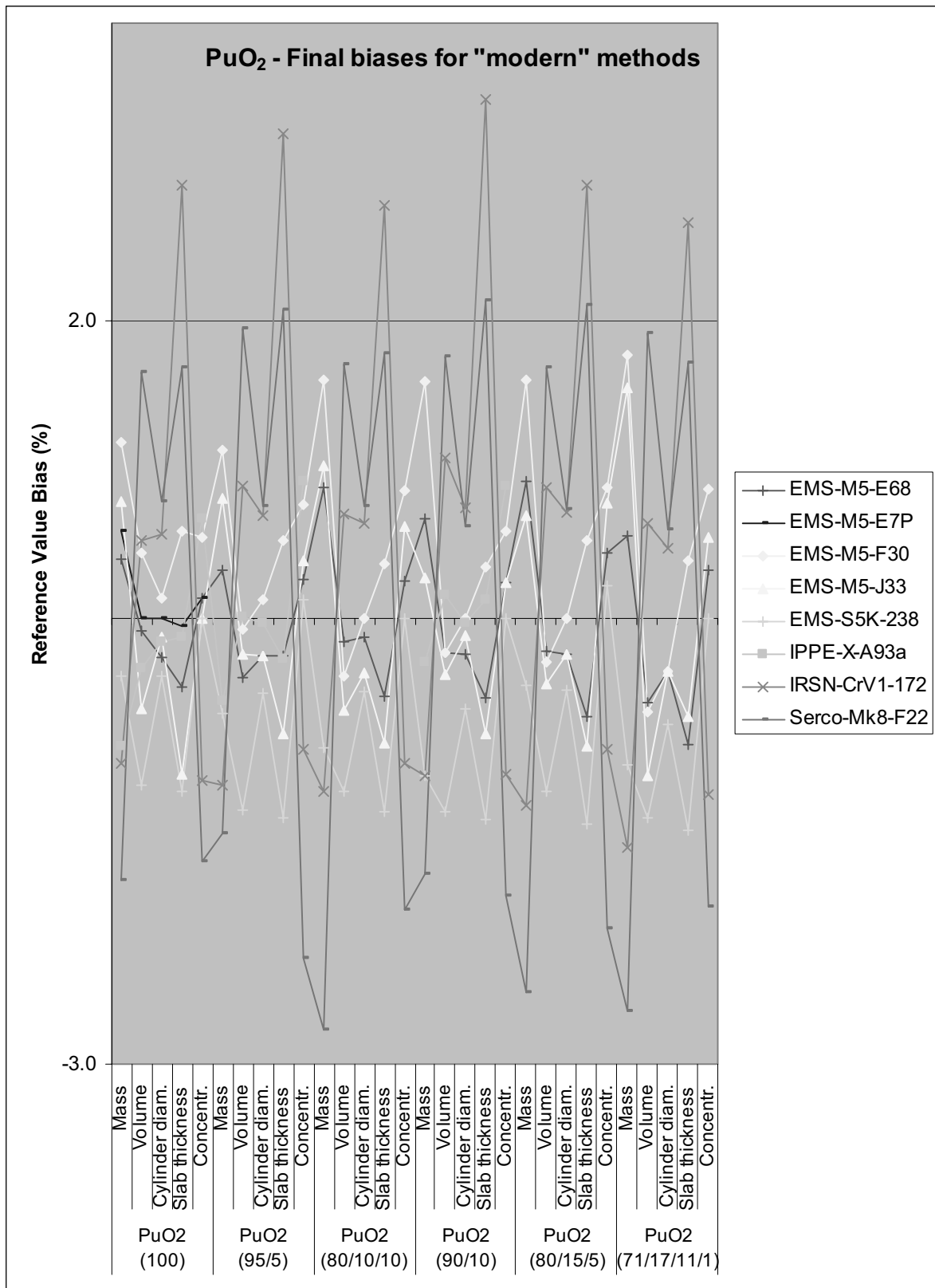


Figure 12. PuNH reference values – Estimated total biases for each method

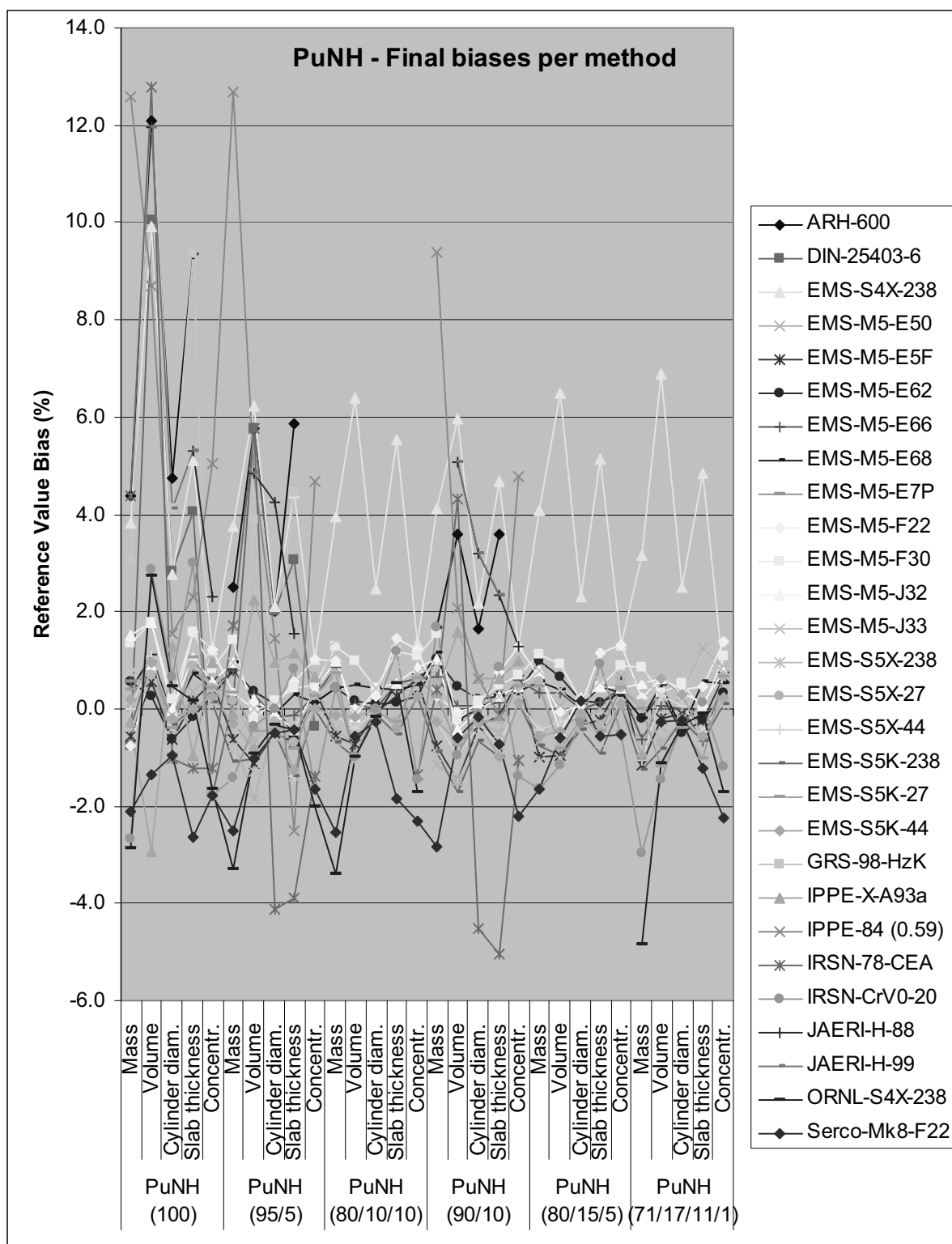


Figure 13. PuNH reference values – Estimated total biases for each method (enlarged)

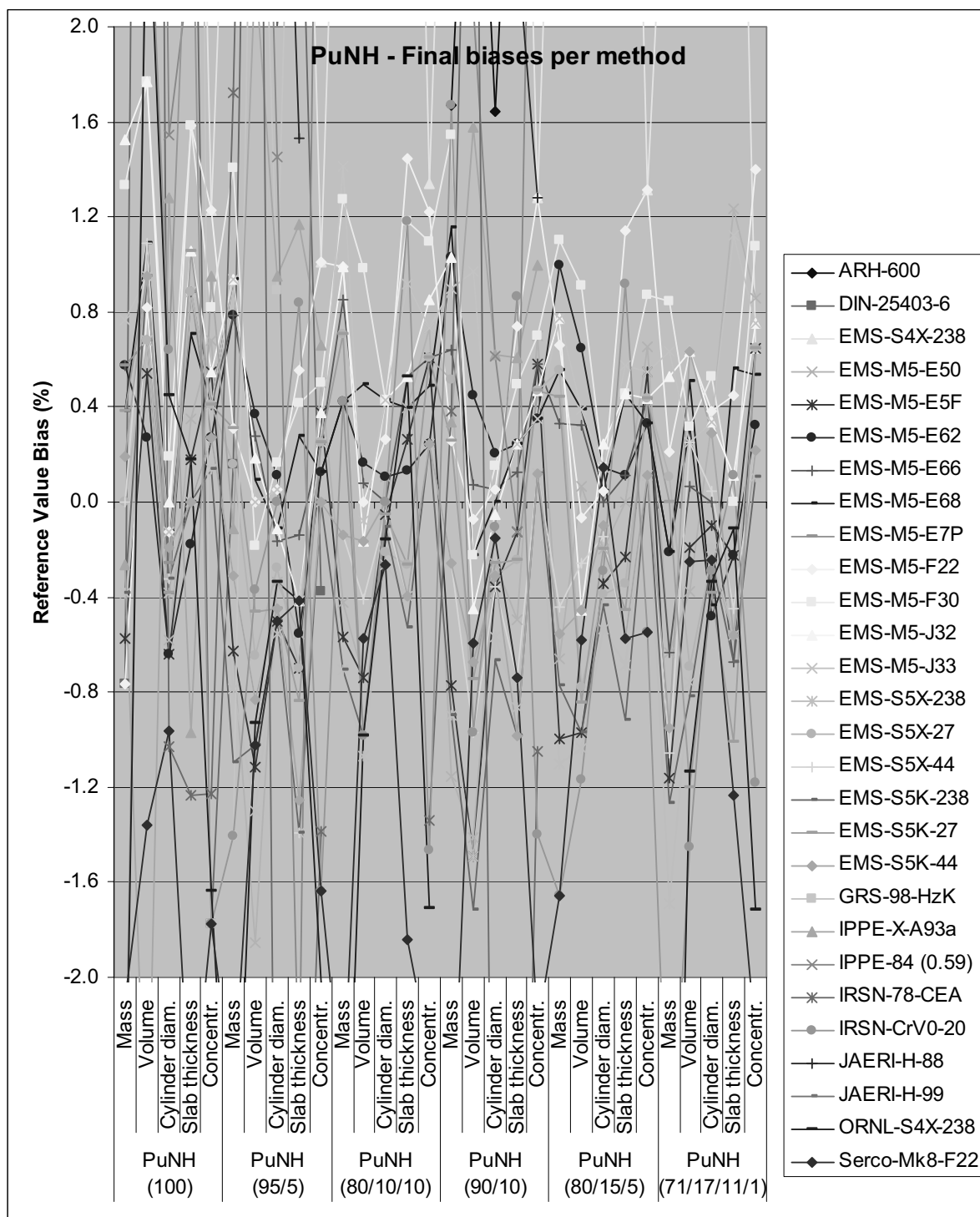
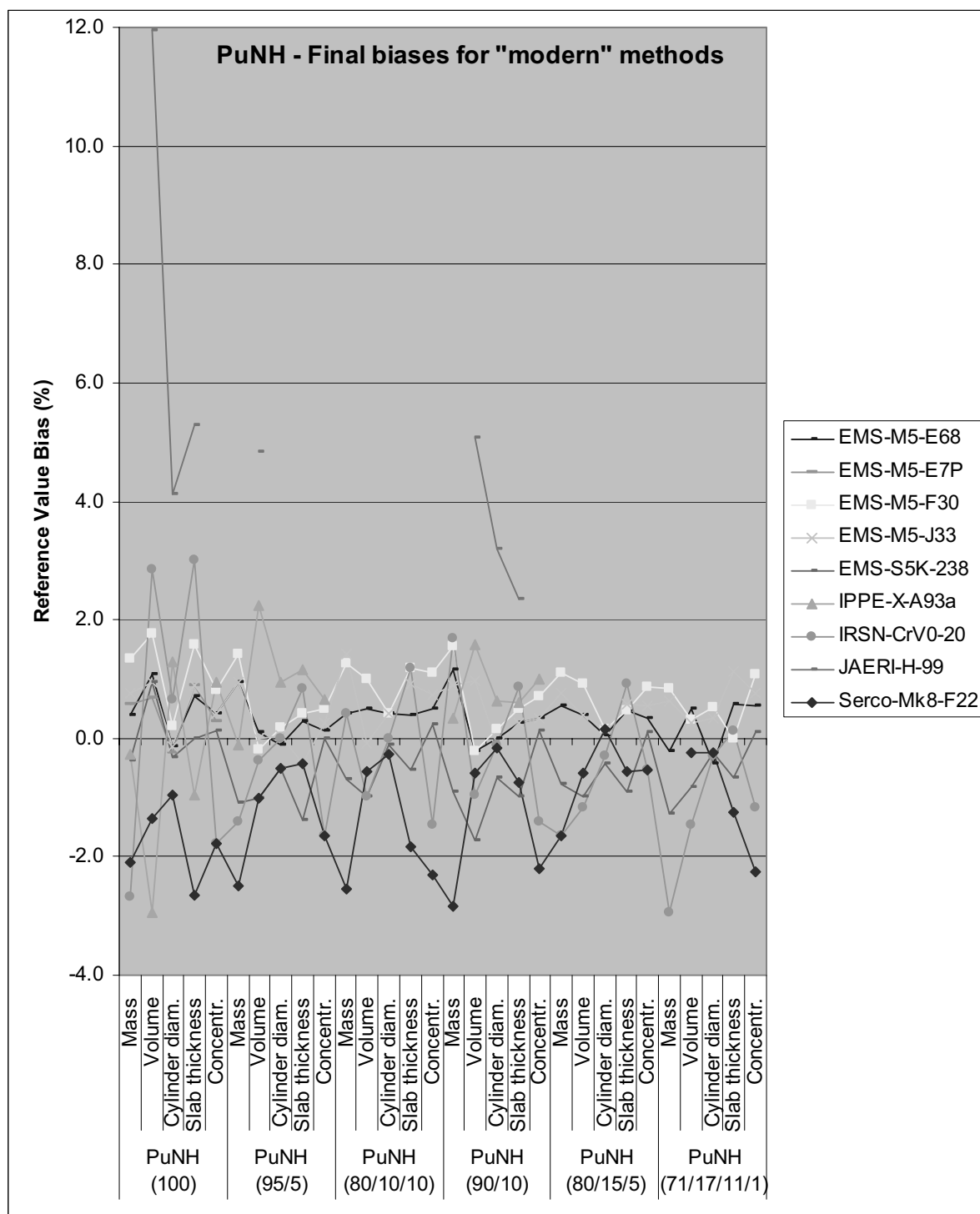


Figure 14. PuNH reference values – Estimated total biases for “modern” methods (enlarged)



DISCUSSION OF THE RESULTS OF THE STUDY

The availability of a large number of evaluated high-quality benchmarks [68] made it reasonable to expect that a comparison of best estimate results from validated methods would lead to quite close agreement. All the selected systems represent real operations and designs. Many experiments cover similar fissile materials and moderations.

If the best estimate values don't agree within reasonable uncertainty ranges, it could be a sign of inadequate validation. This was already clear during the selection of benchmarks; they are not sufficient for many reference systems. The evaluation of the validation results is very subjective.

Very late in the evaluation, comparisons of nuclide density methods were made. This is something that several contributors, in particular IRSN, had pointed out as a difficult area during the study. However, the main evaluator and report writer (EMS) had not previously been involved in such evaluations. The effort to compile conclusions from other participants in early 2005 turned out to be very complicated. The information was not very clear. Many contributors were busy with other projects, reducing the possibility for information exchange.

Some of the major experiences during the final evaluation from August 2004 until April 2005 are described below.

Insufficient accuracy in deterministic code applications

Experience from using the SCALE 4 and 5 deterministic code XSDRNPM showed early during the study that the default SCALE parameters were not sufficient to get accurate results for fast systems or for systems with thin slabs. The SCALE 5 results using XSDRNPM reported here have been confirmed with KENOvA calculations using the same cross-section libraries. The preliminary SCALE 5 results were not as accurate. For slabs, a finer mesh was required. For spheres in particular, but also for cylinders and maybe for slabs, increased (from 8 up to 64) orders of angular quadrature were required.

Preliminary IRSN CRISTAL calculations for fast system slabs and to some extent also for volumes (spheres) and cylinders showed that the default parameters (including cross-sections) for thermal systems were not sufficient. This has been recognised by IRSN; the results were preliminary and not intended as best estimate values. If used in safety applications, the errors would have been large and non-conservative.

IPPE, in their 1984 Handbook [20], made it very clear that the methods were not rigorous. However, the validation was sufficient to point out the errors and uncertainties. In many cases, the errors were cancelling each other. The results from this handbook (IPPE-84) are often deviating significantly from the best estimate results in this report.

Correlations between reference values

There are many correlations between the reference values. The calculation codes and cross-sections are not always independent even if they are developed or processed at different sites. The benchmarks are not independent. The nuclide density methods are not independent for each reference system or for each contribution. The input data for calculations of reference values are not independent. Statistical evaluations of outputs, biases and uncertainties are not independent.

All of the correlations involve errors and uncertainties. An example is the EMS input for MCNP5 calculations, using different cross-section libraries for the same reference system. Geometry and material specifications are identical, only the cross-section identifiers vary. The material specifications are identical to those used by EMS for SCALE 5 calculations. Comparing preliminary results, it was obvious for one reference system, U(100)NH slabs, that the differences between MCNP5 and SCALE 5 results were not credible. Checking the input, it was noticed that a comment “c” character in front of the thermal scattering data input line (MT) for MCNP5 was inadvertently retained. The system is moderated by water and this line should be present. Correcting the input for all 18 cases (2 each for 9 cross-section libraries) made the results consistent with SCALE 5 and other results.

Documentation, source documents, references

It is very important that the source documents are available for checking of information. There are many cases of discrepancies between reported values or methods and the information in the source documents. Sometimes various information sources inside a document are inconsistent as well. Important but unclear information in a reference should be clarified in a later publication.

The IRSN contributions, publications and presentations ([39], [40], [41], [60] and [89]) on the advantage of the isopiestic law compared with a former (1968) ARH-600 law for PuNH systems, as implemented in the pre-processor CIGALES, may at first not be easy to understand. These works pointed out that the density law formerly used by IRSN could lead to a k_{eff} underestimation up to 3.4 %. The problem was known since 1987. IRSN was aware of the 1972 revision of the ARH-600 method, based on a volume addition principle. However, IRSN preferred to wait for the development of an approach based on physical considerations that could take into account higher actinides and high concentrations (> 600 g/l). This development eventually resulted in the extended isopiestic law.

The caution against use of the 1968 ARH-600 PuNH density method is valid. Besides the IRSN use of it in some earlier codes, it may have been used in other safety analyses that are still applied. However, it has been confirmed that some sources, including the IRSN 1978 Standard de Criticité [21] as well as SCALE releases before version 5 are based on the 1972 revision of ARH-600 and do not cause the problems described by IRSN.

Input data for benchmarks

In safety applications, it is a common understanding that the validation of methods should be made with input that is representative of normal use of the methods. That is not a good idea for best estimate determinations, as requested here. The uncertainties should be reduced as much as possible. EMS has used input for validation of 16 methods (10 based on MCNP5 and 6 on SCALE 5) on input data from the ICSBEP Handbook [68]. Considering the lack of time and resources, this introduces much less uncertainties than if independent input data had been generated. However, some input examples from the ICSBEP Handbook may have significant errors and this may influence the bias-corrections for some systems.

A serious input error introduced in the latest version of the ICSBEP Handbook [68] was discovered during this validation work. The thermal plutonium benchmark set Pu-ST-022 contains 18 individual benchmarks. Nine are without neutron poisons, nine have such poisons. Only the first nine, the “clean” benchmarks were used here. The sample MCNP 4 results in the Handbook were surprisingly low, not consistent with other results using the ENDF/B-V cross-section library. A check of the sample input showed that a simple editorial mistake had caused an incorrect material composition for air (lots of cadmium). This is similar to the EMS input mistake mentioned above, under correlations. These benchmarks (Pu-ST-022) had been used in EMS validation before the 2004 issue. The 2004 edition contains corrections of benchmark errors in previous editions. The corrections seem to give very small k_{eff} changes. However, there seems to be other differences between the 2003 and 2004 sample inputs than the changed benchmark “editorial” errors and the changed benchmarks. Further efforts should be made to check the MCNP 5 validation against this benchmark series.

The sample input data and results in the ICSBEP handbook are very valuable to the criticality safety community. It gives us something to compare our own calculations with. It makes it easier to improve the Handbook by finding input mistakes and editorial errors. However, the Handbook input data and sample results are not intended for direct safety applications. They are not reviewed as closely as the benchmark specifications.

Reference system specifications

The study started without specifications of which reference systems to be evaluated. They were introduced during the first two, maybe even three years of the study. Now, it seems as if the specifications for the nitrate systems were not sufficiently clear. The intention was certainly to cover all credible mixtures of the hydrated nitrate crystals with water. However, the reference to solutions is misleading. The crystallised theoretical density material is not a solution. It is homogeneous, uniform and sufficiently realistic for consideration in a safety application. The concentration range between saturation of the solution (solubility limit) and the crystal form was not well defined.

It would have been better if the specifications had expressed clearly that a mixture of saturated solution and crystals needed to be considered. Also, results at crystal density should have been requested even if they are not the minimum values (they are still very important reference values).

Theoretical densities involving actinides with different isotope distributions

The Japanese handbook [24] clearly informs the reader that the theoretical density for UO_2 varies, depending on the enrichment ^{235}U . In connection with work on criticality properties of all actinide nuclides [95], EMS used this information to determine theoretical densities for other nuclides than that for which the original density was specified for. The simple basis is that the material structure of a specific element, and thus its atomic density, doesn’t depend on the mass of the isotope. The atomic number densities remain the same, independent of the isotope. This automatically leads to different theoretical densities for different isotopic distributions. E.g., for UO_2 , the density with natural uranium is 10.96 g/cm^3 while it becomes 10.84 g/cm^3 if all uranium consists of ^{235}U .

It seems as if all contributions, except the IRSN CRISTAL values, have been based on a fixed UO_2 theoretical density of 10.96 g/cm^3 . For fast systems involving $\text{U}(100)\text{O}_2$, this introduces a bias. A correction was determined, based on SCALE 5 calculations. For plutonium systems, the correction is smaller since they are dominated by the isotope ^{239}Pu , for which the PuO_2 theoretical density 11.46 g/cm^3 has been used by most contributors. An exception is IPPE who has used 11.44 g/cm^3 in their recent contributions with ABBN93 cross-sections. The over-prediction of the minimum critical

volume is about 4 ml, or going from 1.148 to 1.144 litres. This is not much in safety applications. For this evaluation of best-estimate values such differences are significant. It is about 0.4 % which is the total uncertainty (one standard deviation) quoted for the MONK 8B contribution from Serco.

Nuclide density methods

A more thorough investigation of the density methods used in different contributions was made very late during the evaluation (end of February, March 2005). At this time it had already been discovered that SCALE 5 had problems with densities above solubility and gave seriously incorrect information about the crystal density.

All contributions, except the IRSN extended isopiestic method, for UNH with uranium having low ^{235}U enrichment involve dubious density methods. The systems at crystal densities are not calculated correctly, except for the IRSN method and the IPPE simple mixing (no solution) method. This is basically a user problem and not a method problem. However, the information given in SCALE (in particular SCALE 5) output about the crystal density is not correct.

The solution equations should not be used above the solubility limits. The Pitzer method, as used in SCALE 5, is not intended for direct calculation of concentrations above the solubility limit [54]. It replaced a method (ARH-600) in earlier versions that also was limited to the solubility range but was commonly applied to higher concentrations.

Sometimes the applicability ranges, as stated by method developers, are even more restricted than the soluble range. The IRSN extended method combines a solution method (the isopiestic law) with crystals in a homogeneous, uniform mixture. That appears to be a reasonable method for covering the whole range of concentrations.

Also below the solubility limits, the different methods vary significantly. It was too late to start validation work of the various methods in March 2005. Instead, the IRSN isopiestic method has been used as a reference when the best estimate reference values have been determined.

JAERI informed the Expert Group in August 2004 about incorrect results due to the Moeken equation, used to derive reference values for UNH in the Japanese Handbook and its associated Data Collection. The information from Serco on the method used to get densities for MONK also appears to demonstrate some weaknesses (non-conservative).

Benchmark accuracies

The selection of benchmarks for bias and uncertainty estimation is very important. Traditional trending against some parameter such as H/X ratio, average fission energy or energy corresponding to average lethargy of neutrons causing fission (EALF) are often useful for simple systems like the ones included in this study. Enrichment ^{235}U is also a likely trending parameter. During the evaluation of this study, the new techniques in SCALE 5, TSUNAMI-IP ([79], [86], [87] and [88]) were also taken advantage of (see APPENDIX H).

Information about the similarities of benchmarks to applications is very important. However, equally (?) important to the weighting of benchmarks is the accuracy of the benchmarks. A single benchmark with an accuracy of 0.001 in k_{eff} has the same statistical weight as nine independent benchmarks, each with an accuracy of 0.003 in k_{eff} . Many benchmarks have much larger uncertainties.

Criticality Safety Handbooks

The various handbooks are very valuable to criticality safety specialists. However, each handbook contains errors and uncertainties. Several have been discovered or demonstrated during this study and during the final evaluation. Even the most recent one, the Japanese Handbook version 2 [24], contains a serious error. The minimum critical mass for $\text{U}(20)\text{O}_2$ is given in the Handbook and in the first contribution to the study as 7.43 kg ^{235}U . This is about 40 % too high. JAERI is aware of the problem (simple mistake) and a new value has been contributed.

Validation for Safety or Best Estimate evaluations

The traditional methods for safety validation have not been very useful in determining bias-corrections for the requested reference values. The ORNL validation report [52] used by EMS in 2001 and referred to by ORNL covers a wide range of systems. The uncertainties appear large enough to cover incorrect bias-corrections. A similar problem also appears to be the case for the validation and bias-corrections used to determine the values in the Japanese Handbooks.

Fissionable material reactivity comparison

The preliminary classification of the order of plutonium isotope distributions was based on the fraction of fissile plutonium isotopes as opposed to fissionable-only isotopes in the total plutonium element. When the fissile fractions were equal, the ^{241}Pu isotope was weighted higher than ^{239}Pu .

When all results have been compiled and evaluated, the reactivity classification worked, except for one reference system. A water-reflected $\text{Pu}(80/10/10)\text{O}_2$ critical slab is thinner than a water-reflected $\text{Pu}(95/5)\text{O}_2$ critical slab. For identical materials in sphere and cylinder forms, the opposite conclusions can be drawn about the corresponding reference values.

This experience demonstrates some of the complications that can be expected when reactivity equivalencing is applied.

RECOMMENDATIONS FOR FURTHER WORK

The study should be completed by striving for a consensus on best-estimate reference values and uncertainties. This is covered by the scope and objectives for the work reported here. As stated frequently during the first part of the study, the values are physical constants. Their accuracies depend on the availability of benchmarks (cross-sections, nuclide densities, etc.), of quality methods and on quality evaluation techniques. Such efforts fit very well in the structure of the OECD/NEA and with efforts carried out by other international organisations such as IAEA and ISO.

Clearer specifications of the nitrate reference systems are needed. It is suggested that the solubility limit is stated, when possible. The crystal density should be specified and reference values for this state should be evaluated, whether they correspond to minimum critical values or not. Theoretical densities for all compositions should be specified, including influences of isotopic variations. The H/X atomic ratio is a better reference parameter than concentration in g/cm^3 and should be determined accurately.

The large spread in results for some reference systems indicates that the validation process can be improved significantly. There are many benchmarks that were not included because they appeared to be complicated. However, the complications may not necessarily invalidate them from supporting the evaluation of the selected reference systems.

A complete validation is necessary. This means that benchmarks on nuclide densities are needed. As already pointed out by IRSN, the ICSBEP Handbook often contains sufficient information to expand the current benchmarks to include nuclide density determination based on chemical data.

Modern tools for criticality safety assessment should be used in the work. Further, the work may also lead to suggestions to code developers for additional output information to support the user. An example of recent improvements is the addition of EALF values in SCALE 5 (XSDBNPM/S and KENOVA) and in MCNP5. Use of the new TSUNAMI and SMORES sequences in SCALE 5 as well as options in other methods could lead to suggestions for additional information in the code output.

The issue of k_{eff} versus reference parameter relationships should be discussed. The curves can be approximated using various equations. The k_{eff} versus spherical radius proposed by Rombough [96] is an example. Statistical evaluation methods and uncertainty distributions may also be studied. The issue of k_{eff} correlations when input parameters are independent could easily be demonstrated.

A database of calculated values of k_{∞} for all actinide nuclides as well as for many compositions would be easy to compile and valuable for many purposes. Different reflectors are already included in the scope and objectives of the current study.

The concept of “minimum critical values” is too limited even for the past study (H/X ratios are maximum critical values) and should be replaced by “reference values”.

CONCLUSIONS

As in previous studies on comparisons of criticality safety methods by OECD/NEA Expert and Working Groups, appropriate validation is a necessary key to success. To determine the requested reference values, the traditional method of validation against benchmarks based on critical experiments is not sufficient. Such validation is only partial, like a verification of computer codes and cross-section data. It is obvious that a complete validation requires benchmarks to test nuclide density determination methods. Some of the ICSBEP Handbook benchmarks can be extended for that.

It was not a surprise to find that some of the older data in criticality safety handbooks appear to have large errors, some non-conservative. It was more surprising to find that modern tools seem to be insufficiently validated or documented to warn users about lacking support for certain applications. Deterministic calculations of fast systems require special verification of cross-sections and of input parameters. Actinide nitrate densities outside the soluble ranges that were calculated quite well in a previous version caused SCALE 5 to give seriously incorrect information to the user. Potential consequences of changes to a successful system always need to be checked carefully.

Many discrepancies have been identified and resolved. Most of them have been corrected during the study, without publication. Published incorrect values should be corrected in a public report. Besides the SCALE 5 nitrate density problem, some others should be mentioned. IRSN has reported that the plutonium nitrate density law applied up to the year 2000 in the graphical user interface CIGALES (generates nuclide atom densities) caused serious underestimation in k_{eff} , increasing with plutonium concentration. This old IRSN density method was based on a 1968 release of the ARH-600 handbook. This release may also have been used by other organisations in safety analyses that are still applied. However, the equation was corrected in a 1972 revision of the ARH-600 handbook and this is the method used in SCALE before release 5. A very serious error for the $\text{U}(20)\text{O}_2$ minimum critical mass in the Japanese Handbook [24] was noticed during the evaluation and has been corrected by JAERI. The critical and safe masses in the Handbook are over-predicted by 40%.

One of the reasons for slow progress has been that several participants have not been convinced that the determination of best estimate reference values is feasible for criticality safety applications. It is clearly included in the scope and objectives. Hopefully, this report demonstrates that it is feasible.

Selection of benchmarks for the final evaluation was made using accuracy and simplicity as primary indicators. A single benchmark with a k_{eff} uncertainty of 0.0010 should be weighted as high as ten independent benchmarks, each with a k_{eff} uncertainty of 0.0031. Similarity indices based on the SCALE 5 TSUNAMI sequences as well as on energy corresponding to average lethargy of neutrons causing fission (EALF) seem to work quite well. For some of the reference values, the validation appears very successful while the opposite seems true for other reference values.

A comparison of nuclide densities for nitrate solutions showed surprising variation, even within the soluble range of actinide concentrations. The IRSN work on the extended isopiestic law as reported to the Group has been valuable to support this report.

A solid (theoretical density) Pu(80/10/10)O₂ critical slab is thinner than a solid Pu(95/5)O₂ critical slab when both are water-reflected. This may seem surprising since the opposite is true for sphere and cylinder reference values for the same materials and reflection.

A compilation of calculated values (“raw data”) without support from validation is not very meaningful on its own. The scope of the study is primarily focused on the physical constants, the reference values, and after that on the performance of calculation methods and handbooks. Using the established reference values, the discrepancies in results reported from different methods and handbooks can be evaluated. Also the general performances of common methods and handbooks are of interest to the criticality safety community.

The Expert Group early agreed that the results of the evaluation, when agreed upon, should be in the form of reference values and not as recommended values. It is up to the user to determine how to apply the values. This was confirmed in an enquiry during the 2004 meeting.

The final best estimate reference values reported are for demonstration only. They are not even preliminary values. This conclusion applies even more to the uncertainties. There may still be correlated errors that could lead to significant changes. The evaluation of best estimate reference values is subjective. A consensus on the values has not been requested since it would take considerable time and require additional resources and evaluations. The procedure leading to the determination of each reference value should be clear enough to explain the value and to support improvements.

REFERENCES

Initiation and development of the study

- [1] OECD/NEA Nuclear Science Committee, Working Party on Nuclear Criticality Safety, <http://www.nea.fr/html/science/wpncs/index.html>
- [2] Y. Naito, H-H. Schweer, W. Weber, Basic Minimum Values of Criticality, Proposal of an International Project, 1998-05-12.
- [3] J. Anno, Contributions to elaborate on international standard on minimum critical values, 1998-05-19 and 1999-09-15 (also listed under IRSN contributed papers).
- [4] C. Parks, Minimum Critical Values, Experimental Data, Fax 1999-09-03.
- [5] 1st meeting 1999
- [6] 2nd meeting 2000
- [7] 3rd meeting 2001
- [8] 4th meeting 2002
- [9] Working Party Meeting 2002.
- [10] Informal meeting 2003
- [11] Working Party Meeting 2003.
- [12] 5th meeting 2004
- [13] Request for comments on a number of specific and general questions by D. Mennerdahl during 5th meeting. Extensive replies from almost all participants that were asked, including e-mail from some that were not present (J. Anno, N. Barton).

Published data in Handbooks and other literature

- [14] R.D. Carter, G.R. Kiel, K.R Ridgway, "Criticality Handbook", ARH-600, 1968 with updates up to 1976. Available on the internet at: <http://ncsp.llnl.gov/ARH600/index.htm>.
The original pages and early (before 1972) revised pages are very significant for this study.
- [15] DIN 25403-4, "Kritikalitätssicherheit bei der Verarbeitung und Handhabung von Kernbrennstoffen, Teil 4: Kritikalitätsdaten für Urandioxid-Leichtwasser-Mischungen", Oktober 1995.
- [16] DIN 25403-5, "Kritikalitätssicherheit bei der Verarbeitung und Handhabung von Kernbrennstoffen, Teil 4: Kritikalitätsdaten für Plutonium 239-Dioxid-Leichtwasser-Mischungen", September 2000.
- [17] DIN 25403-6, "Kritikalitätssicherheit bei der Verarbeitung und Handhabung von Kernbrennstoffen, Teil 6: Kritikalitätsdaten für Plutonium 239-Nitrat-Leichtwasser-Mischungen", September 2000.
- [18] DIN 25403-8, "Kritikalitätssicherheit bei der Verarbeitung und Handhabung von Kernbrennstoffen, Teil 8: Kritikalitätsdaten für Uranylnitrat (100 % Uran-235)-Leichtwasser-Mischungen", Oktober 1995.

- [19] Heinicke, Krug, Thomas, Weber, Gmal, Moser, "Handbuch zur Kritikalität", Gesellschaft für Anlagen- und Reaktorsicherheit (GRS), Dezember 1998.
- [20] L.V. Diev, B.G. Ryazanov, A.P. Murashov *et al.*, "Critical Parameters of Fissile Materials and Criticality Safety, Handbook," Moscow, Energoatomizdat, 1984. 4 scanned pages from the original report were sent by IPPE to EMS for verification.
- [21] L. Maubert, "Standard de criticité – Valeurs minimales critiques", CEA-N-2051, 1978.
- [22] "Nuclear Criticality Safety Handbook (English Translation)", JAERI-Review 95-013, September 1995. The Nuclear Safety Bureau/Science and Technology Agency compiled the Japanese original, 1988.
- [23] "Nuclear Criticality Safety Handbook, Version 2", JAERI-1340. In Japanese. 1999.
- [24] "Nuclear Criticality Safety Handbook, Version 2", JAERI-Review 2001-028. English translation. August 2001.
- [25] J. J. Chalmers, G. Walker, J. Pugh, "Handbook of criticality data, Volume I (Amendments and Additions – No.1)", AHSB(S) HANDBOOK 1 (1st revision), UKAEA/AHSB, Price Five Shillings Net. 1967.
- [26] B.G. Dubovskiy *et al.*, "Critical Parameters of Fissionable Materials Systems and Nuclear Safety (A Handbook", TT: 67-32951, Moscow, Atomic Publishing House, 23, 1966. Translation by U.S. Department of Commerce, JPRS: 42,322, 23 August 1967. Available in [28].
- [27] "Guide de Criticité", Rapport CEA-R 3114, CEA, 1967.
- [28] H. C. Paxton, N. L. Pruvost, Critical Dimensions of Systems Containing ²³⁵U, ²³⁹Pu and ²³³U, 1986 Revision", LA-10860-MS, Issued July 1987. A CD-ROM package, with REFSET including the report and most of the references, is available from LANL.

A selection of contributions from participants (alphabetical order of organisations)

EMS, Sweden

- [29] D. Mennerdahl, *Basic Critical Values*, Project report EMS/NC/2001-01, 2001-03-14.
- [30] D. Mennerdahl, *Reference Values for Nuclear Criticality Safety*, Project report (draft) EMS/NC/200401, 2004-02-07.

GRS, Germany

- [31] W. Weber, Minimum Critical Mass of U(05), U(20), U(60), U²³⁵, Pu²³⁹, U²³³ Oxides, SCALE4.3 and MCNP-4A Calculations, Presented at meeting in 1999-09-15.
- [32] W. Weber, "SCALE and MCNP calculation of systems, using nuclide densities by J. Anno, IRSN, UNH-H₂O and PuNH-H₂O spheres, 20 cm H₂O refl", October 2003.
- [33] R. Kilger, B. Gmal, "Density relationships for UO₂F₂-systems and their impact on critical values", A presentation at the meeting in Prague, Czech Republic, 31 August 2004.
- [34] B. Gmal, Comparison of density methods, early versions of ARH-600, e-mail March 2005.

IPPE, Russia

- [35] Y. Rozhikhin, Electronic mail communication (2004). Information on IPPE handbook (1984). IPPE results of benchmark validation and reference values using ABBN93 cross-section library. Comparison of Monte Carlo and deterministic codes using the same cross-section library. 2004.

IRSN (Formerly IPSN), France

- [36] J. Anno, List of Documents from CEA & IPSN/SEC Related to Minimum Critical Values, Presented at meeting 1999-09-15.
- [37] J. Anno, “Contributions to elaborate an international standard on minimum critical values”, Proposal/OECD meeting – Criticality, 1998-05-19 and 1999-09-15.
- [38] J. Anno, Tentative IPSN Contribution Related to General Uncertainty Estimations of the Data, Presented at meeting in 2000-09-13.
- [39] N. Leclaire, G. Poullot, G. Courtois, J. Anno, Lois de dilution des solutions nitriques des actinides et de leur mélange: Uranium (VI), Uranium (IV), Plutonium(IV), Plutonium(III), Americium(III) et Thorium(IV), SEC/T/01.058 Indice A du 21 décembre 2001.
- [40] G. Poullot, J. Anno, G. Courtois, N. Leclaire, *Density laws of actinides nitric solutions and their mixtures:* IRSN report SEC/T/03.023 Indice A. 30 janvier 2003. (translation of SEC/T/01.058 Indice A du 21 décembre 2001)
- [41] J. Anno, “Lois de Dilution Isopiesticques – Valeurs minimales critiques des solutions aqueuses ($H^+ = 0$) du nitrate d’uranyle et du nitrate de plutonium reflechies par de l’eau (20 cm), du beton (60 cm) et le coupe plomb – eau (25 cm + 20 cm)“, SEC/T/01.102 Indice A du 17 février 2002
- [42] J. Anno, General methodology of the MCV data related to IPSN contribution, Presentation related to expert group meeting in 2002.
- [43] IRSN results for UO_2 and PuO_2 . Email May 2005 (late contribution supported by the evaluator and by OECD/NEA).
- [44] Preliminary IRSN results for UO_2 and PuO_2 using default input data and extrapolations. Not intended for publication or contribution as best estimate values. Withdrawn in April 2005.
- [45] V. Rouyer, Information on older IRSN reference values. Email March 2005.
- [46] N. Leclaire, Discussion on ARH-600 as used in IRSN codes. Email March 2005.

JAERI, Japan

- [47] H. Okuno, Critical Masses of Bare ^{235}U and of Its Mixture with Water, Presented at meeting in 1999-09-15.
- [48] H. Okuno, Y. Miyoshi, “Nuclear Criticality Safety Handbook/Data Collection”, A presentation at the meeting in Prague, Czech Republic, 31 August 2004.

NAIS, Japan

- [49] Y. Naito, The present status of the minimum critical data collection and related subjects, 20000907.
- [50] Y. Naito, How to obtain the Minimum Critical Values in the criticality handbook of Japan, Distributed 2002-10-30

NUPEC, Japan

- [51] S. Mitake, Minimum Critical Values of 20% Enriched Uranyl Nitrate Solution, Presented at meeting 2000-09-13.

ORNL, USA

- [52] P.B. Fox, L.M. Petrie Jr. and C.M. Hopper, *Minimum Critical Values Study*, ORNL/TM-2003/211, Draft December 2004.

- [53] L. Petrie, Density method in SCALE 5, e-mail, December 2004 and March 2005.
- [54] C. Weber, The new Pitzer method in SCALE 5, email March 2005.

Serco Ass., UK

- [55] D. Hanlon, J. Mackey, *Details of MONK Minimum Critical Values Study*, Serco report SA/R/PSEG/0509 Issue 1, July 2002.
- [56] D. Hanlon, *Details of MONK Minimum Critical Values Study – Addendum*, Serco report SA/R/PSEG/0509 Addendum Issue 1. February 2003. Electronic format (Word).
- [57] SERCO, *Calculation description*, Calculation_Description_SERCO-1.doc. 2003. 2003-08-16.
- [58] D. Hanlon, Information and correction of some reference values, email March 2005.

Selected presentations by participants at international meetings

- [59] J. Anno, V. Rouyer, N. Leclaire, “Minimum Critical Values of Uranyl and Plutonium Nitrate Solutions Calculated by Various Routes of the French Criticality Codes System CRISTAL using the New Isopiestic Nitrate Density Law”, Proceedings of the seventh international conference on Nuclear Criticality Safety (ICNC 2003), October 20-24, Tokai-mura, Ibaraki, Japan, JAERI-CONF-2003-019, Japan Atomic Energy Research Institute (2003).
- [60] N. Leclaire, J. Anno, G. Courtois, G. Poullot, V. Rouyer, “Isopiestic Density Law of Actinide Nitrates Applied to Criticality Calculations”, ICNC 2003 [59].
- [61] W. Weber, D. Mennerdahl, “Results of an OECD/NEA Comparison of Minimum Critical Values”, ICNC 2003 [59].
- [62] J. Anno, G. Poullot, “IPSN Studies on Dilution Laws”, ICNC ’99, Sixth International Conference on Nuclear Criticality Safety, Versailles, France, September 20-24, 1999.
- [63] P. Dannus, C. Sorel, “A New Concept to Estimate Density of Concentrated Solutions Containing Nitric Acid and Actinide Nitrates”, ICNC ’99, Sixth International Conference on Nuclear Criticality Safety, Versailles, France, September 20-24, 1999.
- [64] Y. Naito, W. Weber, H-H. Schweer, “Collection of Basic Values of Criticality”, ICNC ’99, Sixth International Conference on Nuclear Criticality Safety, Versailles, France, September 20-24, 1999.
- [65] T. Ivanova et. al., “Validation of the KENO/ABBN-93 Package Based on Data from the International Handbook of Evaluated Criticality Safety Benchmark Experiments”, ICNC ’99, Sixth International Conference on Nuclear Criticality Safety, Versailles, France, September 20-24, 1999.
- [66] M. Nikolaev, et. al., “On the Internal Inconsistency of Plutonium-Solution Critical-Experiment Data and the Need to Estimate Correlations Between the Experimental Uncertainties”, ICNC ’99, Sixth International Conference on Nuclear Criticality Safety, Versailles, France, September 20-24, 1999.
- [67] A. Nouri et. al., “Benchmark Review of JEF-2.2 Library for Criticality Analysis”, ICNC ’99, Sixth International Conference on Nuclear Criticality Safety, Versailles, France, September 20-24, 1999. Contains many MONK, APOLLOII-MORETIV and APOLLOII-Sn results.

Other references

- [68] J. B. Briggs, “International Handbook of Evaluated Criticality Safety Benchmark Experiments”, OECD, Paris, NEA/NSC/DOC(95)03. Usually referred to as the “ICSBEP Handbook” (relating to the Project), 2004 edition.

- [69] G. Poullot, D. Doutriaux and J. Anno, "ICSBEP Guide to the Expression of Uncertainties", (rev 1, 2004), in ICSBEP Handbook [68].
- [70] R. K. Disney, "A Review of the Current State-of-the-Art Methodolgy for Handling Bias and Uncertainty in performing Safety Evaluations", INEL-94/0251, October 1994.
- [71] OECD/NEA, "JANIS User's Guide", January 2004. Relates to version 2.0. Later revision to version 2.1 is available. A Java-based Nuclear Data Display Program, (DVD June 2004).
- [72] D. Mennerdahl, "Charts of η for fissionable nuclides and materials", EMS/NC/2004-04 (Internal EMS draft report), 2004-02-27.
- [73] D. Mennerdahl, "Basic criticality data and exception limits for actinide nuclides", EMS/NC/2002-01, (EMS draft report), 2002-07-31.
- [74] I. Duhamel, E. Letang, A. Cossenet, G. Poullot, "Experimental Validation of the APOLLO2-MORET4 Standard Route of the French CRISTAL V1 Package", ICNC 2003 [59].
- [75] S. Connolly, M. Grimstone, "The Development and Validation of a New Collision Processor for MONK", A presentation at ICNC 2003 [59].
- [76] T. T. Ivanova *et al.* "Influence of the Correlations of Experimental Uncertainties on Criticality Prediction", Nuclear Science and Engineering, p. 97, Vol 145, No 1, September 2003.
- [77] T.T. Ivanova *et al.* "Use of International Criticality Safety Benchmark Evaluation Project Data for Validation of the ABBN Cross-Section Library with the MMK-KENO Code", Nuclear Science and Engineering, p. 247, Vol 145, No 2, October 2003.
- [78] S.M. Bowman, W. C. Jordan, J. F. Mincey, C. V. Parks, L. M. Petrie, *Experience With the Scale Criticality Safety Cross-Section Libraries*, NUREG/CR-6686 (ORNL/TM-1999/322), U.S. Nuclear Regulatory Commission, Oak Ridge National Laboratory October 2000
- [79] "SCALE: A Modular Code System for performing Standardized Computer Analyses for Licensing Evaluation", Oak Ridge National Laboratory, NUREG/CR-0200, Rev. 7, Draft, May 2005.
- [80] X-5 Monte Carlo Team, "MCNP – A General Monte Carlo N-Particle Transport Code, Version 5", Los Alamos national Laboratory Report LA-UR-98-5718 (April 2003). Update to Release 1.30, including preliminary ENDF/B-VII cross-sections, late November 2004.
- [81] "ZZ-FSXLIBJ32", A JENDL-3.2 cross-section library for MCNP (ACE-format) from JAERI. Obtained from the OECD/NEA Data Bank, Paris.
- [82] "ZZ-FSXLIBJ33", A JAERI revised JENDL-3.3 based cross section library package for MCNP4C, Available as item NEA-1425/05 from OECD/NEA Data Bank, Paris, (2004).
- [83] Korean Atomic Energy Research Institute (KAERI), personal communication leading to cooperation in testing an ENDF/B-VI.8 cross-section library in ACE-format (MCNP). 2002.
- [84] "ZZ-MCJEF22NEA.BOLIB", An ENEA (Bologna, Italy) JEF 2.2 cross-section library in ACE format (MCNP) available from the OECD/NEA Data Bank as item NEA-1616/04.
- [85] S. Goluoglu, *et al.* "SMORES: A One-Dimensional Material Optimization Module", in [79].
- [86] B.T. Rearden, "TSUNAMI-1D: Control Module for One-Dimensional Cross-Section Sensitivity and Uncertainty Analysis for Criticality", in [79].
- [87] B.T. Rearden, "TSUNAMI-3D: Control Module for Three-Dimensional Cross-Section Sensitivity and Uncertainty Analysis for Criticality", in [79].
- [88] B.T. Rearden, "Sensitivity Utility Modules", covers TSUNAMI-IP, in [79].
- [89] N. Leclaire *et al.*, "Criticality Calculations Using the Isopiestic Density Law of Actinide Nitrates", Nuclear Technology Vol. 144, pp. 303-323, December 2003.
- [90] C.F. Weber, C.M. Hopper, "Modeling Actinide Solution Densities with the Pitzer Method", Transactions of American Nuclear Society, Vol. 89, pp. 123-124, November 2003.
- [91] C.F. Weber, C.M. Hopper, "Application of the Pitzer Method for Modelling Densities of Actinide Solutions in the SCALE Code System", Approved for publication in Nuclear Technology, 2005.

- [92] D. Mennerdahl, "A Declaration of Independence – What Is It Worth?", pp. 109-110, Vol. 90, Transactions of ANS Annual Meeting, Pittsburgh, June 13-17, 2004.
- [93] D. Mennerdahl, "SCALE on Large and Small Computers", pp. 125-131 in Workshop on the SCALE-3 Modular System, Saclay, 24-27 June 1986. NEA Data Bank Newsletter No. 33, October 1986. Describes use of SCALE on a personal computer.
- [94] NCSL International, "U.S. Guide to the Expression Of Uncertainty in Measurement", ANSI/NCSLZ540-2-1997 (R2002). American National Standard for Calibration. ANSI approved the standard 1997, reaffirmed it 2002.
- [95] C. Lavarenne, D. Mennerdahl, C. Dean, "Evaluation of nuclear criticality safety data and limits for actinides in transport", SEC/T/03.146, May 2003
- [96] C.T. Rombough, S.H. Martonak, N.L. Pruvost, "Search Technique for Calculating Critical and Subcritical Configurations with MCNP", Transactions of American Nuclear Society, Vol. 76, pp. 197-200, June 1996.
- [97] S.C. van der Marck, A. Hogenbirk, "Criticality Benchmark Results, The new releases JEFF3.0, ENDF/B-VI.8 and JENDL-3.3", JEF/DOC-955, April 2003.
- [98] R. E. MacFarlane, "Testing New Actinide Cross-Sections Proposed for ENDF/B-VII", presentation at the Nuclear Data conference in Santa Fe, NM, September 2004.
- [99] J. Anno, "Renouvellement du Standard de Criticité – Valeurs Minimales Critiques, Phase I, Compilation Comparative-Etat des Connaissances", SEC/DI 96/16 (Rev. 01/07/96), 1996.
- [100] D.E. Cullen, *et. al.*, "Static and Dynamic Criticality: Are They Different?", UCRL-TR-201506, November 22, 2003.
- [101] H. Dias, N. Tancock, A. Clayton, "Critical Mass Calculations for Am-241, Am-242m and Am243", A presentation at ICNC 2003 [59].
- [102] D. Mennerdahl, "Critical Split-Table Subcritical Assemblies and Fissile Natural Uranium Dummy Drivers", pp. 601-602, Vol. 91, Transactions of ANS Annual Meeting, Washington D.C., November 14-18, 2004.

Some earlier OECD/NEA studies on nuclear criticality safety and validation

- [103] OECD/NEA CSNI Working Group, "Standard Problem Exercise on Criticality Codes for Spent LWR Fuel Transport Containers", CSNI Report No. 71. May 1982.
- [104] OECD/NEA CSNI Working Group, "Standard Problem Exercise on Criticality Codes for Large Arrays of Fissile Materials", CSNI Report No. 78. August 1984.
- [105] OECD/NEA NEACRP Working Group, "Standard Problem Exercise on Criticality Codes for Dissolving Fissile Oxides in Acids", NEACRP-L-306, April 1990.

Appendix A **SCOPE AND OBJECTIVES²**

Scope

Basic minimum critical values are important physical constants needed for assessing safety margins in criticality and are used for licensing. The scope of the expert group is to compile minimum critical values of $^{235}\text{U}/^{238}\text{U}$ -, Pu-, MOX-, and ^{233}U - systems. Homogeneous systems with uniform distribution of the fissile material will be covered. Discrepancies in the data will be identified and an explanation of discrepancies sought.

Objectives

Under the guidance of the Working Party on Nuclear Criticality Safety, the expert group will:

- collect data from different countries, including a short description of the methods used to achieve the data;
- identify discrepancies and propose explanations;
- address effects of engineering data, of density formulae, reflector materials;
- provide technical input to the International Community, e.g. ISO;
- supply a general reference for criticality safety analyses that use/include minimum critical values.

2. The formal “Scope and objectives” as published on the OECD/NEA/NSC [www](http://www.oecd.org) page

Appendix B **TERMINOLOGY**

The terminology is included for the purpose of this report and is limited to a few concepts that are important to nuclear criticality safety, have caused discussion and even confusion during the study or are not clearly defined in international glossaries, guides and standards.

Actinides

It is convenient to refer to actinides as a group of elements rather than to list them. The systems studied in this report are limited to uranium and plutonium. The benchmarks include other actinides. The actinide group consists of 14 elements starting with atomic number 90 and finishing with number 103. Actinium (89) is not an actinide. Sometimes single nuclides like ^{235}U and ^{239}Pu are simply referred to as actinides but it is more appropriate to call them actinide nuclides. There are other elements above the actinides that could be significant in future criticality safety applications.

Atomic number density

The density of a nuclide is often specified in number of atoms per barn-cm (10^{-24} cm^3). The determination of such atomic number densities is very important to get a good result from a neutron transport calculation. A computer code system may convert other input specifications into atomic number densities.

Best estimate value

At a certain time and for a given purpose, this value is the most accurate estimation available to the publisher or to the contributor. By definition this means that there was no bias in the value that was known to or assumed by the publisher or contributor. The *uncertainties* should be specified separately.

Bias

A bias is the difference between a calculated or measured result and a best estimate result. It can be a constant or a function of one or more parameters. In this context, bias should not be confused with systematic error. The bias is an error with an estimated (“known”) sign and magnitude; while the systematic error is not known to the evaluator (could be known to others). The uncertainty of a bias often results in a systematic effect.

Bias-correction

A bias-correction is used to obtain a best estimate value from a calculation, measurement or other procedure. It has the same value as the bias but with a reversed sign. A positive bias-

correction is always required in safety applications to correct a likely under-estimation of k_{eff} . A negative bias-correction is often not allowed. The reason for this is not obvious. Use of inferior methods may be encouraged. The motivation for more critical experiments may be reduced if they lead to more positive (including changing negative to positive) biases. However, the potential for using a negative bias-correction based on inappropriate validation must be recognised. It is a realistic safety threat.

Critical system

A system of fissionable and other materials that, through fission and other processes caused by free neutrons, produces as many neutrons as are lost (absorption and leakage).

Critical value

A critical value is a parameter value that determines a critical system. This value is a physical constant and is included in the concept “reference value”.

Cross-sections for neutrons

A neutron cross-section for a nuclide or material gives the probability for a reaction between a free neutron and the nuclide or material. The cross-section is dependent on the energy of the neutron, the properties of the nuclide and the environment of the nuclide (material properties, temperature). The cross-sections are evaluated from measurements and theoretical models.

EALF – Energy corresponding to average lethargy of neutrons causing fission

This parameter is considered more useful than the average energy since the importance of thermal neutron fissions is clearer. The EALF value is an average and will not always be a clear indicator of the neutron physics of the system. It could be like comparing the average colour of the rainbow with the colour of a mud pool. However, EALF has been found to be useful in many cases. Some computer codes include EALF in the output.

Eta – η

A function defined as the ratio of produced to absorbed neutrons for a certain fissionable nuclide, element, compound, solution or mixture. The function is dependent on neutron energy but integral (total energy range or limited energy ranges) values may be of use as well. The JANIS 2.1 code [71] is useful in generating charts of this parameter.

Fissile

A fissile nuclide can be fissioned by slow neutrons. The distinction between fissile and non-fissile (and between many other adjectives such as homogeneous/heterogeneous, soft/hard, good/bad, etc.) depends on the application. In nuclear criticality safety, the fissile property is usually related to the support for criticality when water is added to the system. In some criticality safety applications, special moderators such as graphite, beryllium and deuterium may need to be considered in the definition of fissile. Natural uranium is a fissile material in some applications but can be neglected as a criticality safety hazard in the absence of other fissile materials or large quantities of special moderators.

Fissionable

A fissionable nuclide can be fissioned by a free neutron at some energy. In criticality safety applications, this energy needs to be credible during handling, storage and transport operations. A fissionable element, material, system, etc. contains sufficient quantities and concentrations of fissionable nuclides for the neutron-induced fission process to be considered significant. As with the fissile concept, the definition of fissionable is application-dependent.

Handbooks and other reference value compilations

Values given in handbooks and other sources in the form of text, tables and charts are used for different purposes. Safety handbooks may use approaches that are different than other handbook types. Safety handbooks may use different criteria for deriving and presenting the values, even when they have the same “label”. This should be understood when a value from a handbook is used together with methods or values from other sources.

Human error

Human error is used here loosely as a category to cover deviations between the documented information and the real facts and which lie outside the reported accuracy claims. These claims may not always be obvious but should be available in some form. Many of the discrepancies requested in the scope of this work can be referred to this category. Human errors range from editorial errors to fundamental flaws in established theories and methods.

K_{∞} and k_{eff}

See neutron multiplication factor, infinite and effective respectively.

Maximum critical value

One or more parameters are optimized while other conditions are fixed to give a maximum critical value for a specified parameter. An example is the maximum critical atomic moderation ratio H/X , where X corresponds to a fissionable nuclide or element.

Minimum critical value

One or more parameters are optimized while other conditions are fixed to give a minimum critical value for a specified parameter. Examples are critical mass and dimensions assuming that the water moderation is optimized. The minimum critical mass is normally expected to have the shape of a sphere but this is not a criterion.

Neutron multiplication factor, k_{eff} and k_{∞}

This factor is the ratio between produced and lost (absorption and leakage) neutrons. The infinite neutron multiplication factor k_{∞} corresponds to an infinite system of a homogeneous fissionable material or an infinite lattice of fissionable and other materials. The effective neutron multiplication factor k_{eff} includes the effect of neutron leakage, absorption and moderation in the surrounding materials. The moderation effect can make k_{eff} larger than k_{∞} . In criticality safety evaluations, the real (dynamic) k_{eff} is not of interest (it is for measurements or accident evaluations) [100]. The requested k_{eff} should inform the evaluator about the properties

of the system if it was critical or almost critical. What really happens in a system with k_{eff} of 0.70 or 1.60 is not a criticality safety issue (with the exceptions given above).

Random effect

If a value changes between applications, consistently with a certain probability distribution, the variation may be considered as giving a truly random effect for each application. If there is a trend in the variation of the value that applies to several applications, the trend becomes a systematic effect for the applications. It is essential for some evaluations to separate random and systematic effects of each component of the combined uncertainty and to combine them separately.

Reactivity

Reactivity is a change in k_{eff} . It can be defined in different ways, it is often normalised to one, or criticality. In this report, reactivity will be used as the absolute change in k_{eff} without normalisation. For practical reasons, the unit *mk* is used in many of the tables. A mk is the reactivity multiplied by 1000. This is the intended accuracy for the reference values to be determined. One mk is also used to determine the number of significant digits in the reference values.

Reference values

A value that corresponds to clearly defined conditions and is used in criticality safety applications. The exact specifications may not always be given. In this study, the optimization procedure contributes to the total bias and uncertainty. Examples of reference values are maximum and minimum critical values, k_{∞} for nuclides and materials, critical values for crystals of soluble materials, etc.

Safe values

A safe value is associated with a special operation or type of operation involving fissionable materials. The magnitude of the value does not necessarily in itself inform about the safety margin or even if the operation is safe or unsafe.

Sensitivity

The sensitivity is a change of a variable due to a small variation in a parameter. An example is the change in k_{eff} that corresponds to a small change in the material mass. “Small” is not defined but is related to the validity range of the relationship. A linear sensitivity has a smaller range of validity than a more complicated relationship. A combined change based on several sensitivities need to comply with the same principle; the total change should be within the validity range for each sensitivity.

Statistical distributions – Normal, Gaussian

Input parameters are often assumed to be known with some uncertainty based on a normal or Gaussian probability distribution. It is very unlikely that the corresponding k_{eff} uncertainties have the same distribution, unless the uncertainties are very small. An example is the steel thickness of plates between fuel assemblies in water. Assume that the thickness uncertainty

complies with a Gaussian distribution. There is often a plate thickness for which k_{eff} increases, whether it is increased or reduced. For other input parameter uncertainties, the k_{eff} relationships are not linear. This can be seen in the results of this report. In its first contribution, EMS reports reference value uncertainties based on k_{eff} uncertainties (Gaussian distribution). The positive and negative k_{eff} limits of confidence are not symmetrical.

Systematic effects (but not systematic errors or uncertainties)

An uncertainty that represents a potential error that is common to more than one application or common to more than one evaluation of the same application has sometimes in the past been called a systematic error or systematic uncertainty. To be consistent with [94], it is now called just “an uncertainty”. This uncertainty shall be included in the combined uncertainty for the calculation or measurement. However, the systematic effects of different components of each combined uncertainty need to be understood and combined properly when this is motivated.

Examples of systematic effects are calibration errors that remain unchanged between measurements and are not corrected for, a single calculation value that is applied to several operations or designs, validation uncertainties (not biases) determined from statistical evaluations, etc. The systematic effect can be dependent on time and other variables. It is important in assessing the safety of a facility with many operations or designs or of a particular design that is used in many operations. It is also important in assessing the cost of large uncertainties for such facilities or multiple uses of a design.

Theoretical density

The theoretical density is a maximum density based on pure material properties under conditions that are likely to be maintained in all credible environments. It is used to estimate densities in mixtures of materials. The sum of volume fractions of each material is normally assumed to be one. Void may then be considered as a material with a volume fraction. The densities of nuclides in solutions are important in this study and need further verification. They are often based on empirical studies.

Uncertainty, single

An uncertainty is usually a statistical result of calibration or validation. It is separated from the bias, which has a known sign and a probable magnitude. There are many sources for uncertainties. The uncertainty is usually specified by a statistical measure, such as a confidence level or a standard deviation, often assuming a normal distribution of the probabilities. The uncertainty can lead to both random and systematic effects.

A large uncertainty can be converted to a bias and a smaller uncertainty using more resources during evaluations (including more experiments or better evaluations of experiments). An uncertainty is thus a subjective view as seen by one evaluator. To another evaluator the uncertainty may be partially known (a bias), leaving only a smaller remaining uncertainty. A numerical rounding effect is a bias to the person who knows a higher precision and an uncertainty to the one who does not know. The effect can be systematic (multiple use) or random (single use).

Uncertainty, combined

The combined uncertainty may be derived from individual uncertainties in a procedure that

needs to be validated in each case. The combination of uncertainties into a single combined uncertainty does not mean that each uncertainty can be forgotten. Evaluation of systematic effects requires consideration of each uncertainty. Independent uncertainties are described separately. The reason for this emphasis on uncertainties is that they are very important in the evaluation of critical experiments, of reference values and of safety of real systems.

Uncertainties, independence

For any system evaluated in this report (critical experiment benchmarks and reference value applications), there are no independent uncertainties in k_{eff} or in the associated reference value, see Appendix M and [92]. All k_{eff} uncertainties are correlated. The uncertainties of the input parameters may be independent but the uncertainties in k_{eff} (and in the associated reference value) are not. An example based on a system with a metal plate in a fissile material shows this clearly. The input parameters are plate thickness and plate absorption cross-sections. The input parameter uncertainties are independent. If the plate thickness is smaller, the uncertainty in the absorption cross-sections will have a reduced effect on k_{eff} (extreme: if the plate is not there at all, the cross-section uncertainty has no influence at all on k_{eff}). Similarly, if the absorption cross-section is much smaller than expected, due to less boron in the aluminium, the reactivity influence of the plate thickness is reduced (no boron at all may actually increase reactivity of the plate compared with water).

Validation

Validation of a value or a method involves evaluation of the total bias and uncertainties for a defined range of applications.

Verification

Verification of a value or a method is more limited than validation. It relates to components of the method or a sub-range of the application range of the value.

Appendix C

DESCRIPTION OF EVALUATION METHODS

For each source of calculation results and of critical values, a brief summary of the methods applied is given below. Relevant information could include:

- calculation of atomic number densities (stoichiometric formula of material, theoretical density of materials, atomic weights, Avogadro's number, isotopic composition of fissile elements, material and solution mixing relations, etc.) ;
- description of computation (type and version of code, cross-section-library, nuclides used) ;
- geometry and reflector representation ;
- numerical model: mesh points, convergence criteria, Sn-order, Pl-order, MC-tracking (confidence level, convergence of eigen-distribution, tracking error checks) ;
- validation description ;
- description of method for bias correction ;
- type of provided value: calculation-only, best-estimate.

ARH, USA

Hanford, Fluor Federal Services, Inc has recently supported a release of the classical criticality safety handbook on the web for interactive use. It is also referred to as a source for nuclide density equations and other material properties. Further work on an update is planned.

ARH-600

The criticality safety handbook ARH-600 (Atlantic Richfield Hanford) from 1968 and revised up to 1976 is available on the internet; <http://ncsp.llnl.gov/ARH600/index.htm>. Many reference values can be obtained from the curves in the handbook. The handbook is also a widely used reference for other information such as properties of fissile and other materials. The GAMTEC-II cross-section processing code (from 18 groups to 2 groups) and the HFN 1D diffusion theory code were used.

When references are made to the ARH-600 it is important to know which revision, which page and which equation, table or curve that was used. There may be multiple sources in the same revision.

Significant uncertainties are introduced from reading the curves. In some cases, results for U(100) and U(100)O₂F₂ were reported as U(100)O₂ results. They may be essentially identical in many cases, but this needs to be confirmed.

Validation was important when the handbook was released. Each section reports results from calculations on critical experiments. Some of those may be used in ICSBEP handbook benchmark models but no effort has been made in this study to determine bias corrections based on the current information on the experiments.

DIN, Germany

The German institution DIN (Deutsches Institut für Normung) has released some standards with reference values related to this study.

DIN 25403-4

The reference values for $U(100)O_2$, $U(20)O_2$, $U(5)O_2$ are given but the calculations are not described in the standard. The reference values in the standard are based on a report SR-2010 from NUKEM.

DIN 25403-5

The reference values for $Pu(100/0/0/0)O_2$ and $Pu(95/5/0/0)O_2$ are given but the calculations are not described in the standard. The reference values in the standard are based on a 1997 report from Forschungsinstitut für Kerntechnik und Energieumwandlung.

DIN 25403-6

The reference values for $Pu(100/0/0/0)NH$ and $Pu(95/5/0/0)NH$ are given but the calculations are not described in the standard. The reference values in the standard are based on a 1997 report from Forschungsinstitut für Kerntechnik und Energieumwandlung.

DIN 25403-8

The reference values for $U(100)NH$ are given but the calculations are not described in the standard. The reference values in the standard are based on a report SR-2010 from NUKEM.

EMS, Sweden

The EMS (E Mennerdahl Systems) contribution EMS-S4X-238 from early 2001 was considered a first step towards a more focused validation for best estimate value determination, rather than for direct criticality safety application. For various reasons, this continuation was not carried out. However, in September 2004, EMS was asked to complete a final evaluation and report for the study. Further calculations were necessary to carry out this work and several methods were used. The newly released code packages SCALE 5 (from RSICC in June 2004) [79] and MCNP5 releases 1.20 and 1.30 (from RSICC late November 2004) [80] were used.

The pre-compiled Windows versions of SCALE and MCNP were used. The differences between MCNP4C2, MCNP5 release 1.20 and release 1.30 are not considered significant concerning precision of calculated values. SCALE 5 contains some improvements over SCALE 4.4 in default convergence and mesh parameters but no major differences are expected. The cross-section libraries are identical. The two SCALE 5 codes, KENOv and XSDRNP/S as well as MCNP5 calculate the EALF (Energy corresponding to Average Lethargy of neutrons causing Fission) parameter by default.

SCALE 5 contains a new method for calculation of nuclide densities for solutions, the Pitzer method. SCALE 4 and earlier used the ARH-600 method. Re-calculations of previous SCALE 4.4 input data for uranyl nitrate solutions caused SCALE 5 to reject the suggested densities at room temperature (293K). The user is told that the density is above the crystal density, which is not correct.

Both EMS and ORNL had used this temperature (293K) for their contributions. At the default temperature of 300K, the results were very different but still not correct. For plutonium nitrate solutions, the problem occurred also for 298K, the temperature at which many parameters are determined. Eventually it has become clear that the problem is not with the Pitzer method but in the SCALE implementations of first the ARH-600 and then the Pitzer methods for solution densities. The solution methods are used to determine the crystal densities instead of using the theoretical density of the crystal (salt). ORNL is aware of the problem and is considering a prevention of calculations with actinide concentrations above the solubility limit. The user is already warned by SCALE if the solubility limit is exceeded.

The nuclide density input data for the MCNP optimum systems were based on SCALE 4 calculations in 2000. However, for solutions, the actinide element densities from 2000 were used in SCALE 5 to generate new nuclide densities for MCNP5. This means that the new Pitzer method was applied to MCNP5 input. As is pointed out above and elsewhere, there is a serious problem with the SCALE 5 implementation of the Pitzer method. The temperature was changed from 293K to 300K for low-enriched systems when the SCALE 5 nuclide densities to be used by MCNP5 were determined. The densities are still not correct.

For MCNP5 calculations, not all benchmark nuclides or elements were available in the same cross-section release (identifier .XXc). Since the purpose was to validate the cross-sections for the reference value applications, missing cross-sections were taken from later releases, in particular from ENDF/B-VI.8 (KAERI).

EMS-S1K-27

A few calculations were made with an older calculation method. A modification of SCALE1 codes with a SCALE-0 version of the 27-group cross-section library was installed by EMS on an IBM PC AT computer with 640 kb RAM in 1985 [93]. The SCALE-0 library was replaced with a SCALE-3 library in February 1986. The reason was a problem pointed out during a NEA working group study on dissolution, including gadolinium experiments. The gadolinium cross-section (27th group) in SCALE was changed by several orders of magnitude after SCALE-0. The change in cross-section format should probably have been accompanied by the new version of NITAWL for treating the revised format properly. However, EMS used the SCALE-1 version of NITAWL with the SCALE-3 version of the 27-group library. Benchmarking did not indicate any large or inconsistent error.

SCALE-1 contained KENO-V rather than -Va. Due to memory constraints with the Intel 80286 computer chip (segmented) and operating system limitations (640 kb RAM including space for the operating system), the size of each generation in KENO-V was often limited to 100. It was replaced in 1988 with an 80386 version with fewer restrictions. The 1985 version was used in many projects, including NEA criticality studies, licensing and other research.

A few reference value applications have been calculated with the 1985 SCALE 1 PC-version and the SCALE-3 27-group library. The statistics were 330 000 neutrons of which 30 000 were skipped (100 neutrons per generation). The optimum moderation fissile material and water fractions were based

on SCALE 4 calculations, but the number densities were generated with SCALE 1.

EMS-S4-CSAS

The first release of SCALE 4 for mainframe computers was installed by EMS on a PC in 1992. The 27 group burnup library was required for the NEA working group studies. This implementation was used in this study only to calculate pre-SCALE-5 number densities, based on the ARH-600 methods.

EMS-S4X-238

In 2000 and early 2001, a PC-based, ORNL-compiled executable version of SCALE 4.4 together with the 238 group ENDF/B-V cross section library were used by EMS. The 1D deterministic transport code XSDRNPM/S was used to calculate the minimum critical values. Default convergence parameters were used and this turned out to be insufficient in some cases. Some uncertainties in the results remain due to this issue.

Optimum moderation was determined for a few densities close to the optimum and then using interpolation to get the optimised value. XSDRNPM search techniques were used to calculate parameters (sphere radius, cylinder diameter, and slab thickness) for specified k_{eff} values. Thus, linear interpolation based on sensitivity of k_{eff} to a parameter was not used.

Validation was not carried out in detail. Agreement with some results from calculations carried out by ORNL, the developer of the method, was judged sufficient to assume that the methods were essentially identical. A validation report by ORNL was then used to derive biases and uncertainties for each fissile material. The validation base included many complicated systems as well as benchmarks with large uncertainties, giving a large spread of results for most material types.

A more focused approach to validation for each selected fissile system would improve the bias corrections and reduce the uncertainties.

EMS-S5X-238

This is essentially the same method as used in 2000 (XSDRNPM/S with 238-group cross-sections). However, default input data for convergence was tightened in SCALE 5. Further, mesh and angular quadrature input were improved over the default input in SCALE 5. For spheres, the ISN parameter was increased by the evaluator to 64 and for cylinders and slabs to 32 or 64 for all fast systems and for some slow systems. The mesh distribution was improved for fast slab systems and for a few slow slab systems by setting the size factor SZF to 0.5. The improvements were significant.

A 30 cm water reflector was used. However, it was found that 20 cm is sufficient and that some previous improvements by using a 30 cm reflector were more related to inadequate mesh or angular quadrature settings than the actual reflection from the extra 10 cm of water.

A few benchmarks based on 1-dimensional spherical models were calculated. However, they were not evaluated directly for biases and uncertainties. Instead, comparisons between SCALE 1X (XSDRNPM/S) and SCALE-25 (KENOVa) calculations were made. They show that there are essentially no differences between XSDRNPM/S and KENOVa calculations when the same cross-section library is used. The improved mesh and angular quadrature input mentioned above are important for getting agreement.

EMS-S5X-27

The same method and input data as for EMS-S5X-238 were used, except for the 27-group ENDF/B-IV cross-section library.

EMS-S5X-44

The same method and input data as for EMS-S5X-238 were used, except for the 44-group ENDF/B-V cross-section library.

EMS-S5K-238

The same method and input data as for EMS-S5X-238 were, except that the KENOv Monte Carlo code was used rather than the 1D XSDRNPM/S code. A major difference in input data compared with default input, both for validation and for the reference value applications, is that more neutrons were tracked and, in particular, more initial neutrons were skipped. The number of tracked neutrons was set with the goal of obtaining a statistical uncertainty of 0.0005 or lower. This was achieved for the reference value applications but not always for benchmarks.

EMS-S5K-27

The same method and input data as for EMS-S5K-238 were used, except for the 27-group ENDF/B-IV cross-section library.

EMS-S5K-44

The same method and input data as for EMS-S5K-238 were used, except for the 44-group ENDF/B-V cross-section library.

EMS-M5-E50

MCNP5 with the LANL ENDF/B-V cross-section sets identified with .50c was used. A problem with the ^{239}Pu set was observed; see EMS-M5-E5F below. Most calculations were made with the MCNP5 release 1.20. The older S(a,b) thermal scattering data set lwtr.01t was used.

As with KENOv Monte Carlo calculations, the number of skipped initial neutron histories was increased during the validation process, compared with examples in the ICSBEP Handbook. For many of the older examples the total number of neutrons was also increased significantly. The number of tracked neutrons was set with the goal of obtaining a statistical uncertainty of 0.0005 or lower. This was achieved for the reference value applications, but not always for benchmarks.

The material input specifications were based on the optimisation process carried out in 2000, using the EMS-S4X-238 method. The optimum parameters are not so sensitive to small changes in the neutron spectrum so this approximation is not considered significant. However, this conclusion has not been verified. For solutions, the number densities were calculated with SCALE 5 as mentioned above.

EMS-M5-E5F

Exactly the same as EMS-M5-E50, except that the ^{239}Pu cross-section set .50c was replaced with the .55c set. Both are used in the examples of the ICSBEP handbook but the .55c is more frequent. The

.50c set is an interim version while the .55c is the final version (according to Russ Mosteller, LANL). It was decided to use both sets in the validation and reference value applications.

EMS-M5-E62

MCNP5 and the LANL ENDF/B-VI-2 cross-section sets identified as .60c were used. Other sets such as .62c and .49c had been used with MCNP4C2 previously, without giving significant differences. The older S(a,b) thermal scattering data set lwtr.01t was used

EMS-M5-E66

MCNP5 and the LANL ENDF/B-VI.6 cross-sections identified as .66c were used consistently for all nuclides. The LANL library contains some more recent ENDF/B-VI.8 cross-sections for non-fissionable nuclides but they were not used in this method. The new S(a,b) thermal scattering data set lwtr.60t was used

EMS-M5-E68

MCNP5 and an ENDF/B-VI.8 library processed by KAERI, S. Korea (obtained through private communication) in the autumn of 2002 were used. The new S(a,b) thermal scattering data set lwtr.60t from LANL was used.

EMS-M5-E7P

MCNP5 and the preliminary ENDF/B-VII set of cross-sections (identified by .69c) supplied by LANL in the Release 1.30 of MCNP5 were used. The only plutonium isotope included is ²³⁹Pu. Default (no specification of the version) cross-sections were used for all nuclides. This means that some ENDF/B-VI.8 cross-sections (e.g. for hydrogen and oxygen) were used. The new S(a,b) thermal scattering data set lwtr.60t from LANL was also used.

EMS-M5-F22

MCNP5 and a JEF 2.2 cross-section library processed by ENEA [84], Italy were used. The S(a,b) thermal scattering data set is from the same JEF 2.2 library.

EMS-M5-F30

MCNP5 and a limited set of cross-sections from JEFF-3.0, processed in December 2004 by Dr. Yolanda Rugama, OECD/NEA for this evaluation, were used. The new S(a,b) thermal scattering data set lwtr.60t from LANL was used together with the JEFF-3.0 cross sections. The JEFF-3.0 cross-sections were limited to those used in the reference value calculations. Other nuclides were necessary for the benchmark calculations. Cross-sections from the ENDF/B-VI.8 library (KAERI) were used to allow validation of the uranium and plutonium isotopes together with water and nitrogen.

EMS-M5-J32

MCNP5 and a JENDL-3.2 cross-section library processed by JAERI [81] were used. The older S(a,b) thermal scattering data set lwtr.01t from LANL was used together with the JENDL-3.2 data.

EMS-M5-J33

MCNP5 and a JENDL-3.3 revision 1 cross-section library, processed by JAERI [82], were used. The new S(a,b) thermal scattering data set lwtr.60t from LANL was used together with the JENDL3.3 data.

GRS, Germany

GRS-HzK-98

Most of the GRS (Gesellschaft für Anlagen- und Reaktorsicherheit) values are obtained from the GRS Handbuch zur Kritikalität [19]. Values are calculation results based on older methods such as GAMTEC-II together with DTF-IV and SCALE 4/XSDRNPM together with 27-group cross-sections. Sometimes results by both methods are included in the handbook. The contributed results for U(100)O₂ are based on a low maximum uranium density. Since the optimum values are for full density material, these values have been removed from the evaluation.

GRS-M4-E50

A method based on MCNP4A with ENDF/B-V continuous cross sections.

GRS-S4X-44

A method based on SCALE 4.3 and XSDRNPM/S with 44group ENDF/BV cross sections.

IPPE, Russia

The IPPE methods and calculations are described [35] with some more detail than other methods since the IPPE methods may not be as familiar to criticality safety specialists in countries outside of Russia. In the future, similar information about other methods should be compiled and compared to explain and reduce the spread of results. It is noted that the chemical forms for PuNH in the two IPPE contributions appear to be different. In IPPE-84 there are six water molecules in the crystal form while IPPE-ABBN93 and other sources are based on only five water molecules in the crystal form. In criticality safety references, it is usually assumed that the number five should be used. The chemical properties of soluble fissionable materials are important for safety.

IPPE-84.

The originally reported data (IPPE-84) were taken from a Russian criticality safety handbook issued in 1984. All the reported data are given in the handbook as the minimal critical values with infinite water reflector. The data are calculation values.

The values for the uranium systems were calculated with the KRAB-1 one-dimensional code, using the S_n -method in S_8 -approximation. The ABBN-78 26-group cross sections were used. The order of cross section scattering anisotropy was P_1 .

The uncertainties for the uranium systems are estimated in the handbook as follows: The handbook says that for the uranium systems, the calculation approach gives basically conservative results, i.e. the calculation values of minimum critical parameters are less than experimental values practically in the whole region of existence.

The total uncertainty of the calculations of critical parameters for the uranium systems with high enrichment (more than 5 %) weakly depends on uranium concentration, almost does not depend at all on the type of mixture and does not exceed 0.5 % in k_{eff} , 2% in critical dimension, and 6% in critical mass. For the systems with low enrichment at moderation ratios of $H/^{235}\text{U} < 20$ and $H/^{235}\text{U} > 800$, the uncertainty of calculation is comparable with the uncertainty for the systems with high enrichment.

The values for the plutonium systems were calculated with the KRAB-1 one-dimensional code using the P_1 -method in P_1 -approximation. The ABBN-78 26-group cross sections were used. Order of cross sections scattering anisotropy was P_1 .

The uncertainties for the plutonium systems are estimated in the handbook as follows: The handbook says that the approach used for the processing of the cross sections led to significant errors in the values of critical parameters for the plutonium systems at the moderation range of $500 > H/\text{Pu} > 20$. The error of calculation of multiplication factor is about 5%, critical dimension – 15%, and critical mass – 45%. At the same time, the use in the calculations of the P_1 -method of the P_1 -approximation led to errors in accounting for anisotropy of the neutron flux that fully compensate the mentioned errors.

The result is that the critical parameters of homogeneous plutonium systems with $H/\text{Pu} > 20$ are calculated with an acceptable accuracy (no more than 5% for critical dimension). This conclusion is supported by results of calculations of experiments.

Concentrations for the homogeneous mixture of uranium dioxide with water were calculated using the equation:

$$H/U = \frac{238 - 3x_5}{9} \left(\frac{1}{C_U} - 0.103 \right)$$

where x_5 – uranium enrichment, $C_U = 0.8814 g_{\text{UO}_2}$ – uranium concentration, g_{UO_2} – density of uranium dioxide assumed to be 10.96 g/cm^3 .

Concentrations for the homogeneous mixture of crystalhexohydrate of uranyl nitrate $[\text{UO}_2(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}]$ with water were calculated using the equation:

$$H/U = 26.14/C_U - 19.65 \quad (C_U \leq 1.33 \text{ g/cm}^3)$$

Density of $\text{UO}_2(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ was assumed to be 2.807 g/cm^3 .

Concentrations for the homogeneous mixture of plutonium dioxide with water were calculated using the equation:

$$H/Pu = 26.59/C_{Pu} - 2.629$$

where $C_{Pu} = 0.8819g_{PuO_2}$ – plutonium concentration, g_{PuO_2} – density of plutonium dioxide is assumed to be 11.46 g/cm^3 . According to IPPE an appendix of the Handbook gives a density of 11.44 g/cm^3 which explains why this value was used in 2004.

Concentrations for the homogeneous mixture of hexohydrate of plutonium $[Pu(NO_3)_4 \cdot 6H_2O]$ with water were calculated using the equation:

$$H/Pu = 26.556/C_{Pu} - 9.4$$

Density of $Pu(NO_3)_4 \cdot 6H_2O$ was assumed to be 2.9 g/cm^3 .

IPPE-04, IPPE-ABBN93 or just ABBN93

The IPPE-ABBN93 data are new calculations performed specially for this project. The 299-group ABBN-93.01a cross-sections were used for the calculations. The order of the cross sections scattering anisotropy was P_5 . The temperature was 300K. The code used for the calculations was XSDRNPM from the ORNL SCALE-4.3 package. The S_{16} -approximation was used. The thickness of the water reflector in the calculations was 30 cm. Mesh size was 0.5 cm in the reflector and from 0.03 to ~0.5 cm in the core. Atomic weights and Avogadro's number used for the atomic densities calculations were taken from the ICSBEP Handbook. The following chemical formulas of the compounds and the densities were used for the atomic density calculations:

- $UO_2 - 10.96 \text{ g/cm}^3$
- $UO_2(NO_3)_2 \cdot 6H_2O - 2.807 \text{ g/cm}^3$
- $PuO_2 - 11.44 \text{ g/cm}^3$ (this value has been confirmed – 11.46 is the established value)
- $Pu(NO_3)_4 \cdot 5H_2O - 2.9 \text{ g/cm}^3$
- $H_2O - 1 \text{ g/cm}^3$.

The atomic densities were calculated as a mechanical mixture of the compound and water.

IRSN (formerly IPSN), France

IRSN (formally IPSN) contributed data from three major sources; a 1978 handbook, a 1996 internal update of this handbook and recent calculations using the CRISTAL code system. Validation has always been important, but the actual biases and uncertainties are not specifically documented together with the contributions. On the other hand, IRSN tries to validate the whole system, including nuclide density calculations. This is a necessary procedure to assure safety.

IRSN validation shows that there are positive biases (about 0.005% in Dk) both when all methods are covered and when only older methods are selected. The biases are slightly lower for the older methods but the spread of results is larger.

The IRSN position on the issue of reference values related to this study is explained in [59]. The intention has not been to determine the best possible value but to demonstrate the safety of the complete procedure. A few results that IRSN consider more accurate, obtained with TRIPOLI 4.1 and JEF 2.2 as well as ENDF/B-VI cross sections in continuous energy form, show significant differences. Further, calculations with the full 172 group library, rather than with the collapsed 20-group set, show some deviations that indicate that the full library may give more accurate values.

Two different versions of CRISTAL were used in the contributions to this study. For uranium and plutonium nitrate systems, version V0 with the CEA93 V4 JEF-2.2 based cross-section library was used. A 20-group collapsed set of the 172 group library was used. The deterministic code APOLLO2 (S_n code, the order n was 8, P3 anisotropy) was used to obtain k_{eff} .

For uranium and plutonium dioxide systems, version V1.0 with the CEA93 V6 JEF-2.2 based cross-section library was used. The full 172 group library was used. The deterministic code APOLLO2 (S_n code, the order n was 32, P5 anisotropy) was used to obtain k_{eff} .

The geometry mesh distribution for all plutonium dioxide systems and for uranium dioxide systems with 100% ^{235}U was set to 10 points per cm of fissile material. For other uranium dioxide as well as for all uranium and plutonium nitrate systems the number of mesh points was 1 per cm of fissile material.

A significant contribution to biases for nitrate systems is the nuclide density calculation methods. IRSN has shown that older methods can give significant errors and that the new extended isopiestic law developed by IRSN and included in CRISTAL is quite accurate, in particular for the systems covered by this study. For older IRSN reference value evaluations of PuNH systems, the densities corresponding to minimum critical masses are good. For PuNH systems corresponding to minimum critical geometry (volume, cylinder, slab), the old method densities lead to serious under-predictions, up to 3.4% in k_{eff} .

ICSBEP handbook benchmarks were used [39], [40] to compare the results based on direct benchmark specifications, on the isopiestic law and on the ARH-600 (1968 version)/Leroy-Jouan laws for solutions. Five series of benchmarks were selected: PU-SOL-THERM-001 (6 configurations), LEU-SOL-THERM-004 (7 configurations), LEU-SOL-THERM-016 (7 configurations), HEU-SOL-THERM-001 (10 configurations), and MIX-SOL-THERM-003 (10 configurations). The HEU-SOL-THERM-001 and LEU-SOL-THERM-016 have also been selected for the reference value evaluation in this study. The APOLLO2-MORET4 system was used. The results are important and should be used as a basis for further studies.

IRSN contributed the results as best estimates, even though it is clear that there are biases and uncertainties. The importance of making more accurate determinations was not considered sufficient to motivate further validation at the time. Biases and uncertainties for various fissile systems are discussed and rough numerical values were given in the IRSN presentations to the expert group.

The IRSN methods as referred to in this report are specified as follows:

IRSN-CR-Spec

The nuclide densities specified in ICSBEP benchmarks were used [39], [40] with the CRISTAL V0 package route APOLLO2 (S_n code, the order n was 8, P3 anisotropy) and the CEA93 V4 172 group cross-section library. This method was used during validation work only.

IRSN-CR-Isop-172

The new extended isopiestic (isopiestic law only below the solubility limit with volume addition above the solubility limit) law [39], [40] was used to calculate nuclide densities for use with the CRISTAL V0 package route APOLLO2 (S_n code, the order n was 8, P3 anisotropy) and the CEA93 V4 172 group cross-section library (JEF 2.2). This method is separated from the method IRSNCrV020 below by using the full 172-group rather than the 20-group collapsed set used in APOLLO2 calculations of reference values.

IRSN-Pre-Iso

This method, sometimes referred to by IRSN as “the ARH-600 law” (1968 release of the ARH600 handbook) for PuNH and as the Leroy-Jouan law for UNH, was used [39], [40] to calculate nuclide densities for use with the CRISTAL V0 package route APOLLO2 (S_n code, the order n was 8, P3 anisotropy) and the CEA93 V4 172 group cross-section library (JEF 2.2).

IRSN-CrV0-20

The isopiestic law was used [40] to calculate nuclide densities for use with the CRISTAL V0 package route APOLLO2 (S_n code, the order n was 8, P3 anisotropy) and the CEA93 V4 20 group sub-set of the 172 group cross-section library (JEF 2.2).

The default mesh distribution is set to 1 point per cm in the fissionable material, 2 points per cm in the first 5 cm of the reflector and 1 point per cm further out. The default convergence criterion is 10^{-5} . The report [40] contains several evaluations of interest to the expert group. Influence of different reflectors, including a water layer between the fissile material and the reflector is calculated.

Many of the results were not included in a formal report but contributed in a compilation, including number densities. These number densities would be useful in a continued evaluation study, including effects of different nuclide density calculation methods.

IRSN-CrV1-172

A recent update of the CRISTAL package to version V1.0 and of the 172 group cross-section library to V6 was used to calculate reference values for uranium and plutonium dioxide systems. In addition to using the full 172/group library, the angular quadrature order was increased to 32 and the anisotropy order was increased to P5. For all plutonium dioxide systems and for uranium dioxide systems with 100 % ^{235}U , the number of mesh points in the fissile material was increased to 10 per cm.

IRSN-78-CEA

The 1978 criticality standard [21] is based on calculations with the 1D S_n code DTF-IV (the angular quadrature order n was 4) and various CEA cross-section sets. Results for UNH with low-enriched uranium are identical to a table in the German Handbook.

IRSN-96

The standard from 1978 was reviewed and updated in a 1996 internal IRSN report using similar methods (DTF-IV). The report does not explain how the values were determined but gives references to other internal IRSN documents.

JAERI, Japan

JAERI contributed results from two versions of the Japanese Criticality Safety Handbook. The handbooks give best estimate critical values based on validation and bias correction. The JACS code system was used to calculate the handbook data.

JAERI-H-88

The first version of the Japanese Handbook [22] was released in 1988, with a translation into English published in 1995. The Data Collection contains the reference values and is included as a second part of the translation. The Handbook contains many different kinds of useful information about methods, materials, etc. The reference values were calculated with a code system, JACS, developed by JAERI.

The handbook contains information on calculation and validation of the JACS system for different fissionable materials. The reference values in the handbook are bias-corrected. It is possible to derive the direct calculation results from the validation information. The following information (explained in Appendix D of the handbook) for simple systems as revised in 1987 (Table 2.3) in the handbook (as opposed to Table 5.3 in the Data Collection, revised 1985):

- Homogeneous, low-enriched uranium: The critical value is 0.991, giving a bias of -0.009. A standard deviation of 0.004 is reported.
- Homogeneous, high-enriched uranium: The critical value is 0.985, giving a bias of -0.015. A standard deviation of 0.013 is reported.
- Homogeneous plutonium: The critical value is 1.008, giving a bias of 0.008. A standard deviation of 0.011 is reported.
- There is no separation of fast and slow systems for high-enriched uranium and for plutonium.

Appendix C of the handbook contains a large number of calculation results for benchmarks used in the validation of the JACS system. This was long before the first ICSBEP Handbook was released. It would be interesting to identify these benchmarks according to the ICSBEP Handbook identifications. A source for improvement is the better knowledge of biases and uncertainties of the benchmarks today.

It is interesting to note that there are no data for the U(20)NH material that was used to fabricate the fuel for the JOYO reactor and that was handled at JCO for many years, before the release of the first version of the handbook. NUPEC contributed calculations for this material type separately.

JAERI-H-99

The second version of the JAERI handbook [23] was released in Japanese in 1999. A translation into English was released in 2001 [24]. A second release of the Data Collection is expected soon. The handbook contains some revised reference values. Most of the Handbook version 2 values seem to be identical to version 1 (no revision).

An example of a serious error in version 2 is based on Figure 5.5 in the Data Collection section of version 1. The figure does not show the minimum value, since the curve does not go low enough in uranium concentration. The lowest value is quoted in version 2 as the minimum critical value. This value was also reported to the expert group. The error had been found by JAERI earlier but no correction was made. During the final evaluation, the error was pointed out by the evaluator and soon confirmed as well as explained by JAERI [48]. The error is serious since even the “safe” value is critical.

The Moeken model for nitrate nuclide densities that was used in the first release of the Data Collection will be replaced in the second release. For $\text{UO}_2(\text{NO}_3)_2$ solution with uranium enrichments of 3 and 4% ^{235}U by mass of uranium, the new mass and volume reference values are more than 10% smaller than release one and which were reported to the OECD/NEA expert group.

The second version of the handbook was prepared before the JCO accident (September 30, 1999). Like the first version, it does not contain data for U(20)NH material.

A second version of the Data Collection that was issued in relation to the first issue of the Japanese Handbook has been announced [48] but was not yet released at the end of March 2005.

NUPEC, Japan

NUPEC-S4X-44

NUPEC used SCALE 4.3 and the 44-group library to calculate minimum critical mass and volume for U(20)NH. This complements the data from the Japanese handbooks (JAERI-H-88 and -H-99). Validation was not reported but can be found in several published reports from other sources.

ORNL, USA

ORNL-S4X-238

SCALE 4.3 and the 238-group ENDF/B-V cross-section library were used by ORNL [52]. The convergence criteria were tightened compared with the default values in SCALE 4.3. Information on the calculation procedures and on nuclide density determination methods is provided in the draft ORNL report. Only calculated results were included in the ORNL submittal; no bias and uncertainty estimates were made. However, the ORNL draft report refers to a published ORNL report on validation [78]. This

was also used by EMS in its 2001 contribution [29] to obtain bias corrections.

The reference values submitted by ORNL were not always for optimum systems. The nearest calculation value was chosen and sometimes this caused significant deviations (e.g. 3 % in mass). Differences between EMS-S4X-238 results (“evaluated” interpolation was used) and ORNL results may either be due to this or to the better convergence criteria used by ORNL. Differences for fast systems between the ORNL results and the SCALE 5 results from EMS may also be due to a tighter mesh for slab systems and a higher angular quadrature order for spheres and cylinders in the EMS evaluations.

Serco Ass., United Kingdom

Serco Ass. made the calculations with the code system MONK [55], [56] and [57]. Two different versions, MONK-8A and MONK-8B were used together with continuous energy cross sections. The differences in the methods are negligible for the fissile systems selected. MONK-8A was used in the determination of reference values for critical masses and concentrations while MONK-8B was used for determination of reference values for critical volumes, cylinder diameters and slab thicknesses.

The WIMS system was used in preparatory calculations to support the optimisation.

The cross-section library DICE96 (point data) used by Serco is based on JEF-2.2.

Serco Ass. reported validation efforts and supplied bias-corrected critical values and uncertainties. Calculation of nuclide densities is described in the contributed papers. As an example, the maximum uranium concentration in UNH is 1.257 kg/l (slightly higher for some reference values). This does not seem to be correct. For PuNH, the corresponding maximum plutonium concentration is 1.20 kg/l. This information is valuable for continued studies of differences between methods. Like the IRSN reports, Serco mentions that plutonium solutions are likely to contain mixtures of Pu(III), Pu(IV) and Pu(VI), where III, IV and VI are valence numbers. This influences the reference values. Only Pu(IV) was assumed in the calculations.

The Serco validation shows that for uranium and reference values for volumes, cylinders and slabs there are no trends against enrichment ^{235}U and no trends against energy. The mean k_{eff} value was 1.0016. The bias correction is thus -0.0016 for all uranium systems. The uncertainty is estimated from a simple statistical evaluation based on the maximum benchmark uncertainty and the number of benchmarks (13 systems with 80 configurations). This uncertainty is combined with the MONK uncertainty.

For uranium and reference values for masses and concentrations, a similar procedure carried out earlier gave a slightly lower bias correction; -0.0014.

For plutonium, evaluation of thirteen independent systems with over 100 configurations indicates a k_{eff} over-prediction by about 0.5 %. No definite trend could be determined related to energy or to the plutonium isotope distribution. A flat bias correction of -0.5 % was assumed. Two experimental systems were excluded due to likely discrepancies in some specifications. This evaluation covers all plutonium reference values.

SENSITIVITIES OF REFERENCE VALUES TO k_{eff} CHANGES

The k_{eff} sensitivity to a change from the critical value in one of the selected parameters mass, volume, cylinder diameter, slab thickness and concentration (g/cm^3 or H/X) is a physical constant in the same way as the critical value itself is. If the sensitivity is determined at some other base value, it may be significantly different.

The reciprocal sensitivities of reference parameters to small k_{eff} changes are particularly useful in adjusting the calculated reference values for small biases in k_{eff} . Uncertainties in k_{eff} can easily be converted to reference value uncertainties.

Another use of these sensitivities is to determine the precision of a reference value that is equivalent to a specific k_{eff} precision. The precision in k_{eff} that is applied in the final presentation of reference values in this report is 0.001. A unit, “mk” is used to represent this number (representing a k_{eff} change, a reactivity). Each sensitivity is represented as parameter change per mk. Examples are kg/mk , litre/mk , cm/mk , $\text{g}/\text{l}/\text{mk}$ and $\text{H}/\text{X}/\text{mk}$ where H/X is the atomic number density ratio of hydrogen to specified fissionable nuclides. The logarithm of the sensitivity indicates the last significant figure before (positive) or after (negative) the decimal point. The specified value will have a precision corresponding to a range of 0.0001 to 0.001 in k_{eff} .

If the sensitivities can be confirmed using different methods, it will be easier to correct calculated values to account for biases. New or improved validation results may be applied directly, without recalculations of the selected application systems.

The sensitivities in Table D1 and the associated precision values (negative logarithm values; they indicate significant figures after the decimal point) in Table D2 were calculated with SCALE 4.4 using XSDRNPM and 238-group cross sections with default convergence and mesh input parameters. The preferred way would have been to use SCALE 5 with better convergence and mesh input parameters.

Further, the sensitivities were not determined in a consistent way. In most cases, the calculated sensitivity is based on a 0.005 change in k_{eff} . Sometimes the change is smaller and in a few cases larger. The sensitivity is not linear in this wide range. It would have been better to fix the change to 0.001. The best way would be to generate equations (curve-fitting) that correspond to the non-linear behaviour of the sensitivity.

The sensitivities have been confirmed using MCNP5 with many cross section libraries and with MONK sensitivities. There is a small statistical spread in the Monte Carlo sensitivities.

It appears as if the sensitivities are not very sensitive to the different cross section sets used. The material input parameters for all MCNP5 calculations were based on SCALE results for each optimum system. If the cross sections vary significantly between different libraries, individual optimisation should result in different systems. In reality, there is only one optimum system. So far, there is no indication that the deviation from optimum is significant for any calculation method. This should be confirmed in future studies.

Table D1. Reference value sensitivities to small k_{eff} changes

Fissionable material	Value sensitivity to small k_{eff} changes					
	Mass (kg/mk)	Volume (litre/mk)	Cylinder diameter (cm/mk)	Slab thickness (cm/mk)	Concentration	
					(g/l/mk)	(H/X/mk)
U(100)O ₂	0.00355	0.0188	0.0222	0.0137	0.0235	-4.18
U(20)O ₂	0.0261	0.0502	0.0324	0.0211	0.131	-0.850
U(5)O ₂	0.240	0.166	0.0564	0.0364	0.670	-0.214
U(4)O ₂	0.394	0.229	0.0662	0.0427	0.899	-0.172
U(3)O ₂	0.790	0.397	0.0855	0.0557	1.353	-0.130
U(100)NH	0.00358	0.0278	0.0245	0.0156	0.0238	-4.15
U(20)NH	0.0312	0.0780	0.0382	0.0250	0.135	-0.845
U(5)NH	0.658	0.666	0.106	0.0681	0.811	-0.218
U(4)NH	1.54	1.40	0.155	0.0995	1.17	-0.178
U(3)NH	7.53	5.91	0.336	0.217	2.13	-0.142
Pu(100/0/0/0)O ₂	0.00235	0.00425	0.0116	0.00627	0.0138	-7.18
Pu(95/5/0/0)O ₂	0.00292	0.00440	0.0120	0.00652	0.0154	-6.81
Pu(80/10/10/0)O ₂	0.00337	0.00479	0.0122	0.00687	0.0162	-6.77
Pu(90/10/0/0)O ₂	0.00378	0.00483	0.0122	0.00681	0.0171	-6.52
Pu(80/15/5/0)O ₂	0.00464	0.00505	0.0126	0.00693	0.0189	-6.32
Pu(71/17/11/1)O ₂	0.00478	0.00526	0.0127	0.00709	0.0195	-6.19
Pu(100/0/0/0)NH	0.00234	0.0324	0.0266	0.0171	0.0139	-7.17
Pu(95/5/0/0)NH	0.00303	0.0499	0.0326	0.0211	0.0155	-6.85
Pu(80/10/10/0)NH	0.00354	0.0586	0.0355	0.0233	0.0164	-6.77
Pu(90/10/0/0)NH	0.00390	0.0654	0.0374	0.0241	0.0173	-6.53
Pu(80/15/5/0)NH	0.00475	0.0788	0.0408	0.0270	0.0190	-6.33
Pu(71/17/11/1)NH	0.00526	0.0827	0.0419	0.0270	0.0195	-6.27

Table D2. Precision of reference values corresponding to 1 mk reactivity

Fissionable material	Requested precision – Significant figures after decimal point					
	Mass (kg)	Volume (litre)	Cylinder diameter (cm)	Slab thickness (cm)	Concentration	
					(g/l)	(H/X)
U(100)O ₂	3	2	2	2	2	0
U(20)O ₂	2	2	2	2	1	1
U(5)O ₂	1	1	2	2	1	1
U(4)O ₂	1	1	2	2	1	1
U(3)O ₂	1	1	2	2	0	1
U(100)NH	3	2	2	2	2	0
U(20)NH	2	2	2	2	1	1
U(5)NH	1	1	1	2	1	1
U(4)NH	0	0	1	2	0	1
U(3)NH	0	0	1	1	0	1
Pu(100/0/0/0)O ₂	3	3	2	3	2	0
Pu(95/5/0/0)O ₂	3	3	2	3	2	0
Pu(80/10/10/0)O ₂	3	3	2	3	2	0
Pu(90/10/0/0)O ₂	3	3	2	3	2	0
Pu(80/15/5/0)O ₂	3	3	2	3	2	0
Pu(71/17/11/1)O ₂	3	3	2	3	2	0
Pu(100/0/0/0)NH	3	2	2	2	2	0
Pu(95/5/0/0)NH	3	2	2	2	2	0
Pu(80/10/10/0)NH	3	2	2	2	2	0
Pu(90/10/0/0)NH	3	2	2	2	2	0
Pu(80/15/5/0)NH	3	2	2	2	2	0
Pu(71/17/11/1)NH	3	2	2	2	2	0

Appendix E

VALIDATION OF EVALUATION METHODS

Properties of the applications versus benchmarks

The fissionable material system applications considered in this study are geometrically simple. The material compositions are few and without impurities. Real applications often involve complicated systems that are difficult to assess exactly but can be confidently assured to be safe based on conservative approximations. Critical experiment benchmarks are usually in between; their geometry and material compositions are often specified with high accuracy. However, there are uncertainties and errors in the specifications. They are estimated, but additional errors and uncertainties should be assumed to remain. For that reason, independent critical experiments of similar systems are valuable.

The uncertainties in the selected applications are not found by evaluation of benchmarks based on critical experiments. The uncertainties primarily involve atomic number densities (or equivalent specifications) and optimisation of the moderation. Other benchmarks are needed to verify such input. Comparison of contributions, preferably independent, based on the specifications of the selected applications in this study is hopefully leading to identification of uncertainties and even discrepancies.

Validation or verification?

The validation reported here is limited to computer codes and cross-sections. Determination of atomic number densities or equivalent information is very important and can include significant uncertainties, in particular for water-soluble fissile compositions. Determination of optimum moderation is another uncertainty source that is not directly covered in this section.

Convergence criteria, mesh distribution, angular quadrature, etc. can involve significant uncertainties for deterministic codes. They are considered in a few of the validation cases, where the default code input has been modified.

Convergence criteria can be very important also in Monte Carlo calculations. The total number of neutron histories is obviously important, but also removal of a sufficient of neutron histories from the first part of the neutron tracking (the “transient” phase before convergence) can be important. Determination of k_{eff} and other values should be based on a converged source distribution of neutrons. The convergence should be established before the scoring is started. Absorption rates, fission distribution and sensitivities are usually much more sensitive than k_{eff} to early transients. Source convergence in Monte Carlo has been considered in all validation cases by removing (skipping) more initial neutron histories and often by increasing the total number of histories.

It is clear that this validation is not complete; it is more of a verification of computer codes and cross-sections. Other important input specifications for the selected applications are not verified separately or included in the validation effort.

Selection of critical experiment models for validation

The validation cases were selected subjectively by looking at the ICSBEP Handbook specifications from evaluations of critical experiments. The new TSUNAMI capabilities in SCALE 5 (86-88) were used later to evaluate similarities between applications and benchmarks.

- Priority is given to simple experiments with few material constituents, pure water moderation and reflection, no neutron absorbers and a geometry that can easily be modelled. Simplicity may reduce unknown errors and uncertainties. That is not necessarily always true (more material constituents could mean better chemical analysis, not more complications, etc.).
- Some critical experiments involve a chain of experiments with similar materials, equipment, measurement procedures, chemical assays, etc. They will be extremely valuable in determining trends due to the changed parameters. However, they are not independent. Priority is given to one set of results from a series of correlated experiments, in the hope that there will be a sufficient number of independent experiments to establish a bias and uncertainty. The single set of results could include a combined evaluation of all correlated and similar experiments in a series, leading to a smaller uncertainty than for any single experiment.
- Whether identical or different weights are given to the selected benchmarks, the reasons should be understood and described. This conclusion is independent on whether the selection is based on reasoning alone or on a combination of reasoning with more systematic statistical and numerical evaluations. Statistical models need to reflect the properties of the database.
- The validation is primarily intended for finding best estimates of the requested values. A validation with the purpose of finding safe values would very likely be different, in particular in the selection of benchmarks and in the determination of biases and uncertainties.
- Preference is given to benchmarks with low uncertainties. A result for a single benchmark with an uncertainty of 0.0010 in k_{eff} is statistically worth the same as results for ten completely uncorrelated benchmarks, each with an uncertainty of 0.0031. The uncertainty is an important parameter in weighting the benchmarks.
- In the past, benchmark error sources often were of two types. One was chemical analysis and presence of impurities. This would usually lead to a super-critical benchmark model. Another error source type is the presence of more reflecting materials than documented. Reflection from distant walls could be inferred by k_{eff} sensitivity to array size. This error type leads to a sub-critical benchmark model. The ICSBEP evaluators seem to be well aware of these potential error types.
- The results are displayed in table and graph formats. The charts were created automatically, using Microsoft Excel. A legend is displayed in each sub-section and applies to all charts in that sub-section. Trend lines are inserted for trial use only. The equations generated are not reliable for so few and often very uncertain data points. Extrapolation is certainly not recommended. Discussion of bias and uncertainty determination for all systems and methods is covered in Appendix I.

Input data for benchmarks

Time and resources did not allow for independent generation of input data for the benchmarks. Input files were taken from the CD-ROM containing the ICSBEP Handbook, 2004 edition or from appendix A of the benchmark specifications in the Handbook. The input data have not been checked properly to be trusted for validation of safety applications. A major purpose of using these input files is that they give excellent information on differences due to cross-sections.

The reference to the ICSBEP handbook benchmarks should be easy to recognize. In the tables and figures, the identification of methods has been shortened to reduce space. The identifications may vary but in general M stands for MCNP and S for SCALE with the version number following directly (M5, S5, etc.). The cross-section library is specified by the number of energy groups (e.g. 238, 27, and 44) or a letter (E for ENDF/B, J for JENDL and JF or only F for JEF(F)) plus release number for the source library for evaluated continuous energy cross-sections (e.g. E50 means ENDF/B-5.0, F22 means JEF-2.2, etc.).

Values may be added late during the evaluation. The purpose is to give additional information on the methods. All results are not necessarily included in the charts or in the evaluations. However, a selection of methods that is considered essential has been identified and the corresponding results are included, when available. The “major 6” methods include those that have been bias-corrected and use the latest cross-section library available for the method.

The major 6 methods are:

- EMS-S5K-238. The cross-sections are old but the validation appears appropriate and the results appear to respond to the physics variations of the benchmark and reference systems. This is not always true for the 44-group and 27-group libraries.
- EMS-M5-E7P and EMS-M5-E68. These are the latest ENDF/B cross-sections available. The only plutonium isotope available in the preliminary ENDF/B-VII library is ²³⁹Pu. Rather than mixing the libraries for plutonium with other isotopes, the ENDF/B-VI.8 library was used. This library was obtained from KAERI, S. Korea for evaluation.
- EMS-M5-J33. Revision 1 of the JENDL-3.3 library was released during 2004.
- EMS-M5-F30. Dr. Yolanda Rugama prepared a sub-set of JEFF-3.0 in ACE-format (used by MCNP) containing the nuclides involved in the reference systems.
- Serco-Mk8-F22. Serco used bias-corrections based on reasonable validation.
- IPPE-04 or ABBN93. In addition to handbook values from 1984, IPPE submitted new results both for the reference systems and for the benchmark systems. IPPE claims that the validation using KENOv is valid for the XSDRNPM/S calculations of reference systems when the same ABBN93 library is used. This is credible since the same conclusion was reached for those codes within the SCALE 5 system and all of the 238-, 44- and 27-group libraries.

Sometimes, values using one of the 6 methods are not available. This will be noted by referring to the selection as the “major 5”.

The IRSN-CR-Isop-172 and IRSN-CrV0-20 methods are validated for criticality safety but not quite for best estimate evaluations. Even so, they usually have small biases and are considered when the best estimate results are determined.

The Japanese handbook values are bias-corrected, but it seems as if the validation is not so successful for best-estimate evaluations. One reason is that the validation was carried out a long time ago, long before the first version of the ICSBEP handbook was available. The biases in the benchmarks, as documented at that time, were not always clear. A new Data Collection Release 2 that will reduce the problems is expected soon.

The EMS-S4X-238 values are bias-corrected. However, the validation from ORNL appears too “broad” to be used for best-estimate evaluations of the reference systems. Sometimes a large positive bias correction suggested by the ORNL validation report is changed into a negative bias-correction when more focused validation is carried out.

Selected ICSBEP Handbook benchmarks

Table E1. Fast HEU systems

ICSBEP id.	Description	Case	Model
HEU-MF-001	Bare U(94) metal sphere, LANL 1950’s. Small uncertainty	1	Godiva Shell
HEU-MF-004	Water-reflected U(96) metal sphere, LANL 1976. Small uncertainties	1	3D 1D
HEU-MF-008	Bare U(90) metal sphere, VNIITF 1982. Similar to HEUMF-018	1	
HEU-MF-015	Bare U(96) metal sphere, VNIITF 1984. Similar to HEUMF-065	1	
HEU-MF-018	Bare U(90) metal sphere, VNIIEF 1962. Small uncertainties	1 1	Detail Simple
HEU-MF-020	Polyethylene-reflected U(90) metal sphere, VNIIEF 1962	1 1	Detail Simple
HEU-MF-065	Bare U(96) metal cylinder, VNIITF 1987. Small uncertainty	1	

Table E2. Thermal compound and metal HEU systems

ICSBEP id.	Description	Case
HEU-CT-011	Four clusters of square-pitched 21x21 lattices of U(80)O ₂ + Al fuel rods, stainless steel clad and water-moderated. Kurchatov 1997. Large uncertainty.	1
		2
		3
HEU-MT-011	Arrays of U(93) — aluminium alloy plates. Water-moderated and reflected. Valduc 1969. Small uncertainties.	1
		3
		5
		7
		35
		37
		39
		41

Table E3. Thermal HEU solution systems

ICSBE id.	Case	Case
HEU-ST-001	Minimally reflected cylinders of U(93)NH-solution. Rocky Flats 1976. Large uncertainties.	01
		02
		03
		04
		05
		06
		07
		08
		09
		10
HEU-ST-009	Water-reflected 6.4 litre spheres of U(93)O ₂ F ₂ solutions. ORNL 1954 and 1958. Large uncertainties.	1
		2
		3
		4
HEU-ST-010	Water-reflected 9.7 litre spheres of U(93)O ₂ F ₂ solutions. ORNL 1950.	1
		2
		3
		4
HEU-ST-011	Water-reflected 17 litre spheres of U(93)O ₂ F ₂ solutions. ORNL 1954 and 1957.	1
		2
HEU-ST-012	Water-reflected 91 litre sphere of U(93)O ₂ F ₂ solution. ORNL 1958. Large uncertainty	1
HEU-ST-025	Water-reflected cylinder with U(89)NH solution. IPPE 1987.	1
HEU-ST-027	Water-reflected cylinder with U(89)NH solution. IPPE 1961. Large uncertainty	1
HEU-ST-028	Water-reflected cylinder with U(89)NH solution. IPPE 1961. Large uncertainty (case 9)	1
		9
HEU-ST-029	Water-reflected cylinder with U(89)NH solution. IPPE 1961. Very large uncertainty	1
HEU-ST-030	Water-reflected cylinder with U(89)NH solution. IPPE 1961. Very large uncertainty (case 4).	1
		4
HEU-ST-033	Concrete-reflected annular cylinders with U(89)NH solution. Rocky Flats 1980. Extremely large uncertainties.	11A-S
		11B-S
HEU-ST-035	Water-reflected cylinder with U(89)NH solution. IPPE 1961. Large uncertainties.	1
		5
		7
HEU-ST-036	Water-reflected cylinder with U(89)NH solution. IPPE 1969. Large uncertainty.	1
HEU-ST-037	Water-reflected cylinder with U(89)NH solution. IPPE 1961. Large uncertainty.	1
		3
		6
HEU-ST-038	Two interacting slab tanks with U(93)NH solution. LANL 1988.	1
HEU-ST-042	Bare large-diameter cylinders of U(93)NH solution. ORNL 1950. Large uncertainties.	1
		2
		3
		4
		5
		6
		7
		8
HEU-ST-043	Bare large-diameter cylinders of U(93)O ₂ F ₂ solutions. ORNL 1957.	1
		2
		3

Table E4. Thermal LEU compound and solution systems

ICSBE id.	Description	Case
LEU-CT-001	Water-moderated U(2.35)O ₂ rods in square-pitched arrays. PNL 1977.	1
		2
LEU-CT-002	Water-moderated U(4.31)O ₂ rods in square-pitched arrays. PNL 1977.	1
		4
LEU-CT-013	Water-moderated U(4.31)O ₂ rods in square-pitched arrays. PNL 1980. Steel and water reflection.	1
LEU-CT-014	Water-moderated and –reflected U(4.31)O ₂ rods in square-pitched arrays. PNL 1982.	1
		6
LEU-CT-039	Incomplete arrays of water-moderated and –reflected U(4.738)O ₂ rods in square-pitched arrays. Valduc 1978.	1
LEU-CT-049	MARACAS: U(5)O ₂ powder, heterogeneously moderated and reflected by polyethene. Valduc 1983. Large uncertainty.	1-Simple
LEU-CT-061	Water-moderated and –reflected U(4.4)O ₂ hexagonal-pitched lattices of fuel rods (VVER). Kurchatov 1993.	1
LEU-CT-070	Water-moderated and –reflected U(6.5)O ₂ hexagonal-pitched lattices of fuel rods (VVER). Kurchatov 1989.	1
LEU-ST-001	Unreflected U(5)O ₂ F ₂ +H ₂ O cylindrical assembly (Sheba-II). LANL 1994.	1
LEU-ST-003	Full and truncated bare spheres of U(10)NH solutions in water. IPPE 1965. Large uncertainties.	1
		2
		3
		4
		5
		6
		7
		8
		9
LEU-ST-007	Bare cylinder of U(10)NH solution in water. NUCEF 1995. Small uncertainties.	1
		2
		3
		4
		5
LEU-ST-016	Water-reflected slabs of U(10)NH solution in water. NUCEF 1997. Small uncertainties.	1
		2
		3
		4
		5
		6
		7
LEU-ST-017	Bare slabs of U(10)NH solution in water. NUCEF 1997. Small uncertainties.	1
		2
		3
		4
		5
		6
LEU-ST-020	Water-reflected cylinder of U(10)NH solution in water. NUCEF 1998. Small uncertainties.	1
		2
		3
		4
LEU-ST-021	Bare cylinder of U(10)NH solution in water. NUCEF 1998. Small uncertainties.	1
		2
		3
		4

Table E5. Fast Pu metal systems

ICSBEP id.	Description	Case	Model
Pu-MF-001	Bare Pu(95/5/0/0) metal sphere, LANL 1950.	1	
Pu-MF-002	Bare Pu(76/20/3/0.4) metal sphere, LANL 1964.	1	
Pu-MF-003	Bare, unmoderated Pu(93.5/6/0.5/0) metal button array. LLNL 1965.	1	
		2	
		3	
		4	
		5	
Pu-MF-005	Tungsten-reflected Pu(95/5/0/0) metal sphere, LANL 1958. Small uncertainty.	1	
Pu-MF-011	Water-reflected Pu(94.5/5/0.5/0) metal (alpha-phase) sphere, LANL 1968. Small uncertainty.	1	
Pu-MF-016	Water-flooded 3x3x3 array of 3-kg Pu(94/6/0/0) metal cylinders. Rocky Flats 1982. Large uncertainty.	1	
Pu-MF-022	Bare Pu(98/2/0/0) metal (delta-phase) sphere, VNIIEF 1956.	1	Simplified
Pu-MF-029	Bare Pu(88.5/9/1.5/0) metal (alpha-phase) sphere, VNIIEF 1965.	1	Simplified
Pu-MF-037	Water-flooded 2x2x2 arrays of 3-kg Pu(94/6/0/0) metal cylinders. Rocky Flats 1973. Large uncertainties.	1	
		5	
		7	
		10	
		12	
		15	
		16	

Table E6 Thermal Pu solution systems .

ICSBEP id.	Description	Case
Pu-ST-009	Bare Pu(97/3/0/0)NH solution sphere, PNL 1978. Large uncertainties.	1
		2
		3
Pu-ST-014	Pu(95/4/0/0)NH solution cylinders, interacting in air without reflection. Valduc 1968. Large uncertainties.	1
		2
Pu-ST-015	Pu(95/4/0/0)NH solution cylinders, interacting in air without reflection. Valduc 1968. Large uncertainties.	1
		2
Pu-ST-022	Pu(74/19/6/1)NH solution in an annular cylinder tank with water reflection. Valduc 1973.	1
		2
		3
		4
		5
		6
		7
		8
		9
Pu-ST-025	Water-reflected slabs of Pu(95/5/0/0)NH, Pu(76/18/5/1)NH and Pu(72/23/4/1)NH solutions. PNL 1967. Large uncertainties.	1
		7
		14
		21
		28
		34
Pu-ST-026	Bare slabs of Pu(95/5/0/0)NH, Pu(76/18/5/1)NH and Pu(72/23/4/1)NH solutions. PNL 1967. Large uncertainties.	39
		1
		4
		9
		15
		17

Appendix F BENCHMARK CALCULATION RESULTS

Fast high-enriched uranium system validation results

Figure F1. Fast HEU. S5+ 238

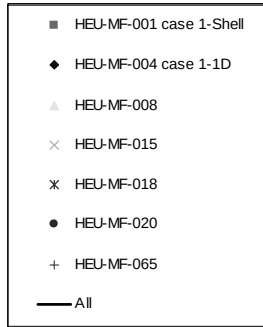


Figure F4. Fast HEU. S5+ 238

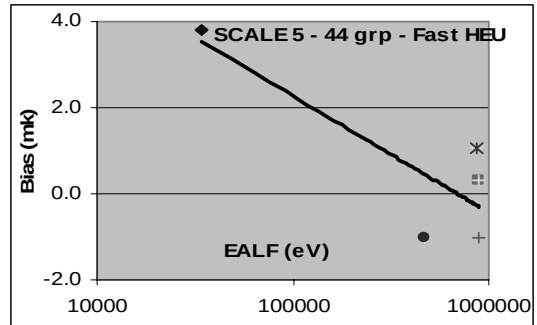


Figure F2. Fast HEU. S5+ 238

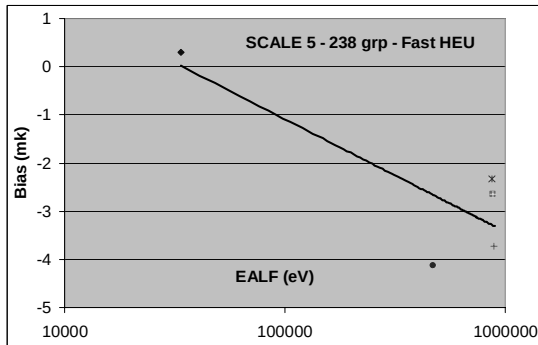


Figure F5. Fast HEU. M5+E50

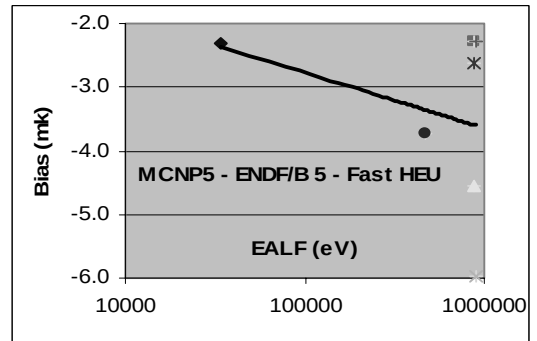


Figure F3. Fast HEU. S5+ 238

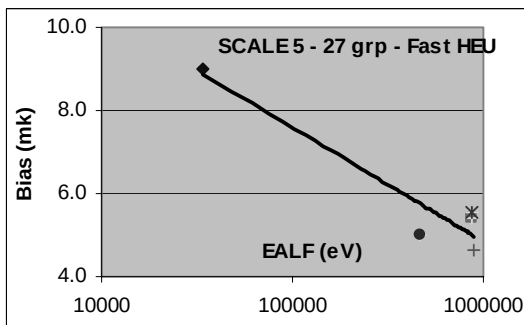


Figure F6. Fast HEU. M5+E62

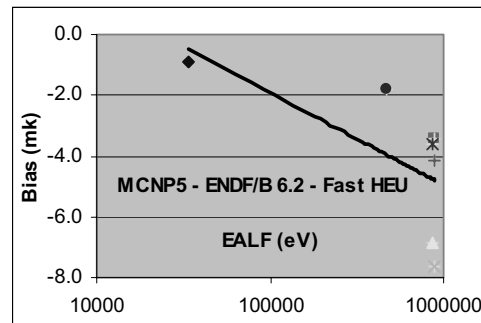


Figure F7. Fast HEU. M5+E66

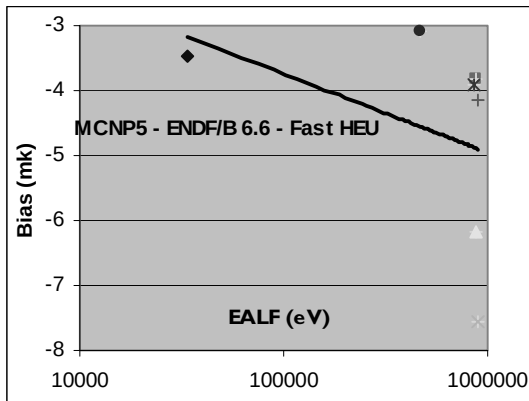


Figure F10. Fast HEU. M5+JF 2.2

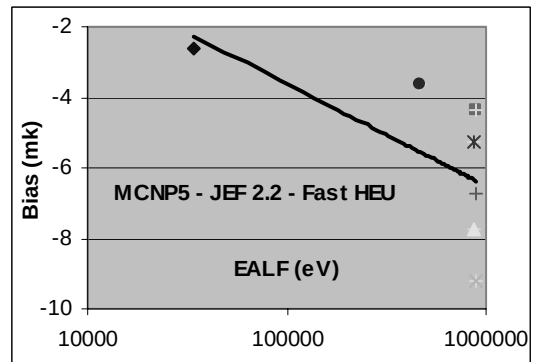


Figure F8. Fast HEU. M5+E68

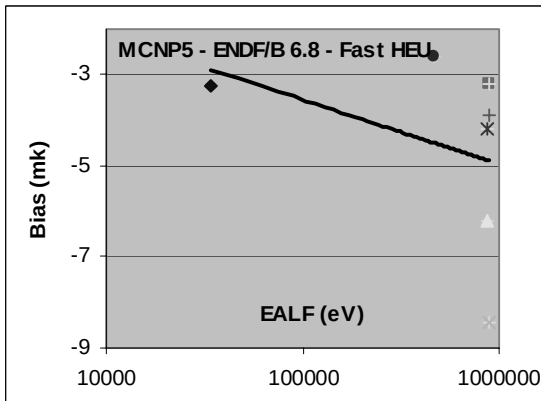


Figure F11. Fast HEU. M5+ JF3.0

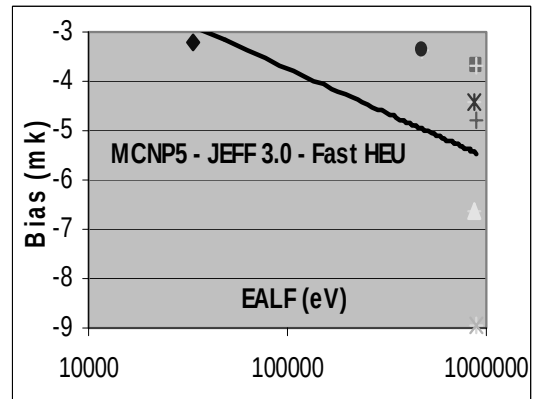


Figure F9. Fast HEU. M5+E7P

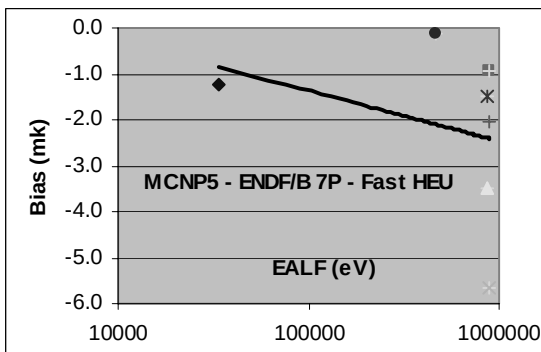


Figure F12. Fast HEU. M5+ JENDL 3.2

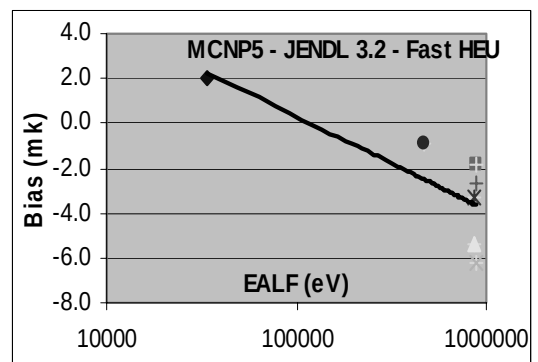


Figure F13. Fast HEU, M5 + JENDL 3.3

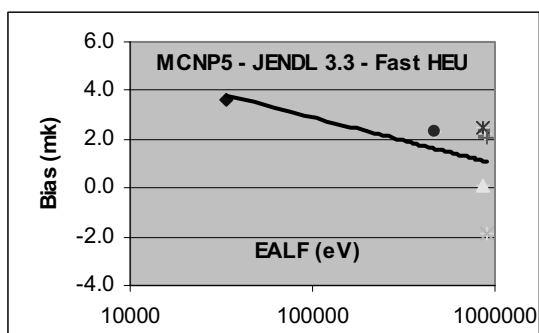


Figure F14. Fast HEU, ABBN-93

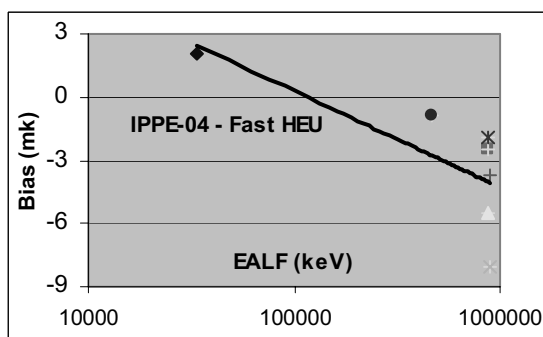


Figure F15. Legend for all HEU results

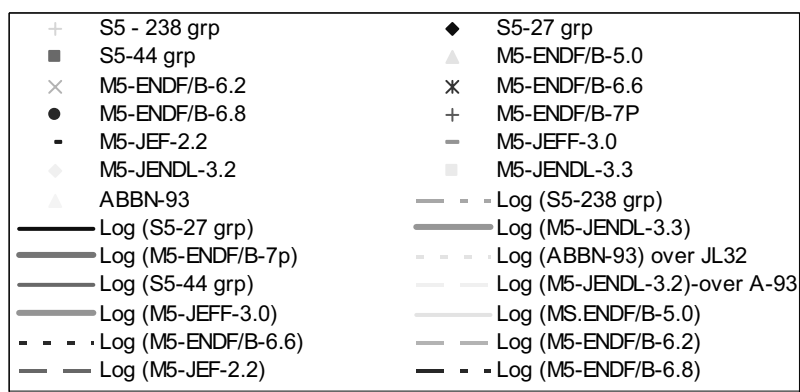


Figure F16. All results for fast HEU benchmark

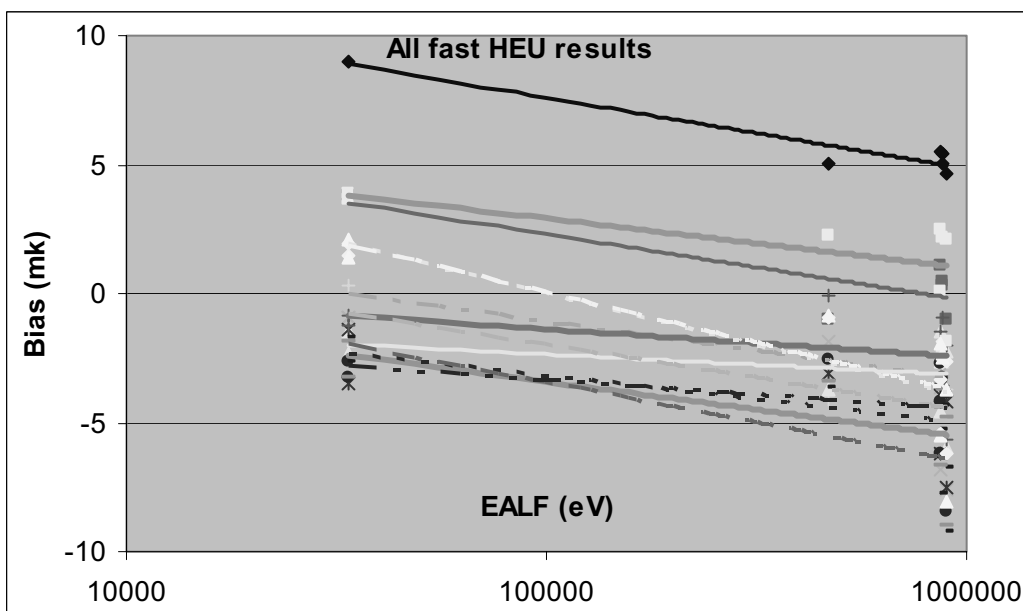


Table F1. HEU-MF-001 Case 1

ICSBEP benchmark	HEU-MF-001		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark – Godiva	1.000	0.001		
EMS-S5-238	0.9971	0.0003	-0.0029	947814
EMS-S5-27	1.0050	0.0003	0.0050	897082
EMS-S5-44	1.0004	0.0003	0.0004	903682
EMS-M4-E50	0.9980	0.0003	-0.0020	
EMS-M4-E62	0.9970	0.0003	-0.0030	
EMS-M4-E68	0.9967	0.0003	-0.0033	
IPPE-ABBN93	0.9977	0.0001	-0.0023	
Benchmark – Shell	1.000	0.001		
EMS-S5-238	0.9974	0.0003	-0.0027	948334
EMS-S5-27	1.0054	0.0003	0.0054	897747
EMS-S5-44	1.0003	0.0003	0.0003	904592
EMS-M5-E50	0.9977	0.0003	-0.0023	956420
EMS-M5-E62	0.9966	0.0003	-0.0034	835230
EMS-M5-E66	0.9962	0.0003	-0.0038	828620
EMS-M5-E68	0.9968	0.0003	-0.0032	827220
EMS-M5-E7P	0.9991	0.0003	-0.0009	822690
EMS-M5-F22	0.9957	0.0003	-0.0043	832620
EMS-M5-F30	0.9963	0.0003	-0.0037	823440
EMS-M5-J32	0.9981	0.0003	-0.0019	875360
EMS-M5-J33	1.0022	0.0003	0.0022	838920
IPPE-ABBN93	0.9976	0.0001	-0.0024	

Table F2. HEU-MF-004 Case 1

ICSBEP benchmark	HEU-MF-004		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark – 3D	1.002	0.000		
EMS-M5-E50	1.0005	0.0006	-0.0015	31824
EMS-M5-E62	1.0010	0.0006	-0.0010	26557
EMS-M5-E66	1.0006	0.0006	-0.0014	26824
EMS-M5-E68	0.9993	0.0006	-0.0027	27131
EMS-M5-E7P	1.0011	0.0006	-0.0009	27143
EMS-M5-F22	1.0003	0.0006	-0.0017	26824
EMS-M5-F30	1.0001	0.0006	-0.0019	27130
EMS-M5-J32	1.0035	0.0005	0.0015	27950
EMS-M5-J33	1.0058	0.0006	0.0038	28343
IPPE-ABBN93	1.0034	0.0001	0.0014	
Benchmark – 1D	0.9985	0.0000		
EMS-S5-238	0.9988		0.0003	31450
EMS-S5-27	1.0075		0.0090	28700
EMS-S5-44	1.0023		0.0038	30250
EMS-M5-E50	0.9962	0.0006	-0.0023	32717
EMS-M5-E62	0.9976	0.0005	-0.0009	27420
EMS-M5-E66	0.9950	0.0006	-0.0035	27650
EMS-M5-E68	0.9952	0.0005	-0.0033	28041
EMS-M5-E7P	0.9973	0.0006	-0.0012	28171
EMS-M5-F22	0.9959	0.0006	-0.0026	27886
EMS-M5-F30	0.9953	0.0006	-0.0032	27546
EMS-M5-J32	1.0005	0.0006	0.0020	29369
EMS-M5-J33	1.0022	0.0006	0.0037	29258
IPPE-ABBN93	1.0006	0.0001	0.0021	

Table F3. HEU-MF-008 Case 1

ICSBEP benchmark	HEU-MF-008		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9989	0.0016		
EMS-M5-E50	0.9944	0.0003	-0.0045	938390
EMS-M5-E62	0.9921	0.0003	-0.0068	824200
EMS-M5-E66	0.9927	0.0003	-0.0062	818050
EMS-M5-E68	0.9927	0.0003	-0.0062	816980
EMS-M5-E7P	0.9954	0.0003	-0.0035	809330
EMS-M5-F22	0.9912	0.0003	-0.0077	818630
EMS-M5-F30	0.9923	0.0003	-0.0067	809430
EMS-M5-J32	0.9935	0.0003	-0.0054	859910
EMS-M5-J33	0.9990	0.0003	0.0001	822970
IPPE-ABBN93	0.9934	0.0001	-0.0055	

Table F4. HEU-MF-015 Case 1

ICSBEP benchmark	HEU-MF-015		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9996	0.0017		
EMS-M5-E50	0.9936	0.0003	-0.0060	967640
EMS-M5-E62	0.9920	0.0003	-0.0076	844270
EMS-M5-E66	0.9921	0.0003	-0.0076	837820
EMS-M5-E68	0.9912	0.0003	-0.0085	837060
EMS-M5-E7P	0.9939	0.0003	-0.0057	834570
EMS-M5-F22	0.9904	0.0003	-0.0092	843460
EMS-M5-F30	0.9906	0.0003	-0.0090	835940
EMS-M5-J32	0.9934	0.0003	-0.0062	887870
EMS-M5-J33	0.9977	0.0003	-0.0019	849810
IPPE-ABBN93	0.9916	0.0001	-0.0080	

Table F5. HEU-MF-018 Case 1

ICSBEP benchmark	HEU-MF-018		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark – Detailed	1.0000	0.0014		
EMS-M4-E50	0.9986	0.0003	-0.0014	
EMS-M4-E62	0.9965	0.0003	-0.0035	
EMS-M4-E68	0.9973	0.0003	-0.0027	
IPPE-ABBN93	0.9981	0.0001	-0.0019	
Benchmark - Shell	1.0000	0.0014		
EMS-S5-238	0.9977	0.0003	-0.0023	929858
EMS-S5-27	1.0055	0.0003	0.0055	878854
EMS-S5-44	1.0011	0.0003	0.0011	886655
EMS-M5-E50	0.9974	0.0003	-0.0026	939360
EMS-M5-E62	0.9964	0.0003	-0.0036	822880
EMS-M5-E66	0.9961	0.0003	-0.0039	816570
EMS-M5-E68	0.9958	0.0003	-0.0042	816210
EMS-M5-E7P	0.9985	0.0003	-0.0015	808200
EMS-M5-F22	0.9948	0.0003	-0.0052	815760
EMS-M5-F30	0.9956	0.0003	-0.0044	808710
EMS-M5-J32	0.9967	0.0003	-0.0033	859140
EMS-M5-J33	1.0025	0.0003	0.0025	822320

Table F6. HEU-MF-020 Case 1

ICSBEP benchmark	HEU-MF-020		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark – Detail	1.0000	0.0028		
IPPE-ABBN93	0.9991	0.0001	-0.0009	
Benchmark - Shell	1.0000	0.0028		Benchmark
EMS-S5-238	0.9959	0.0003	-0.0041	508936
EMS-S5-27	1.0050	0.0003	0.0050	462172
EMS-S5-44	0.9990	0.0003	-0.0010	482797
EMS-M5-E50	0.9963	0.0003	-0.0037	515040
EMS-M5-E62	0.9982	0.0003	-0.0018	434860
EMS-M5-E66	0.9969	0.0003	-0.0031	434210
EMS-M5-E68	0.9974	0.0003	-0.0026	432640
EMS-M5-E7P	0.9999	0.0003	-0.0001	430030
EMS-M5-F22	0.9964	0.0003	-0.0036	430060
EMS-M5-F30	0.9966	0.0003	-0.0034	429030
EMS-M5-J32	0.9991	0.0003	-0.0009	453120
EMS-M5-J33	1.0023	0.0003	0.0023	439220
Serco-Mk7-F22				

Table F7. HEU-MF-065 Case 1

ICSBEP benchmark	HEU-MF-065		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9995	0.0013		
EMS-S5-238	0.9958	0.0003	-0.0037	958879
EMS-S5-27	1.0041	0.0003	0.0046	908464
EMS-S5-44	0.9985	0.0003	-0.0010	915390
EMS-M5-E50	0.9972	0.0003	-0.0023	967620
EMS-M5-E62	0.9953	0.0003	-0.0042	844900
EMS-M5-E66	0.9953	0.0003	-0.0042	837180
EMS-M5-E68	0.9956	0.0003	-0.0039	836050
EMS-M5-E7P	0.9975	0.0003	-0.0021	834000
EMS-M5-F22	0.9928	0.0003	-0.0068	842210
EMS-M5-F30	0.9947	0.0003	-0.0048	836020
EMS-M5-J32	0.9968	0.0003	-0.0027	888370
EMS-M5-J33	1.0016	0.0003	0.0021	850160
IPPE-ABBN93	0.9958	0.0001	-0.0038	

Thermal high-enriched uranium system validation results

The trend lines are based on inserted extra values for $EALF = 10\,000$ eV. These values are taken from the evaluation of biases for fast high-enriched uranium systems. In Figure D.29 there are no such extra values, explaining the different trends compared with earlier charts. The trend lines are described in Appendix G.

Figure F17. Legend for HEU-XT systems

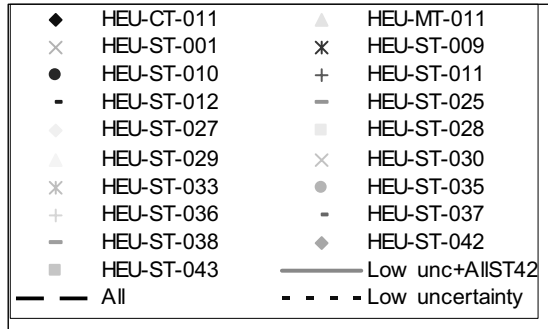


Figure F20. EALF. SCALE 5 + 44-group

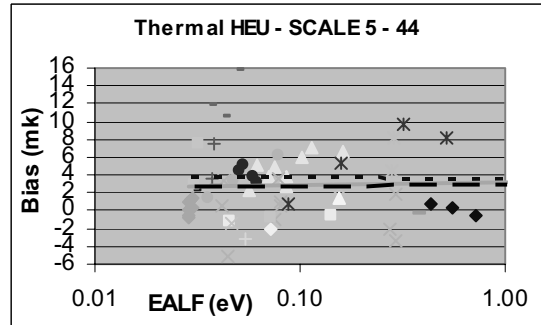


Figure F18. EALF. SCALE 5 + 238-grp

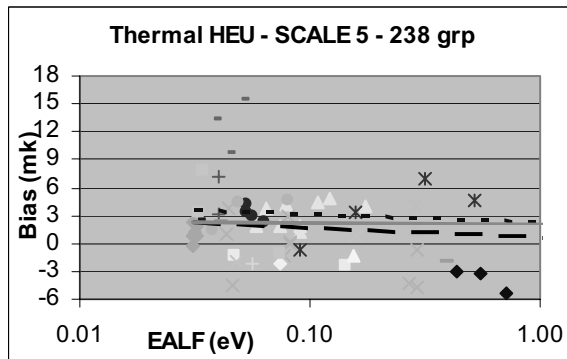


Figure F21. EALF. MCNP5+ENDF/B-5

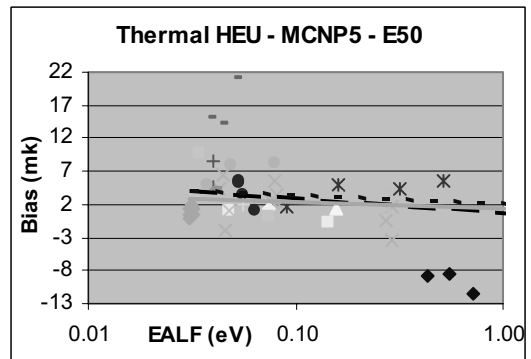


Figure F19. EALF. SCALE 5 + 27-group

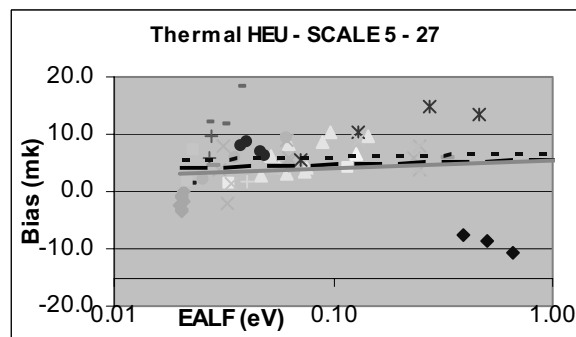


Figure F22. EALF. MCNP5+ENDF/B-6.2

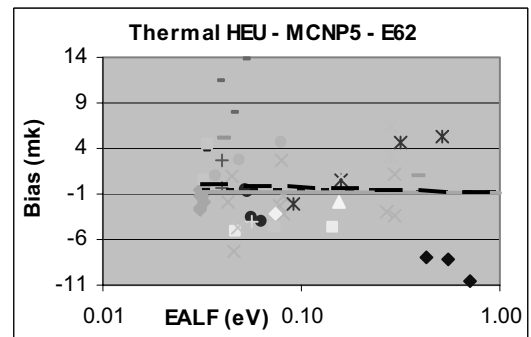


Figure F23. EALF. MCNP5+ENDF/B-6.6

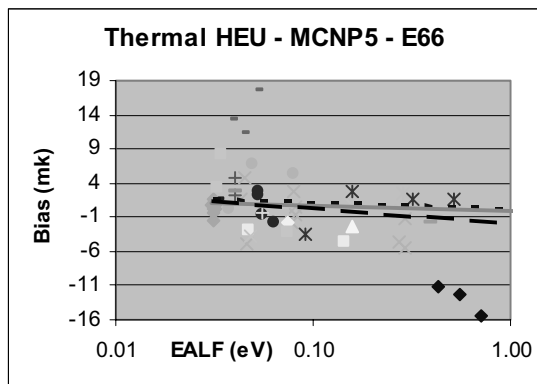


Figure F26. EALF. MCNP5+ JEF 2.2

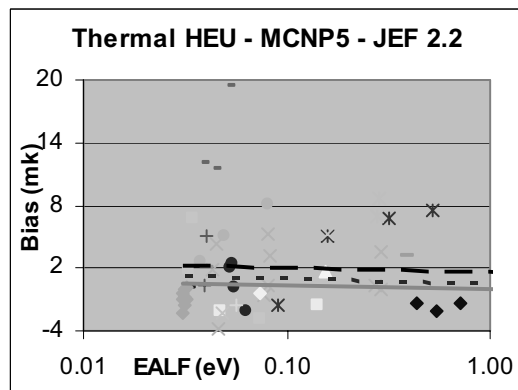


Figure F24. EALF. MCNP5+ENDF/B-6.8

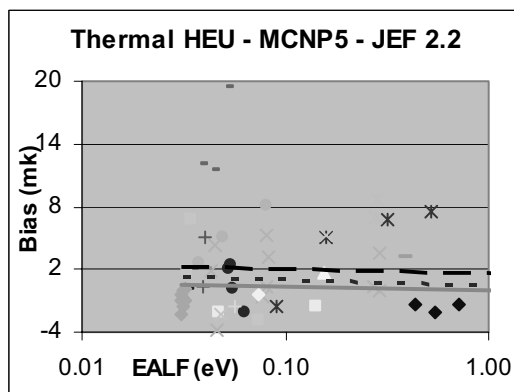


Figure F27. EALF. MCNP5+ JEFF 3.0

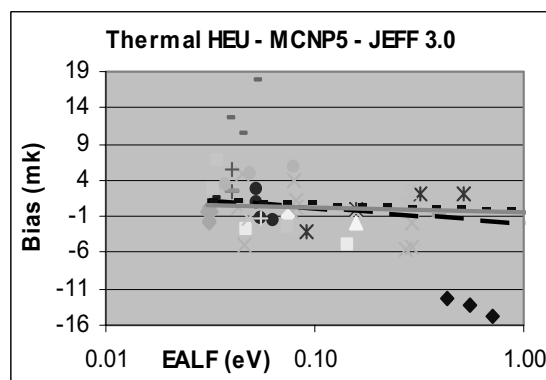


Figure F25. EALF. MCNP5+prel ENDF/B-7

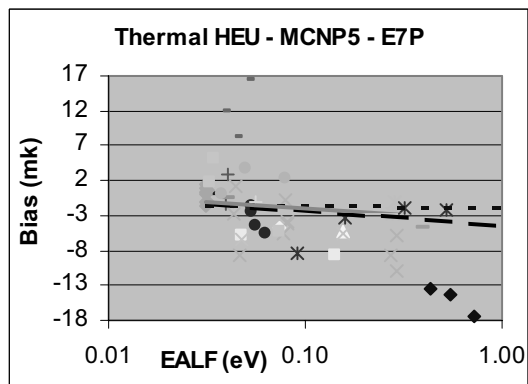


Figure F28. EALF. MCNP5+ JENDL 3.2

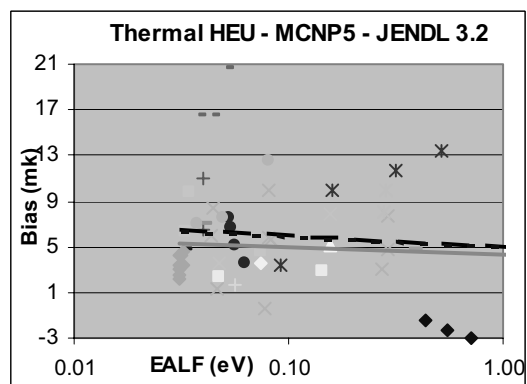


Figure F29. EALF. MCNP5+ JENDL 3.3

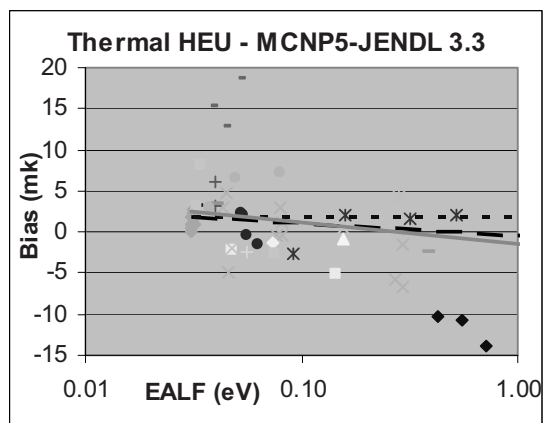


Figure F30. EALF. IPPE-ABBN93

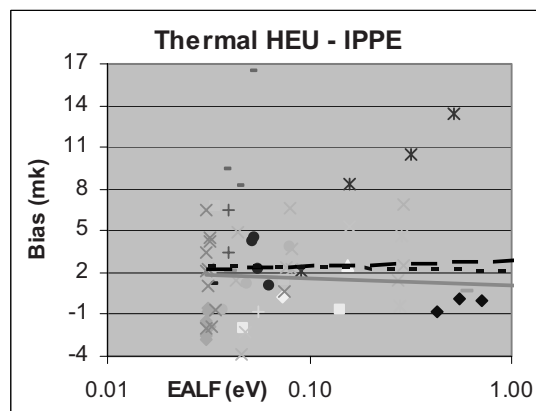


Figure F31. EALF. All MCNP5 results

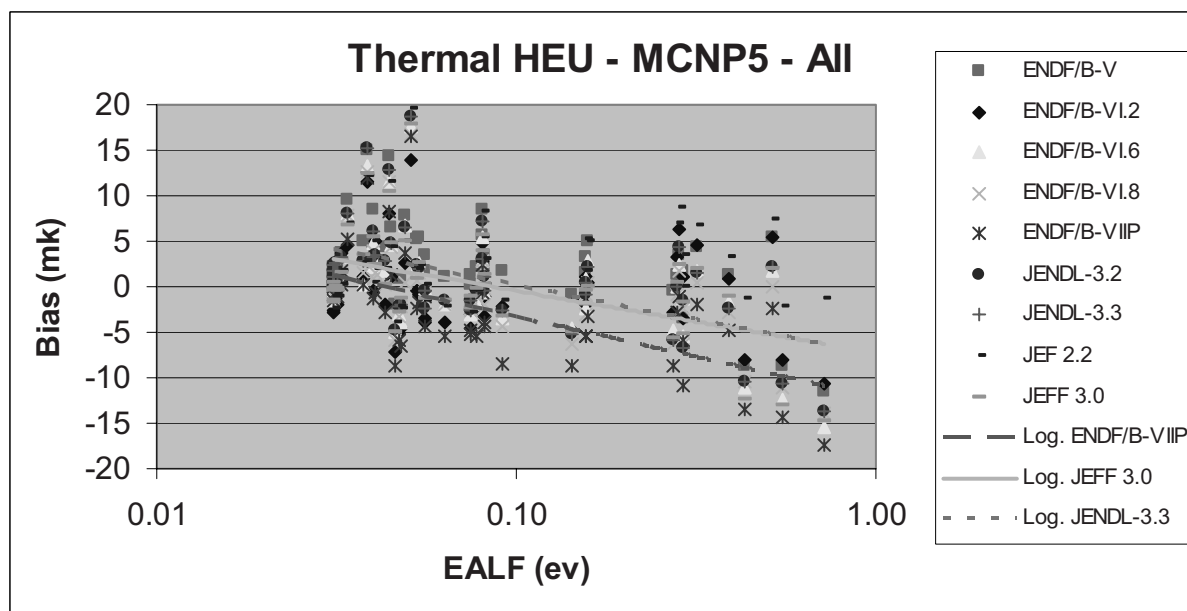


Table F8. HEU-CT-011 Case 1

ICSBEP benchmark	HEU-CT-011		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9988	0.0042		
EMS-S5-238	0.9935	0.0004	-0.0053	0.7203
EMS-S5-27	0.9880	0.0004	-0.0108	0.6527
EMS-S5-44	0.9982	0.0004	-0.0007	0.7148
EMS-M5-E50	0.9872	0.0005	-0.0116	0.7412
EMS-M5-E62	0.9882	0.0006	-0.0106	0.7237
EMS-M5-E66	0.9834	0.0006	-0.0154	0.7094
EMS-M5-E68	0.9849	0.0006	-0.0139	0.7046
EMS-M5-E7P	0.9814	0.0006	-0.0174	0.7114
EMS-M5-F22	0.9974	0.0006	-0.0014	0.7197
EMS-M5-F30	0.9841	0.0006	-0.0147	0.7067
EMS-M5-J32	0.9959	0.0006	-0.0029	0.6903
EMS-M5-J33	0.9850	0.0006	-0.0138	0.7080
IPPE-ABBN93	0.9987	0.0004	-0.0001	

Table F9. HEU-CT-011 Case 2

ICSBEP benchmark	HEU-CT-011		Case 2	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9988	0.0042		
EMS-S5-238	0.9955	0.0004	-0.0033	0.5523
EMS-S5-27	0.9903	0.0004	-0.0085	0.4977
EMS-S5-44	0.9992	0.0004	0.0003	0.5507
EMS-M5-E50	0.9902	0.0006	-0.0086	0.5677
EMS-M5-E62	0.9907	0.0006	-0.0081	0.5557
EMS-M5-E66	0.9865	0.0006	-0.0123	0.5426
EMS-M5-E68	0.9877	0.0006	-0.0111	0.5422
EMS-M5-E7P	0.9845	0.0006	-0.0143	0.5481
EMS-M5-F22	0.9967	0.0006	-0.0021	0.5501
EMS-M5-F30	0.9857	0.0006	-0.0131	0.5461
EMS-M5-J32	0.9965	0.0006	-0.0023	0.5350
EMS-M5-J33	0.9881	0.0006	-0.0107	0.5453
IPPE-ABBN93	0.9989	0.0004	0.0001	

Table F10. HEU-CT-011 Case 3

ICSBEP benchmark	HEU-CT-011		Case 3	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9988	0.0042		
EMS-S5-238	0.9957	0.0004	-0.0031	0.4322
EMS-S5-27	0.9912	0.0004	-0.0076	0.3882
EMS-S5-44	0.9995	0.0004	0.0007	0.4303
EMS-M5-E50	0.9900	0.0006	-0.0088	0.4438
EMS-M5-E62	0.9908	0.0006	-0.0080	0.4357
EMS-M5-E66	0.9877	0.0006	-0.0111	0.4253
EMS-M5-E68	0.9885	0.0006	-0.0103	0.4271
EMS-M5-E7P	0.9854	0.0006	-0.0134	0.4272
EMS-M5-F22	0.9975	0.0006	-0.0013	0.4323
EMS-M5-F30	0.9864	0.0005	-0.0124	0.4287
EMS-M5-J32	0.9973	0.0006	-0.0015	0.4193
EMS-M5-J33	0.9884	0.0006	-0.0104	0.4266
IPPE-ABBN93	0.9980	0.0004	-0.0008	

Table F11. HEU-MT-011 Case 1

ICSBEP benchmark	HEU-MT-011		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0010		
EMS-S5-238	1.0048	0.0004	0.0048	0.1183
EMS-S5-27	1.0102	0.0004	0.0102	0.0974
EMS-S5-44	1.0070	0.0004	0.0070	0.1148
IPPE-ABBN93	1.0104	0.0004	0.0104	

Table F12. HEU-MT-011 Case 3

ICSBEP benchmark	HEU-MT-011		Case 3	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0005		
EMS-S5-238	1.0042	0.0004	0.0042	0.0771
EMS-S5-27	1.0081	0.0004	0.0081	0.0627
EMS-S5-44	1.0048	0.0004	0.0048	0.0753
IPPE-ABBN93	1.0069	0.0004	0.0069	

Table F13. HEU-MT-011 Case 5

ICSBEP benchmark	HEU-MT-011		Case 5	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0005		
EMS-S5-238	1.0038	0.0004	0.0038	0.0638
EMS-S5-27	1.0061	0.0004	0.0061	0.0517
EMS-S5-44	1.0050	0.0004	0.0050	0.0624
IPPE-ABBN93	1.0049	0.0004	0.0049	

Table F14. HEU-MT-011 Case 7

ICSBEP benchmark	HEU-MT-011		Case 7	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0006		
EMS-S5-238	1.0020	0.0004	0.0020	0.0574
EMS-S5-27	1.0028	0.0004	0.0028	0.0465
EMS-S5-44	1.0023	0.0004	0.0023	0.0563
IPPE-ABBN93	1.0008	0.0004	0.0008	

Table F15. HEU-MT-011 Case 35

ICSBEP benchmark	HEU-MT-011		Case 35	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0017		
EMS-S5-238	1.0041	0.0004	0.0041	0.1671
EMS-S5-27	1.0096	0.0004	0.0096	0.1430
EMS-S5-44	1.0067	0.0004	0.0067	0.1620
IPPE-ABBN93	1.0111	0.0004	0.0111	

Table F16. HEU-MT-011 Case 37

ICSBEP benchmark	HEU-MT-011		Case 37	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0005		
EMS-S5-238	1.0043	0.0004	0.0043	0.1052
EMS-S5-27	1.0087	0.0004	0.0087	0.0899
EMS-S5-44	1.0059	0.0004	0.0059	0.1028
IPPE-ABBN93	1.0081	0.0004	0.0081	

Table F17. HEU-MT-011 Case 39

ICSBEP benchmark	HEU-MT-011		Case 39	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0006		
EMS-S5-238	1.0019	0.0004	0.0019	0.0880
EMS-S5-27	1.0043	0.0004	0.0043	0.0751
EMS-S5-44	1.0037	0.0004	0.0037	0.0862
IPPE-ABBN93	1.0045	0.0004	0.0045	

Table F18. HEU-MT-011 Case 41

ICSBEP benchmark	HEU-MT-011		Case 41	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0010		
EMS-S5-238	1.0018	0.0004	0.0018	0.0720
EMS-S5-27	1.0031	0.0003	0.0031	0.0615
EMS-S5-44	1.0039	0.0003	0.0039	0.0708
IPPE-ABBN93	1.0001	0.0004	0.0001	

Table F19. HEU-MT-011 Case 43

ICSBEP benchmark	HEU-MT-011		Case 43	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0006		
EMS-S5-238	1.0011	0.0004	0.0011	0.0871
EMS-S5-27	1.0036	0.0004	0.0036	0.0743
EMS-S5-44	1.0027	0.0004	0.0027	0.0854
IPPE-ABBN93	1.0029	0.0004	0.0029	

Table F20. HEU-ST-001 Case 01

ICSBEP benchmark	HEU-ST-001		Case 01	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0004	0.006		
EMS-S5-238	1.0006	0.0005	0.0002	0.0821
EMS-S5-27	1.0064	0.0005	0.0060	0.0620
EMS-S5-44	1.0014	0.0005	0.0010	0.0797
EMS-M5-E50	1.0026	0.0006	0.0022	0.0840
EMS-M5-E62	0.9972	0.0006	-0.0032	0.0837
EMS-M5-E66	0.9998	0.0006	-0.0006	0.0815
EMS-M5-E68	0.9985	0.0006	-0.0019	0.0815
EMS-M5-E7P	0.9961	0.0005	-0.0043	0.0817
EMS-M5-F22	1.0007	0.0006	0.0003	0.0853
EMS-M5-F30	1.0006	0.0005	0.0002	0.0815
EMS-M5-J32	1.0062	0.0005	0.0058	0.0827
EMS-M5-J33	1.0000	0.0006	-0.0004	0.0815
IPPE-ABBN93	1.0027	0.0002	0.0023	

Table F21. HEU-ST-001 Case 02

ICSBEP benchmark	HEU-ST-001		Case 02	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0021	0.0072		
EMS-S5-238	0.9979	0.0005	-0.0042	0.2797
EMS-S5-27	1.0079	0.0005	0.0058	0.2326
EMS-S5-44	1.0000	0.0005	-0.0021	0.2750
EMS-M5-E50	1.0016	0.0006	-0.0005	0.2873
EMS-M5-E62	0.9992	0.0006	-0.0029	0.2832
EMS-M5-E66	0.9974	0.0006	-0.0047	0.2759
EMS-M5-E68	0.9959	0.0006	-0.0062	0.2744
EMS-M5-E7P	0.9933	0.0006	-0.0088	0.2765
EMS-M5-F22	1.0025	0.0006	0.0004	0.2851
EMS-M5-F30	0.9964	0.0006	-0.0057	0.2750
EMS-M5-J32	1.0052	0.0006	0.0031	0.2762
EMS-M5-J33	0.9962	0.0006	-0.0059	0.2762
IPPE-ABBN93	1.0036	0.0002	0.0015	

Table F22. HEU-ST-001 Case 03

ICSBEP Benchmark	HEU-ST-001		Case 03	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0003	0.0035		
EMS-S5-238	1.0032	0.0005	0.0029	0.0807
EMS-S5-27	1.0091	0.0005	0.0088	0.0607
EMS-S5-44	1.0039	0.0005	0.0036	0.0781
EMS-M5-E50	1.0059	0.0005	0.0055	0.0826
EMS-M5-E62	1.0030	0.0006	0.0027	0.0822
EMS-M5-E66	1.0031	0.0006	0.0028	0.0799
EMS-M5-E68	1.0020	0.0005	0.0017	0.0798
EMS-M5-E7P	0.9996	0.0005	-0.0007	0.0800
EMS-M5-F22	1.0056	0.0006	0.0053	0.0836
EMS-M5-F30	1.0041	0.0006	0.0038	0.0801
EMS-M5-J32	1.0103	0.0006	0.0100	0.0813
EMS-M5-J33	1.0033	0.0006	0.0030	0.0800
IPPE-ABBN93	1.0069	0.0001	0.0066	

Table F23. HEU-ST-001 Case 04

ICSBEP Benchmark	HEU-ST-001		Case 04	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0008	0.0053		
EMS-S5-238	1.0001	0.0005	-0.0007	0.2987
EMS-S5-27	1.0088	0.0005	0.0080	0.2494
EMS-S5-44	1.0026	0.0005	0.0018	0.2936
EMS-M5-E50	1.0025	0.0006	0.0017	0.3070
EMS-M5-E62	1.0019	0.0006	0.0011	0.3026
EMS-M5-E66	0.9996	0.0006	-0.0012	0.2932
EMS-M5-E68	0.9983	0.0006	-0.0025	0.2937
EMS-M5-E7P	0.9949	0.0006	-0.0059	0.2951
EMS-M5-F22	1.0043	0.0006	0.0035	0.3043
EMS-M5-F30	0.9990	0.0006	-0.0018	0.2936
EMS-M5-J32	1.0085	0.0006	0.0077	0.2949
EMS-M5-J33	0.9993	0.0006	-0.0015	0.2946
IPPE-ABBN93	1.0077	0.0002	0.0069	

Table F24. HEU-ST-001 Case 05

ICSBEP Benchmark	HEU-ST-001		Case 05	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0001	0.0049		
EMS-S5-238	1.0011	0.0004	0.0010	0.0430
EMS-S5-27	1.0037	0.0005	0.0036	0.0303
EMS-S5-44	1.0006	0.0005	0.0005	0.0412
EMS-M5-E50	1.0043	0.0005	0.0042	0.0438
EMS-M5-E62	0.9982	0.0005	-0.0019	0.0440
EMS-M5-E66	1.0017	0.0005	0.0016	0.0429
EMS-M5-E68	1.0004	0.0005	0.0003	0.0429
EMS-M5-E7P	0.9973	0.0005	-0.0028	0.0430
EMS-M5-F22	1.0020	0.0005	0.0019	0.0447
EMS-M5-F30	1.0003	0.0005	0.0002	0.0429
EMS-M5-J32	1.0061	0.0005	0.0060	0.0437
EMS-M5-J33	1.0030	0.0005	0.0029	0.0429
IPPE-ABBN93	1.0015	0.0001	0.0014	

Table F25. HEU-ST-001 Case 06

ICSBEP Benchmark	HEU-ST-001		Case 06	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0002	0.0046		
EMS-S5-238	1.0040	0.0005	0.0038	0.0446
EMS-S5-27	1.0081	0.0005	0.0079	0.0315
EMS-S5-44	1.0036	0.0005	0.0034	0.0427
EMS-M5-E50	1.0067	0.0005	0.0065	0.0453
EMS-M5-E62	1.0012	0.0005	0.0010	0.0456
EMS-M5-E66	1.0049	0.0005	0.0047	0.0445
EMS-M5-E68	1.0045	0.0005	0.0043	0.0444
EMS-M5-E7P	1.0015	0.0005	0.0013	0.0445
EMS-M5-F22	1.0045	0.0005	0.0043	0.0464
EMS-M5-F30	1.0050	0.0005	0.0048	0.0444
EMS-M5-J32	1.0087	0.0005	0.0085	0.0453
EMS-M5-J33	1.0050	0.0005	0.0048	0.0445
IPPE-ABBN93	1.0052	0.0001	0.0050	

Table F26. HEU-ST-001 Case 06

ICSBEP Benchmark	HEU-ST-001		Case 06	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0002	0.0046		
EMS-S5-238	1.0040	0.0005	0.0038	0.0446
EMS-S5-27	1.0081	0.0005	0.0079	0.0315
EMS-S5-44	1.0036	0.0005	0.0034	0.0427
EMS-M5-E50	1.0067	0.0005	0.0065	0.0453
EMS-M5-E62	1.0012	0.0005	0.0010	0.0456
EMS-M5-E66	1.0049	0.0005	0.0047	0.0445
EMS-M5-E68	1.0045	0.0005	0.0043	0.0444
EMS-M5-E7P	1.0015	0.0005	0.0013	0.0445
EMS-M5-F22	1.0045	0.0005	0.0043	0.0464
EMS-M5-F30	1.0050	0.0005	0.0048	0.0444
EMS-M5-J32	1.0087	0.0005	0.0085	0.0453
EMS-M5-J33	1.0050	0.0005	0.0048	0.0445
IPPE-ABBN93	1.0052	0.0001	0.0050	

Table F27. HEU-ST-001 Case 07

ICSBEP Benchmark	HEU-ST-001		Case 07	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0008	0.004		
EMS-S5-238	0.9995	0.0005	-0.0013	0.0778
EMS-S5-27	1.0053	0.0005	0.0045	0.0585
EMS-S5-44	0.9997	0.0005	-0.0011	0.0755
EMS-M5-E50	1.0029	0.0006	0.0021	0.0795
EMS-M5-E62	0.9986	0.0005	-0.0022	0.0796
EMS-M5-E66	0.9991	0.0006	-0.0017	0.0771
EMS-M5-E68	0.9999	0.0006	-0.0009	0.0772
EMS-M5-E7P	0.9953	0.0005	-0.0055	0.0775
EMS-M5-F22	1.0003	0.0006	-0.0005	0.0807
EMS-M5-F30	1.0005	0.0006	-0.0003	0.0772
EMS-M5-J32	1.0005	0.0006	-0.0003	0.0773
EMS-M5-J33	1.0005	0.0006	-0.0003	0.0773
IPPE-ABBN93	1.0032	0.0001	0.0024	

Table F28. HEU-ST-001 Case 08

ICSBEP Benchmark	HEU-ST-001		Case 08	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9998	0.0038		
EMS-S5-238	0.9997	0.0005	-0.0001	0.0823
EMS-S5-27	1.0051	0.0005	0.0053	0.0622
EMS-S5-44	1.0003	0.0005	0.0005	0.0798
EMS-M5-E50	1.0032	0.0006	0.0034	0.0840
EMS-M5-E62	0.9987	0.0005	-0.0011	0.0840
EMS-M5-E66	1.0003	0.0006	0.0005	0.0815
EMS-M5-E68	0.9996	0.0006	-0.0002	0.0816
EMS-M5-E7P	0.9958	0.0006	-0.0040	0.0817
EMS-M5-F22	1.0030	0.0006	0.0031	0.0850
EMS-M5-F30	1.0011	0.0006	0.0012	0.0815
EMS-M5-J32	1.0055	0.0006	0.0057	0.0830
EMS-M5-J33	1.0010	0.0006	0.0012	0.0818
IPPE-ABBN93	1.0035	0.0002	0.0037	

Table F29. HEU-ST-001 Case 09

ICSBEP Benchmark	HEU-ST-001		Case 09	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0008	0.0054		
EMS-S5-238	0.9961	0.0005	-0.0047	0.2993
EMS-S5-27	1.0047	0.0005	0.0039	0.2499
EMS-S5-44	0.9974	0.0005	-0.0034	0.2947
EMS-M5-E50	0.9973	0.0006	-0.0035	0.3041
EMS-M5-E62	0.9974	0.0006	-0.0034	0.3033
EMS-M5-E66	0.9953	0.0006	-0.0055	0.2937
EMS-M5-E68	0.9944	0.0006	-0.0064	0.2938
EMS-M5-E7P	0.9900	0.0006	-0.0108	0.2967
EMS-M5-F22	1.0008	0.0006	0.0000	0.3047
EMS-M5-F30	0.9955	0.0006	-0.0053	0.2945
EMS-M5-J32	1.0055	0.0006	0.0047	0.2955
EMS-M5-J33	0.9941	0.0006	-0.0067	0.2954
IPPE-ABBN93	1.0033	0.0002	0.0025	

Table F30. HEU-ST-001 Case 10

ICSBEP Benchmark	HEU-ST-001		Case 10	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9993	0.0054		
EMS-S5-238	0.9947	0.0004	-0.0046	0.0462
EMS-S5-27	0.9974	0.0005	-0.0020	0.0327
EMS-S5-44	0.9941	0.0005	-0.0052	0.0443
EMS-M5-E50	0.9974	0.0005	-0.0019	0.0470
EMS-M5-E62	0.9921	0.0005	-0.0072	0.0472
EMS-M5-E66	0.9944	0.0005	-0.0049	0.0461
EMS-M5-E68	0.9934	0.0005	-0.0059	0.0461
EMS-M5-E7P	0.9907	0.0005	-0.0086	0.0460
EMS-M5-F22	0.9954	0.0005	-0.0039	0.0479
EMS-M5-F30	0.9942	0.0005	-0.0051	0.0460
EMS-M5-J32	1.0006	0.0005	0.0013	0.0468
EMS-M5-J33	0.9944	0.0005	-0.0049	0.0460
IPPE-ABBN93	0.9955	0.0001	-0.0038	

Table F31. HEU-ST-009 Case 01

ICSBEP Benchmark	HEU-ST-009		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9990	0.0043		
EMS-S5-238	1.0036		0.0046	0.5284
EMS-S5-27	1.0124		0.0134	0.4611
EMS-S5-44	1.0071		0.0081	0.5207
EMS-M5-E50	1.0045	0.0006	0.0055	0.5450
EMS-M5-E62	1.0044	0.0006	0.0054	0.5364
EMS-M5-E66	1.0007	0.0006	0.0017	0.5228
EMS-M5-E68	0.9989	0.0006	-0.0001	0.5222
EMS-M5-E7P	0.9967	0.0006	-0.0023	0.5224
EMS-M5-F22	1.0065	0.0006	0.0075	0.5352
EMS-M5-F30	1.0011	0.0006	0.0021	0.5204
EMS-M5-J32	1.0124	0.0006	0.0134	0.5196
EMS-M5-J33	1.0011	0.0006	0.0021	0.5233
IPPE-ABBN93	1.0124	0.0003	0.0134	

Table F32. HEU-ST-009 Case 02

ICSBEP Benchmark	HEU-ST-009		Case 2	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0039		
EMS-S5-238	1.0069		0.0069	0.3243
EMS-S5-27	1.0149		0.0149	0.2762
EMS-S5-44	1.0097		0.0097	0.3193
EMS-M5-E50	1.0044	0.0006	0.0044	0.3358
EMS-M5-E62	1.0046	0.0006	0.0046	0.3291
EMS-M5-E66	1.0017	0.0006	0.0017	0.3199
EMS-M5-E68	1.0005	0.0006	0.0005	0.3195
EMS-M5-E7P	0.9980	0.0006	-0.0020	0.3203
EMS-M5-F22	1.0068	0.0006	0.0068	0.3315
EMS-M5-F30	1.0020	0.0006	0.0020	0.3200
EMS-M5-J32	1.0116	0.0006	0.0116	0.3200
EMS-M5-J33	1.0016	0.0006	0.0016	0.3217
IPPE-ABBN93	1.0105	0.0003	0.0105	

Table F33. HEU-ST-009 Case 03

ICSBEP Benchmark	HEU-ST-009		Case 3	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0036		
EMS-S5-238	1.0033		0.0033	0.1603
EMS-S5-27	1.0103		0.0103	0.1302
EMS-S5-44	1.0054		0.0054	0.1572
EMS-M5-E50	1.0050	0.0006	0.0050	0.1646
EMS-M5-E62	1.0004	0.0006	0.0004	0.1639
EMS-M5-E66	1.0027	0.0006	0.0027	0.1591
EMS-M5-E68	1.0004	0.0006	0.0004	0.1586
EMS-M5-E7P	0.9968	0.0006	-0.0032	0.1593
EMS-M5-F22	1.0050	0.0006	0.0050	0.1655
EMS-M5-F30	1.0001	0.0006	0.0001	0.1589
EMS-M5-J32	1.0099	0.0006	0.0099	0.1608
EMS-M5-J33	1.0021	0.0006	0.0021	0.1592
IPPE-ABBN93	1.0084	0.0003	0.0084	

Table F34. HEU-ST-009 Case 04

ICSBEP Benchmark	HEU-ST-009		Case 4	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9986	0.0035		
EMS-S5-238	0.9979		-0.0007	0.0911
EMS-S5-27	1.0040		0.0054	0.0703
EMS-S5-44	0.9994		0.0008	0.0886
EMS-M5-E50	1.0003	0.0007	0.0017	0.0934
EMS-M5-E62	0.9965	0.0007	-0.0021	0.0933
EMS-M5-E66	0.9951	0.0007	-0.0035	0.0906
EMS-M5-E68	0.9943	0.0007	-0.0043	0.0906
EMS-M5-E7P	0.9902	0.0007	-0.0084	0.0909
EMS-M5-F22	0.9971	0.0007	-0.0015	0.0945
EMS-M5-F30	0.9954	0.0007	-0.0032	0.0908
EMS-M5-J32	1.0021	0.0007	0.0035	0.0922
EMS-M5-J33	0.9959	0.0007	-0.0027	0.0906
IPPE-ABBN93	1.0007	0.0003	0.0021	

Table F35. HEU-ST-010 Case 01

ICSBEP Benchmark	HEU-ST-010		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0029		
EMS-S5-238	1.0034		0.0034	0.0528
EMS-S5-27	1.0080		0.0080	0.0383
EMS-S5-44	1.0044		0.0044	0.0508
EMS-M5-E50	1.0052	0.0005	0.0052	0.0537
EMS-M5-E62	0.9995	0.0005	-0.0005	0.0539
EMS-M5-E66	1.0022	0.0005	0.0022	0.0525
EMS-M5-E68	1.0007	0.0005	0.0007	0.0525
EMS-M5-E7P	0.9976	0.0005	-0.0024	0.0526
EMS-M5-F22	1.0020	0.0005	0.0020	0.0548
EMS-M5-F30	1.0009	0.0005	0.0009	0.0526
EMS-M5-J32	1.0075	0.0005	0.0075	0.0535
EMS-M5-J33	1.0023	0.0005	0.0023	0.0526
IPPE-ABBN93	1.0043	0.0003	0.0043	

Table F36. HEU-ST-010 Case 02

ICSBEP Benchmark	HEU-ST-010		Case 2	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0029		
EMS-S5-238	1.0042		0.0042	0.0548
EMS-S5-27	1.0087		0.0087	0.0404
EMS-S5-44	1.0051		0.0051	0.0528
EMS-M5-E50	1.0054	0.0005	0.0054	0.0544
EMS-M5-E62	0.9992	0.0005	-0.0008	0.0546
EMS-M5-E66	1.0027	0.0005	0.0027	0.0531
EMS-M5-E68	1.0015	0.0005	0.0014	0.0531
EMS-M5-E7P	0.9983	0.0005	-0.0017	0.0533
EMS-M5-F22	1.0024	0.0005	0.0024	0.0556
EMS-M5-F30	1.0026	0.0005	0.0026	0.0532
EMS-M5-J32	1.0067	0.0005	0.0067	0.0543
EMS-M5-J33	1.0020	0.0005	0.0020	0.0532
IPPE-ABBN93	1.0045	0.0003	0.0045	

Table F37. HEU-ST-010 Case 03

ICSBEP Benchmark	HEU-ST-010		Case 3	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0029		
EMS-S5-238	1.0028		0.0028	0.0609
EMS-S5-27	1.0070		0.0070	0.0467
EMS-S5-44	1.0038		0.0038	0.0590
EMS-M5-E50	1.0034	0.0005	0.0034	0.0568
EMS-M5-E62	0.9964	0.0005	-0.0036	0.0569
EMS-M5-E66	0.9994	0.0005	-0.0006	0.0553
EMS-M5-E68	0.9989	0.0005	-0.0011	0.0553
EMS-M5-E7P	0.9957	0.0005	-0.0043	0.0554
EMS-M5-F22	1.0001	0.0005	0.0001	0.0577
EMS-M5-F30	0.9988	0.0005	-0.0012	0.0552
EMS-M5-J32	1.0051	0.0005	0.0051	0.0563
EMS-M5-J33	0.9996	0.0005	-0.0004	0.0554
IPPE-ABBN93	1.0022	0.0003	0.0022	

Table F38. HEU-ST-010 Case 04

ICSBEP Benchmark	HEU-ST-010		Case 4	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9992	0.0029		
EMS-S5-238	1.0014		0.0022	0.0632
EMS-S5-27	1.0055		0.0063	0.0489
EMS-S5-44	1.0024		0.0032	0.0613
EMS-M5-E50	1.0003	0.0005	0.0011	0.0576
EMS-M5-E62	0.9952	0.0005	-0.0040	0.0578
EMS-M5-E66	0.9974	0.0005	-0.0019	0.0562
EMS-M5-E68	0.9972	0.0005	-0.0020	0.0561
EMS-M5-E7P	0.9937	0.0005	-0.0055	0.0564
EMS-M5-F22	0.9970	0.0005	-0.0022	0.0587
EMS-M5-F30	0.9978	0.0005	-0.0014	0.0564
EMS-M5-J32	1.0028	0.0005	0.0036	0.0572
EMS-M5-J33	0.9977	0.0005	-0.0015	0.0563
IPPE-ABBN93	1.0002	0.0003	0.0010	

Table F39. HEU-ST-011 Case 01

ICSBEP Benchmark	HEU-ST-011		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0023		
EMS-S5-238	1.0071		0.0071	0.0396
EMS-S5-27	1.0098		0.0097	0.0276
EMS-S5-44	1.0075		0.0075	0.0379
EMS-M5-E50	1.0085	0.0005	0.0085	0.0405
EMS-M5-E62	1.0026	0.0005	0.0026	0.0407
EMS-M5-E66	1.0048	0.0005	0.0048	0.0397
EMS-M5-E68	1.0039	0.0005	0.0039	0.0398
EMS-M5-E7P	1.0028	0.0005	0.0028	0.0398
EMS-M5-F22	1.0051	0.0005	0.0051	0.0413
EMS-M5-F30	1.0054	0.0005	0.0054	0.0398
EMS-M5-J32	1.0109	0.0005	0.0109	0.0404
EMS-M5-J33	1.0061	0.0005	0.0061	0.0399
IPPE-ABBN93	1.0065	0.0003	0.0065	

Table F40. HEU-ST-011 Case 02

ICSBEP Benchmark	HEU-ST-011		Case 2	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0023		
EMS-S5-238	1.0032		0.0032	0.0394
EMS-S5-27	1.0059		0.0059	0.0274
EMS-S5-44	1.0036		0.0036	0.0376
EMS-M5-E50	1.0047	0.0005	0.0047	0.0403
EMS-M5-E62	0.9996	0.0005	-0.0004	0.0405
EMS-M5-E66	1.0021	0.0005	0.0021	0.0396
EMS-M5-E68	1.0008	0.0005	0.0008	0.0395
EMS-M5-E7P	0.9988	0.0005	-0.0012	0.0395
EMS-M5-F22	1.0004	0.0005	0.0004	0.0412
EMS-M5-F30	1.0024	0.0005	0.0024	0.0395
EMS-M5-J32	1.0064	0.0005	0.0064	0.0403
EMS-M5-J33	1.0032	0.0005	0.0032	0.0396
IPPE-ABBN93	1.0034	0.0003	0.0034	

Table F41. HEU-ST-012 Case 01

ICSBEP Benchmark	HEU-ST-012		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9999	0.0058		
EMS-S5-238	1.0023		0.0024	0.0324
EMS-S5-27	1.0013		0.0014	0.0219
EMS-S5-44	1.0022		0.0023	0.0307
EMS-M5-E50	1.0037	0.0003	0.0037	0.0331
EMS-M5-E62	1.0036	0.0003	0.0037	0.0331
EMS-M5-E66	1.0015	0.0003	0.0016	0.0326
EMS-M5-E68	1.0014	0.0003	0.0015	0.0326
EMS-M5-E7P	1.0001	0.0004	0.0002	0.0326
EMS-M5-F22	1.0001	0.0003	0.0002	0.0338
EMS-M5-F30	1.0014	0.0003	0.0014	0.0326
EMS-M5-J32	1.0047	0.0003	0.0048	0.0332
EMS-M5-J33	1.0030	0.0003	0.0031	0.0326
IPPE-ABBN93	1.0011	0.0002	0.0012	

Table F42. HEU-ST-025 Case 01

ICSBEP Benchmark	HEU-ST-025		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0002	0.0025		
EMS-S5-238	1.0026	0.0004	0.0024	0.0406
EMS-S5-27	1.0047	0.0004	0.0045	0.0284
EMS-S5-44	1.0028	0.0004	0.0026	0.0388
EMS-M5-E50	1.0046	0.0004	0.0044	0.0413
EMS-M5-E62	1.0052	0.0004	0.0050	0.0413
EMS-M5-E66	1.0029	0.0004	0.0027	0.0404
EMS-M5-E68	1.0018	0.0004	0.0016	0.0405
EMS-M5-E7P	0.9996	0.0004	-0.0006	0.0406
EMS-M5-F22	1.0022	0.0004	0.0020	0.0422
EMS-M5-F30	1.0025	0.0004	0.0023	0.0405
EMS-M5-J32	1.0073	0.0004	0.0071	0.0412
EMS-M5-J33	1.0036	0.0004	0.0034	0.0405
IPPE-ABBN93	1.0023	0.0008	0.0021	

Table F43. HEU-ST-027 Case 01

ICSBEP Benchmark	HEU-ST-027		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0046		
EMS-S5-238	0.9978	0.0005	-0.0022	0.0747
EMS-S5-27	1.0043	0.0005	0.0043	0.0558
EMS-S5-44	0.9979	0.0005	-0.0021	0.0723
EMS-M5-E50	1.0013	0.0005	0.0013	0.0762
EMS-M5-E62	0.9969	0.0005	-0.0031	0.0763
EMS-M5-E66	0.9983	0.0005	-0.0017	0.0739
EMS-M5-E68	0.9975	0.0005	-0.0025	0.0742
EMS-M5-E7P	0.9952	0.0005	-0.0048	0.0743
EMS-M5-F22	0.9996	0.0005	-0.0004	0.0774
EMS-M5-F30	0.9990	0.0005	-0.0011	0.0741
EMS-M5-J32	1.0036	0.0005	0.0036	0.0754
EMS-M5-J33	0.9986	0.0005	-0.0014	0.0742
IPPE-ABBN93	1.0002	0.0005	0.0002	

Table F44. HEU-ST-028 Case 01

ICSBEP Benchmark	HEU-ST-028		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0023		
EMS-S5-238	0.9988	0.0004	-0.0012	0.0472
EMS-S5-27	1.0013	0.0004	0.0013	0.0337
EMS-S5-44	0.9987	0.0004	-0.0013	0.0453
EMS-M5-E50	1.0009	0.0004	0.0009	0.0481
EMS-M5-E62	0.9948	0.0004	-0.0052	0.0483
EMS-M5-E66	0.9970	0.0004	-0.0030	0.0471
EMS-M5-E68	0.9967	0.0004	-0.0033	0.0471
EMS-M5-E7P	0.9941	0.0004	-0.0059	0.0472
EMS-M5-F22	0.9979	0.0004	-0.0021	0.0491
EMS-M5-F30	0.9971	0.0004	-0.0029	0.0471
EMS-M5-J32	1.0024	0.0004	0.0024	0.0479
EMS-M5-J33	0.9979	0.0004	-0.0021	0.0471
IPPE-ABBN93	0.9981	0.0004	-0.0019	

Table F45. HEU-ST-028 Case 09

ICSBEP Benchmark	HEU-ST-028		Case 9	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0049		
EMS-S5-238	0.9976	0.0005	-0.0024	0.1455
EMS-S5-27	1.0042	0.0005	0.0042	0.1170
EMS-S5-44	0.9994	0.0005	-0.0006	0.1424
EMS-M5-E50	0.9991	0.0004	-0.0009	0.1495
EMS-M5-E62	0.9952	0.0004	-0.0048	0.1484
EMS-M5-E66	0.9954	0.0004	-0.0046	0.1440
EMS-M5-E68	0.9936	0.0004	-0.0064	0.1439
EMS-M5-E7P	0.9913	0.0004	-0.0087	0.1446
EMS-M5-F22	0.9984	0.0004	-0.0016	0.1501
EMS-M5-F30	0.9950	0.0004	-0.0050	0.1442
EMS-M5-J32	1.0028	0.0004	0.0028	0.1453
EMS-M5-J33	0.9949	0.0004	-0.0051	0.1446
IPPE-ABBN93	0.9993	0.0004	-0.0007	

Table F46. HEU-ST-029 Case 01

ICSBEP Benchmark	HEU-ST-029		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0066		
EMS-S5-238	0.9987	0.0005	-0.0013	0.1589
EMS-S5-27	1.0064	0.0005	0.0064	0.1282
EMS-S5-44	1.0013	0.0005	0.0013	0.1557
EMS-M5-E50	1.0015	0.0007	0.0015	0.1631
EMS-M5-E62	0.9981	0.0007	-0.0019	0.1620
EMS-M5-E66	0.9976	0.0007	-0.0024	0.1572
EMS-M5-E68	0.9971	0.0007	-0.0029	0.1573
EMS-M5-E7P	0.9947	0.0007	-0.0053	0.1581
EMS-M5-F22	1.0017	0.0007	0.0017	0.1642
EMS-M5-F30	0.9981	0.0007	-0.0019	0.1570
EMS-M5-J32	1.0052	0.0007	0.0052	0.1589
EMS-M5-J33	0.9991	0.0007	-0.0009	0.1573
IPPE-ABBN93	1.0025	0.0010	0.0025	

Table F47. HEU-ST-030 Case 01

ICSBEP Benchmark	HEU-ST-030		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0039		
EMS-S5-238	0.9981	0.0004	-0.0019	0.0479
EMS-S5-27	1.0013	0.0004	0.0013	0.0342
EMS-S5-44	0.9986	0.0005	-0.0014	0.0460
EMS-M5-E50	1.0012	0.0006	0.0012	0.0488
EMS-M5-E62	0.9954	0.0006	-0.0046	0.0489
EMS-M5-E66	0.9961	0.0006	-0.0039	0.0477
EMS-M5-E68	0.9978	0.0006	-0.0022	0.0477
EMS-M5-E7P	0.9935	0.0006	-0.0065	0.0479
EMS-M5-F22	0.9977	0.0006	-0.0023	0.0497
EMS-M5-F30	0.9988	0.0006	-0.0012	0.0477
EMS-M5-J32	1.0035	0.0006	0.0035	0.0486
EMS-M5-J33	0.9981	0.0006	-0.0019	0.0479
IPPE-ABBN93	0.9977	0.0009	-0.0023	

Table F48. HEU-ST-030 Case 04

ICSBEP Benchmark	HEU-ST-030		Case 4	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0064		
EMS-S5-238	1.0008	0.0005	0.0008	0.1597
EMS-S5-27	1.0089	0.0005	0.0089	0.1287
EMS-S5-44	1.0024	0.0005	0.0024	0.1564
EMS-M5-E50	1.0032	0.0007	0.0032	0.1639
EMS-M5-E62	1.0010	0.0007	0.0010	0.1626
EMS-M5-E66	1.0008	0.0007	0.0008	0.1581
EMS-M5-E68	0.9991	0.0007	-0.0009	0.1578
EMS-M5-E7P	0.9945	0.0007	-0.0055	0.1588
EMS-M5-F22	1.0052	0.0007	0.0052	0.1640
EMS-M5-F30	0.9996	0.0007	-0.0004	0.1582
EMS-M5-J32	1.0079	0.0007	0.0079	0.1599
EMS-M5-J33	1.0004	0.0007	0.0004	0.1580
IPPE-ABBN93	1.0053	0.0009	0.0053	

Table F49. HEU-ST-033 Case 11A-S

ICSBEP Benchmark	HEU-ST-033		Case 11A-S	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9942	0.0112		
EMS-S5-238	0.9982	0.0005	0.0040	0.2916
EMS-S5-27	1.0018	0.0004	0.0075	0.2442
EMS-S5-44	1.0023	0.0004	0.0081	0.2866
EMS-M5-E50	0.9978	0.0012	0.0036	0.2986
EMS-M5-E62	1.0006	0.0001	0.0064	0.2960
EMS-M5-E66	0.9966	0.0011	0.0024	0.2860
EMS-M5-E68	0.9959	0.0011	0.0017	0.2863
EMS-M5-E7P	0.9930	0.0012	-0.0012	0.2881
EMS-M5-F22	1.0028	0.0011	0.0086	0.2981
EMS-M5-F30	0.9966	0.0011	0.0024	0.2880
EMS-M5-J32	1.0041	0.0011	0.0099	0.2881
EMS-M5-J33	0.9985	0.0011	0.0043	0.2878
IPPE-ABBN93	0.9988	0.0009	0.0046	

Table F48. HEU-ST-030 Case 04

ICSBEP Benchmark	HEU-ST-030		Case 4	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0064		
EMS-S5-238	1.0008	0.0005	0.0008	0.1597
EMS-S5-27	1.0089	0.0005	0.0089	0.1287
EMS-S5-44	1.0024	0.0005	0.0024	0.1564
EMS-M5-E50	1.0032	0.0007	0.0032	0.1639
EMS-M5-E62	1.0010	0.0007	0.0010	0.1626
EMS-M5-E66	1.0008	0.0007	0.0008	0.1581
EMS-M5-E68	0.9991	0.0007	-0.0009	0.1578
EMS-M5-E7P	0.9945	0.0007	-0.0055	0.1588
EMS-M5-F22	1.0052	0.0007	0.0052	0.1640
EMS-M5-F30	0.9996	0.0007	-0.0004	0.1582
EMS-M5-J32	1.0079	0.0007	0.0079	0.1599
EMS-M5-J33	1.0004	0.0007	0.0004	0.1580
IPPE-ABBN93	1.0053	0.0009	0.0053	

Table F49. HEU-ST-033 Case 11A-S

ICSBEP Benchmark	HEU-ST-033		Case 11A-S	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9942	0.0112		
EMS-S5-238	0.9982	0.0005	0.0040	0.2916
EMS-S5-27	1.0018	0.0004	0.0075	0.2442
EMS-S5-44	1.0023	0.0004	0.0081	0.2866
EMS-M5-E50	0.9978	0.0012	0.0036	0.2986
EMS-M5-E62	1.0006	0.0001	0.0064	0.2960
EMS-M5-E66	0.9966	0.0011	0.0024	0.2860
EMS-M5-E68	0.9959	0.0011	0.0017	0.2863
EMS-M5-E7P	0.9930	0.0012	-0.0012	0.2881
EMS-M5-F22	1.0028	0.0011	0.0086	0.2981
EMS-M5-F30	0.9966	0.0011	0.0024	0.2880
EMS-M5-J32	1.0041	0.0011	0.0099	0.2881
EMS-M5-J33	0.9985	0.0011	0.0043	0.2878
IPPE-ABBN93	0.9988	0.0009	0.0046	

Table F50. HEU-ST-033 Case 11B-S

ICSBEP Benchmark	HEU-ST-033		Case 11B-S	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9979	0.0109		
EMS-S5-238	0.9993	0.0004	0.0014	0.2877
EMS-S5-27	1.0022	0.0004	0.0043	0.2406
EMS-S5-44	1.0023	0.0004	0.0044	0.2829
EMS-M5-E50	0.9992	0.0012	0.0013	0.2985
EMS-M5-E62	1.0011	0.0011	0.0032	0.2899
EMS-M5-E66	0.9979	0.0011	0.0000	0.2838
EMS-M5-E68	0.9970	0.0011	-0.0009	0.2807
EMS-M5-E7P	0.9951	0.0011	-0.0028	0.2833
EMS-M5-F22	1.0049	0.0011	0.0070	0.2921
EMS-M5-F30	0.9984	0.0010	0.0005	0.2833
EMS-M5-J32	1.0060	0.0010	0.0081	0.2822
EMS-M5-J33	0.9978	0.0011	-0.0001	0.2827
IPPE-ABBN93	0.9974	0.0009	-0.0005	

Table F51. HEU-ST-035 Case 01

ICSBEP Benchmark	HEU-ST-035		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0031		
EMS-S5-238	1.0015	0.0004	0.0015	0.0373
EMS-S5-27	1.0022	0.0004	0.0022	0.0258
EMS-S5-44	1.0014	0.0004	0.0014	0.0356
EMS-M5-E50	1.0049	0.0007	0.0049	0.0380
EMS-M5-E62	1.0010	0.0007	0.0010	0.0381
EMS-M5-E66	1.0003	0.0007	0.0003	0.0372
EMS-M5-E68	1.0015	0.0007	0.0015	0.0373
EMS-M5-E7P	1.0001	0.0007	0.0001	0.0372
EMS-M5-F22	1.0026	0.0007	0.0026	0.0388
EMS-M5-F30	1.0034	0.0007	0.0034	0.0372
EMS-M5-J32	1.0071	0.0007	0.0071	0.0379
EMS-M5-J33	1.0029	0.0007	0.0029	0.0373
IPPE-ABBN93	0.9993	0.0007	-0.0007	

Table F52. HEU-ST-035 Case 05

ICSBEP Benchmark	HEU-ST-035		Case 5	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0033		
EMS-S5-238	1.0043	0.0005	0.0043	0.0494
EMS-S5-27	1.0060	0.0004	0.0060	0.0353
EMS-S5-44	1.0035	0.0004	0.0035	0.0474
EMS-M5-E50	1.0079	0.0009	0.0079	0.0501
EMS-M5-E62	1.0027	0.0008	0.0027	0.0504
EMS-M5-E66	1.0067	0.0009	0.0067	0.0491
EMS-M5-E68	1.0004	0.0009	0.0004	0.0491
EMS-M5-E7P	1.0038	0.0009	0.0038	0.0492
EMS-M5-F22	1.0050	0.0009	0.0050	0.0513
EMS-M5-F30	1.0049	0.0009	0.0049	0.0493
EMS-M5-J32	1.0076	0.0009	0.0076	0.0502
EMS-M5-J33	1.0065	0.0009	0.0065	0.0492
IPPE-ABBN93	1.0012	0.0009	0.0012	

Table F53. HEU-ST-035 Case 07

ICSBEP Benchmark	HEU-ST-035		Case 7	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0035		
EMS-S5-238	1.0046	0.0005	0.0046	0.0808
EMS-S5-27	1.0095	0.0005	0.0094	0.0610
EMS-S5-44	1.0063	0.0005	0.0063	0.0783
EMS-M5-E50	1.0084	0.0009	0.0084	0.0821
EMS-M5-E62	1.0048	0.0009	0.0048	0.0826
EMS-M5-E66	1.0054	0.0009	0.0054	0.0800
EMS-M5-E68	1.0028	0.0010	0.0028	0.0799
EMS-M5-E7P	1.0025	0.0009	0.0025	0.0800
EMS-M5-F22	1.0082	0.0009	0.0082	0.0839
EMS-M5-F30	1.0057	0.0010	0.0056	0.0800
EMS-M5-J32	1.0126	0.0009	0.0126	0.0813
EMS-M5-J33	1.0072	0.0009	0.0072	0.0802
IPPE-ABBN93	1.0038	0.0009	0.0038	

Table F54. HEU-ST-036 Case 01

ICSBEP Benchmark	HEU-ST-036		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9974	0.0045		
EMS-S5-238	0.9951	0.0005	-0.0023	0.0561
EMS-S5-27	0.9991	0.0005	0.0017	0.0407
EMS-S5-44	0.9942	0.0005	-0.0032	0.0540
EMS-M5-E50	0.9992	0.0009	0.0018	0.0570
EMS-M5-E62	0.9935	0.0010	-0.0039	0.0572
EMS-M5-E66	0.9971	0.0010	-0.0003	0.0558
EMS-M5-E68	0.9969	0.0009	-0.0005	0.0556
EMS-M5-E7P	0.9964	0.0009	-0.0011	0.0557
EMS-M5-F22	0.9960	0.0010	-0.0014	0.0581
EMS-M5-F30	0.9960	0.0010	-0.0014	0.0560
EMS-M5-J32	0.9991	0.0009	0.0017	0.0568
EMS-M5-J33	0.9950	0.0010	-0.0024	0.0557
IPPE-ABBN93	0.9966	0.0009	-0.0008	

Table F55. HEU-ST-037 Case 01

ICSBEP Benchmark	HEU-ST-037		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9980	0.0034		
EMS-S5-238	1.0114	0.0004	0.0134	0.0383
EMS-S5-27	1.0102	0.0005	0.0122	0.0266
EMS-S5-44	1.0100	0.0004	0.0120	0.0366
EMS-M5-E50	1.0131	0.0008	0.0151	0.0390
EMS-M5-E62	1.0095	0.0008	0.0115	0.0391
EMS-M5-E66	1.0113	0.0007	0.0133	0.0382
EMS-M5-E68	1.0106	0.0008	0.0126	0.0383
EMS-M5-E7P	1.0100	0.0008	0.0120	0.0382
EMS-M5-F22	1.0101	0.0007	0.0121	0.0397
EMS-M5-F30	1.0105	0.0007	0.0125	0.0382
EMS-M5-J32	1.0145	0.0007	0.0165	0.0390
EMS-M5-J33	1.0132	0.0008	0.0152	0.0382
IPPE-ABBN93	1.0074	0.0008	0.0094	

Table F56. HEU-ST-037 Case 03

ICSBEP Benchmark	HEU-ST-037		Case 3	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9970	0.0042		
EMS-S5-238	1.0068	0.0004	0.0098	0.0442
EMS-S5-27	1.0087	0.0004	0.0117	0.0312
EMS-S5-44	1.0075	0.0004	0.0105	0.0423
EMS-M5-E50	1.0113	0.0008	0.0143	0.0450
EMS-M5-E62	1.0049	0.0008	0.0079	0.0451
EMS-M5-E66	1.0084	0.0008	0.0114	0.0440
EMS-M5-E68	1.0085	0.0008	0.0115	0.0440
EMS-M5-E7P	1.0052	0.0008	0.0082	0.0439
EMS-M5-F22	1.0085	0.0008	0.0115	0.0459
EMS-M5-F30	1.0075	0.0008	0.0105	0.0441
EMS-M5-J32	1.0135	0.0008	0.0165	0.0447
EMS-M5-J33	1.0098	0.0008	0.0128	0.0441
IPPE-ABBN93	1.0052	0.0009	0.0082	

Table F57. HEU-ST-037 Case 06

ICSBEP Benchmark	HEU-ST-037		Case 6	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9960	0.0051		
EMS-S5-238	1.0114	0.0004	0.0154	0.0512
EMS-S5-27	1.0144	0.0004	0.0184	0.0369
EMS-S5-44	1.0117	0.0004	0.0157	0.0493
EMS-M5-E50	1.0171	0.0008	0.0211	0.0521
EMS-M5-E62	1.0098	0.0009	0.0138	0.0523
EMS-M5-E66	1.0137	0.0009	0.0177	0.0510
EMS-M5-E68	1.0128	0.0009	0.0168	0.0508
EMS-M5-E7P	1.0126	0.0009	0.0166	0.0509
EMS-M5-F22	1.0155	0.0009	0.0195	0.0532
EMS-M5-F30	1.0138	0.0009	0.0178	0.0511
EMS-M5-J32	1.0166	0.0009	0.0206	0.0520
EMS-M5-J33	1.0146	0.0009	0.0186	0.0508
IPPE-ABBN93	1.0124	0.0009	0.0164	

Table F58. HEU-ST-038 Case 01

ICSBEP Benchmark	HEU-ST-038		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0025		
EMS-S5-238	0.9980	0.0005	-0.0020	0.3884
EMS-S5-27	1.0057	0.0005	0.0057	0.3285
EMS-S5-44	0.9997	0.0005	-0.0003	0.3821
EMS-M5-E50	1.0014	0.0005	0.0014	0.3988
EMS-M5-E62	1.0009	0.0005	0.0009	0.3927
EMS-M5-E66	0.9982	0.0005	-0.0018	0.3808
EMS-M5-E68	0.9973	0.0005	-0.0028	0.3809
EMS-M5-E7P	0.9951	0.0005	-0.0049	0.3833
EMS-M5-F22	1.0032	0.0005	0.0032	0.3931
EMS-M5-F30	0.9990	0.0005	-0.0010	0.3798
EMS-M5-J32	1.0048	0.0005	0.0048	0.3813
EMS-M5-J33	0.9975	0.0005	-0.0025	0.3818
IPPE-ABBN93	1.0006	0.0004	0.0006	

Table F59. HEU-ST-042 Case 01

ICSBEP Benchmark	HEU-ST-042		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9957	0.0039		
EMS-S5-238	0.9976	0.0003	0.0019	0.0314
EMS-S5-27	0.9957	0.0003	0.0000	0.0208
EMS-S5-44	0.9970	0.0003	0.0013	0.0298
EMS-M5-E50	0.9971	0.0003	0.0014	0.0322
EMS-M5-E62	0.9955	0.0003	-0.0002	0.0324
EMS-M5-E66	0.9965	0.0003	0.0008	0.0317
EMS-M5-E68	0.9969	0.0003	0.0012	0.0318
EMS-M5-E7P	0.9964	0.0003	0.0007	0.0317
EMS-M5-F22	0.9958	0.0003	0.0001	0.0329
EMS-M5-F30	0.9954	0.0003	-0.0003	0.0318
EMS-M5-J32	1.0003	0.0003	0.0046	0.0323
EMS-M5-J33	0.9975	0.0003	0.0018	0.0318
IPPE-ABBN93	0.9950	0.0002	-0.0007	

Table F60. HEU-ST-042 Case 02

ICSBEP Benchmark	HEU-ST-042		Case 2	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9965	0.0036		
EMS-S5-238	0.9973	0.0003	0.0008	0.0313
EMS-S5-27	0.9948	0.0003	-0.0017	0.0207
EMS-S5-44	0.9968	0.0003	0.0003	0.0297
EMS-M5-E50	0.9968	0.0003	0.0003	0.0321
EMS-M5-E62	0.9946	0.0003	-0.0019	0.0323
EMS-M5-E66	0.9968	0.0003	0.0003	0.0317
EMS-M5-E68	0.9962	0.0003	-0.0003	0.0317
EMS-M5-E7P	0.9954	0.0003	-0.0011	0.0317
EMS-M5-F22	0.9954	0.0003	-0.0011	0.0328
EMS-M5-F30	0.9960	0.0003	-0.0005	0.0317
EMS-M5-J32	1.0000	0.0003	0.0035	0.0322
EMS-M5-J33	0.9975	0.0003	0.0010	0.0316
IPPE-ABBN93	0.9946	0.0002	-0.0019	

Table F61. HEU-ST-042 Case 03

ICSBEP Benchmark	HEU-ST-042		Case 3	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9994	0.0028		
EMS-S5-238	1.0006	0.0003	0.0012	0.0308
EMS-S5-27	0.9986	0.0003	-0.0008	0.0204
EMS-S5-44	1.0007	0.0003	0.0013	0.0292
EMS-M5-E50	1.0008	0.0002	0.0014	0.0317
EMS-M5-E62	0.9982	0.0002	-0.0012	0.0319
EMS-M5-E66	1.0005	0.0002	0.0011	0.0312
EMS-M5-E68	1.0001	0.0002	0.0007	0.0309
EMS-M5-E7P	0.9998	0.0002	0.0004	0.0312
EMS-M5-F22	0.9986	0.0002	-0.0008	0.0323
EMS-M5-F30	0.9994	0.0002	0.0000	0.0311
EMS-M5-J32	1.0036	0.0002	0.0042	0.0317
EMS-M5-J33	1.0021	0.0002	0.0027	0.0312
IPPE-ABBN93	0.9985	0.0001	-0.0009	

Table F62. HEU-ST-042 Case 04

ICSBEP Benchmark	HEU-ST-042		Case 4	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0034		
EMS-S5-238	1.0022	0.0003	0.0022	0.0306
EMS-S5-27	0.9989	0.0003	-0.0011	0.0202
EMS-S5-44	1.0012	0.0003	0.0012	0.0290
EMS-M5-E50	1.0021	0.0002	0.0021	0.0314
EMS-M5-E62	0.9994	0.0002	-0.0006	0.0316
EMS-M5-E66	1.0016	0.0002	0.0016	0.0309
EMS-M5-E68	1.0011	0.0002	0.0011	0.0310
EMS-M5-E7P	1.0014	0.0002	0.0013	0.0310
EMS-M5-F22	1.0000	0.0002	0.0000	0.0321
EMS-M5-F30	1.0004	0.0002	0.0004	0.0310
EMS-M5-J32	1.0043	0.0002	0.0043	0.0316
EMS-M5-J33	1.0023	0.0002	0.0023	0.0310
IPPE-ABBN93	0.9995	0.0001	-0.0006	

Table F63. HEU-ST-042 Case 05

ICSBEP Benchmark	HEU-ST-042		Case 5	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0034		
EMS-S5-238	0.9998	0.0003	-0.0002	0.0304
EMS-S5-27	0.9964	0.0002	-0.0036	0.0201
EMS-S5-44	0.9991	0.0003	-0.0009	0.0289
EMS-M5-E50	0.9999	0.0002	-0.0001	0.0313
EMS-M5-E62	0.9972	0.0002	-0.0028	0.0315
EMS-M5-E66	0.9984	0.0002	-0.0016	0.0309
EMS-M5-E68	0.9990	0.0002	-0.0010	0.0308
EMS-M5-E7P	0.9991	0.0002	-0.0009	0.0309
EMS-M5-F22	0.9977	0.0002	-0.0023	0.0320
EMS-M5-F30	0.9982	0.0002	-0.0018	0.0309
EMS-M5-J32	1.0023	0.0002	0.0023	0.0314
EMS-M5-J33	1.0000	0.0002	0.0000	0.0308
IPPE-ABBN93	0.9972	0.0001	-0.0028	

Table F64. HEU-ST-042 Case 06

ICSBEP Benchmark	HEU-ST-042		Case 6	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0037		
EMS-S5-238	0.9998	0.0002	-0.0002	0.0305
EMS-S5-27	0.9968	0.0002	-0.0032	0.0202
EMS-S5-44	0.9995	0.0003	-0.0005	0.0289
EMS-M5-E50	1.0004	0.0002	0.0004	0.0309
EMS-M5-E62	0.9974	0.0002	-0.0026	0.0316
EMS-M5-E66	0.9997	0.0002	-0.0003	0.0309
EMS-M5-E68	0.9994	0.0002	-0.0006	0.0309
EMS-M5-E7P	0.9984	0.0002	-0.0016	0.0309
EMS-M5-F22	0.9985	0.0002	-0.0015	0.0320
EMS-M5-F30	0.9984	0.0002	-0.0016	0.0309
EMS-M5-J32	1.0026	0.0002	0.0026	0.0314
EMS-M5-J33	1.0010	0.0002	0.0010	0.0309
IPPE-ABBN93	0.9975	0.0001	-0.0025	

Table F65. HEU-ST-042 Case 07

ICSBEP Benchmark	HEU-ST-042		Case 7	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0036		
EMS-S5-238	1.0007	0.0002	0.0007	0.0304
EMS-S5-27	0.9975	0.0003	-0.0025	0.0201
EMS-S5-44	1.0001	0.0003	0.0001	0.0288
EMS-M5-E50	1.0013	0.0002	0.0013	0.0313
EMS-M5-E62	0.9988	0.0002	-0.0012	0.0315
EMS-M5-E66	1.0001	0.0002	0.0001	0.0308
EMS-M5-E68	1.0002	0.0002	0.0002	0.0308
EMS-M5-E7P	1.0001	0.0002	0.0001	0.0308
EMS-M5-F22	0.9989	0.0002	-0.0011	0.0319
EMS-M5-F30	0.9995	0.0002	-0.0005	0.0308
EMS-M5-J32	1.0031	0.0002	0.0031	0.0313
EMS-M5-J33	1.0005	0.0002	0.0005	0.0308
IPPE-ABBN93	0.9984	0.0001	-0.0017	

Table F66. HEU-ST-042 Case 08

ICSBEP Benchmark	HEU-ST-042		Case 8	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0035		
EMS-S5-238	1.0009	0.0002	0.0009	0.0303
EMS-S5-27	0.9976	0.0002	-0.0024	0.0200
EMS-S5-44	1.0009	0.0002	0.0009	0.0287
EMS-M5-E50	1.0013	0.0001	0.0013	0.0312
EMS-M5-E62	0.9995	0.0001	-0.0005	0.0313
EMS-M5-E66	1.0009	0.0001	0.0009	0.0307
EMS-M5-E68	1.0006	0.0001	0.0006	0.0307
EMS-M5-E7P	1.0008	0.0001	0.0008	0.0307
EMS-M5-F22	0.9996	0.0001	-0.0004	0.0318
EMS-M5-F30	0.9998	0.0001	-0.0002	0.0307
EMS-M5-J32	1.0034	0.0001	0.0034	0.0312
EMS-M5-J33	1.0018	0.0001	0.0018	0.0307
IPPE-ABBN93	0.9985	0.0001	-0.0015	

Table F67. HEU-ST-043 Case 01

ICSBEP Benchmark	HEU-ST-043		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9986	0.0031		
EMS-S5-238	0.9974		-0.0012	0.0737
EMS-S5-27	1.0025		0.0039	0.0550
EMS-S5-44	0.9978		-0.0008	0.0714
EMS-M5-E50	0.9988	0.0008	0.0002	0.0756
EMS-M5-E62	0.9940	0.0008	-0.0046	0.0756
EMS-M5-E66	0.9955	0.0007	-0.0031	0.0733
EMS-M5-E68	0.9962	0.0007	-0.0025	0.0734
EMS-M5-E7P	0.9934	0.0008	-0.0052	0.0737
EMS-M5-F22	0.9958	0.0007	-0.0028	0.0769
EMS-M5-F30	0.9961	0.0008	-0.0025	0.0733
EMS-M5-J32	1.0032	0.0007	0.0046	0.0747
EMS-M5-J33	0.9960	0.0007	-0.0027	0.0734
IPPE-ABBN93	1.0001	0.0005	0.0015	

Table F68. HEU-ST-043 Case 02

ICSBEP Benchmark	HEU-ST-043		Case 2	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9995	0.0026		
EMS-S5-238	1.0073		0.0078	0.0336
EMS-S5-27	1.0067		0.0072	0.0229
EMS-S5-44	1.0070		0.0075	0.0320
EMS-M5-E50	1.0091	0.0005	0.0096	0.0343
EMS-M5-E62	1.0040	0.0005	0.0045	0.0345
EMS-M5-E66	1.0076	0.0005	0.0081	0.0338
EMS-M5-E68	1.0073	0.0005	0.0078	0.0338
EMS-M5-E7P	1.0047	0.0005	0.0052	0.0337
EMS-M5-F22	1.0064	0.0005	0.0069	0.0351
EMS-M5-F30	1.0062	0.0005	0.0067	0.0337
EMS-M5-J32	1.0093	0.0005	0.0098	0.0344
EMS-M5-J33	1.0076	0.0005	0.0081	0.0337
IPPE-ABBN93	1.0062	0.0007	0.0067	

Table F69. HEU-ST-043 Case 03

ICSBEP Benchmark	HEU-ST-043		Case 3	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9990	0.0025		
EMS-S5-238	1.0023		0.0033	0.0322
EMS-S5-27	1.0007		0.0017	0.0218
EMS-S5-44	1.0020		0.0030	0.0306
EMS-M5-E50	1.0026	0.0004	0.0036	0.0329
EMS-M5-E62	0.9996	0.0004	0.0006	0.0331
EMS-M5-E66	1.0022	0.0004	0.0032	0.0324
EMS-M5-E68	1.0013	0.0004	0.0023	0.0324
EMS-M5-E7P	1.0006	0.0004	0.0016	0.0324
EMS-M5-F22	1.0008	0.0004	0.0018	0.0336
EMS-M5-F30	1.0018	0.0004	0.0028	0.0323
EMS-M5-J32	1.0053	0.0004	0.0063	0.0330
EMS-M5-J33	1.0023	0.0004	0.0033	0.0324
IPPE-ABBN93	1.0010	0.0006	0.0020	

Thermal low-enriched uranium system validation results

The common separation of systems into groups based on uranium that is high-enriched or low-enriched in ^{235}U is based on experience. It is expected that within each group there may also be trends. Some of the charts combine low-enriched and high-enriched systems to support determination of enrichment-dependent trends.

Figure F32. Legend for ^{235}U enrichment

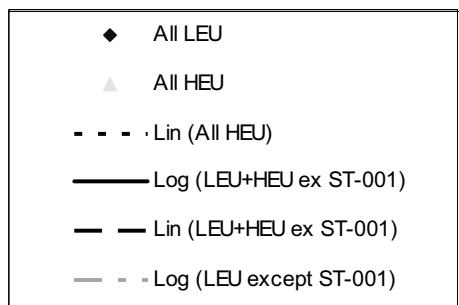


Figure F35. Enr ^{235}U . LEU + HEU, S5-27

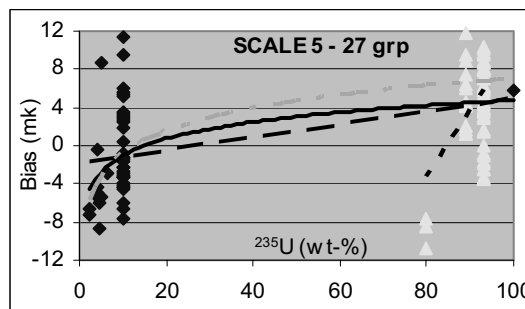


Figure F33. Enr ^{235}U . LEU + HEU, S5-238

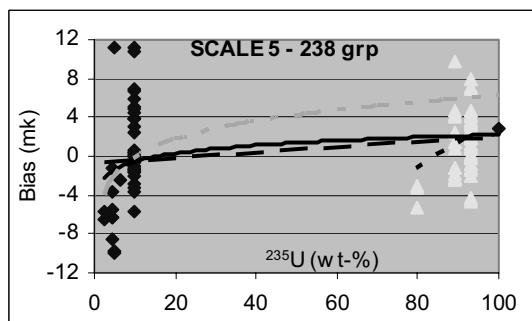


Figure F36. Enr ^{235}U . LEU, S5-27

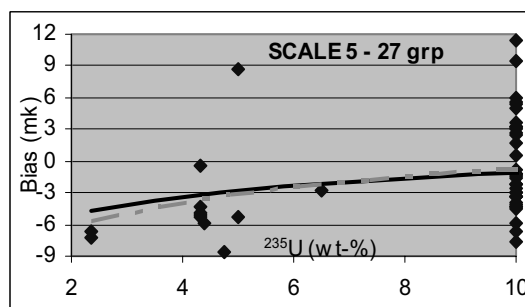


Figure F34. Enr ^{235}U . LEU, S5-238

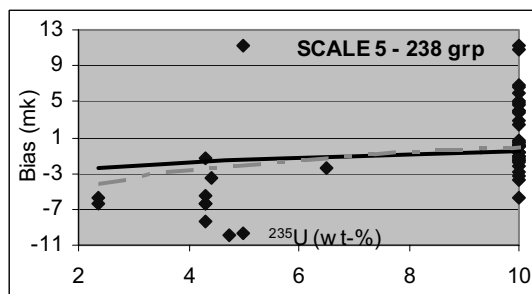


Figure F37. Enr ^{235}U . LEU + HEU, S5-44

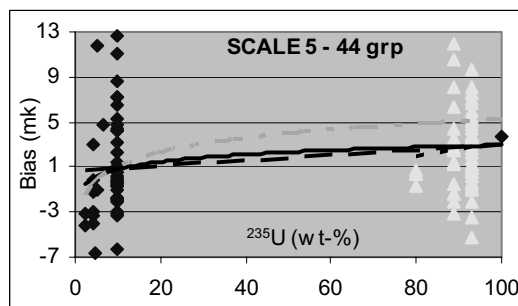


Figure F38. Enr ^{235}U . LEU, S5-44

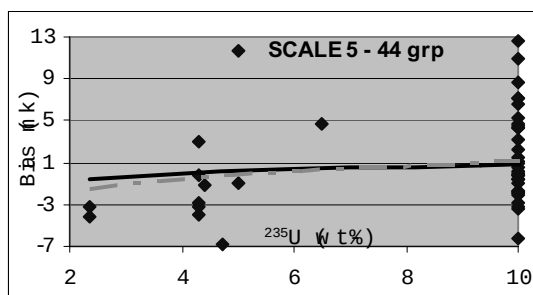


Figure F42. Enr ^{235}U . LEU, M5-E62

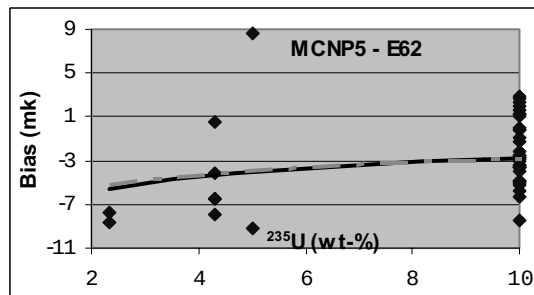


Figure F39. Enr ^{235}U . LEU + HEU, M5-E50

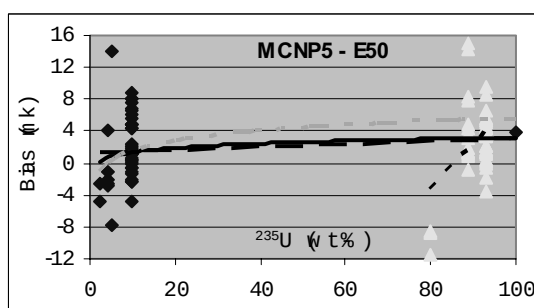
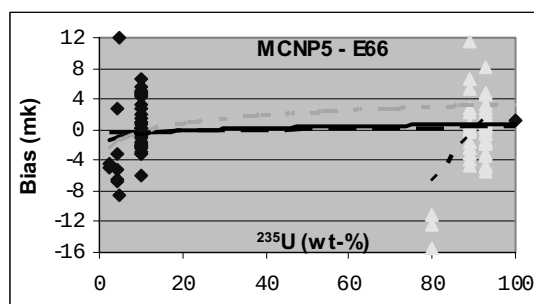


Figure F43. Enr ^{235}U . LEU+HEU, M5-E66



E50 U. LEU, M5- ^{235}U Enr Figure F40.

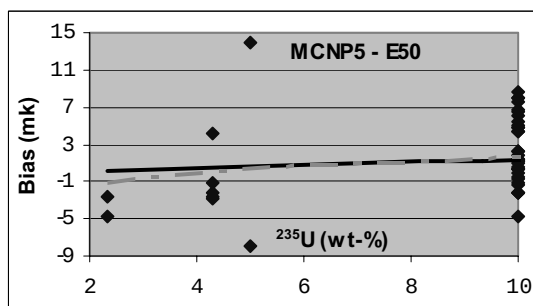


Figure F44. Enr ^{235}U . LEU, M5-E66

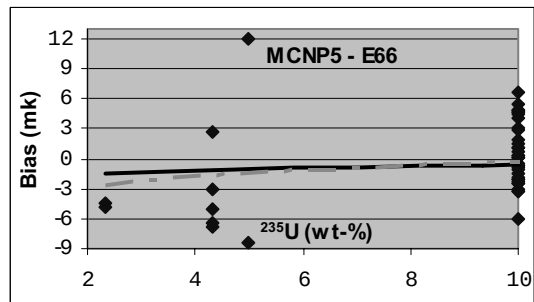


Figure F41. Enr ^{235}U . LEU+HEU, M5-E62

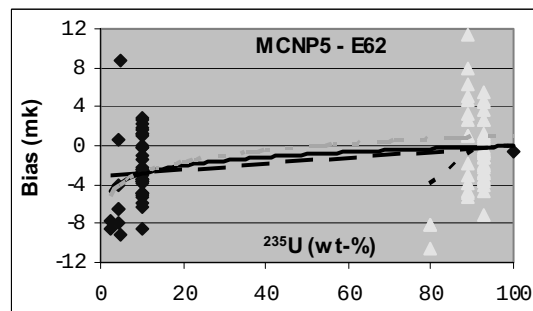


Figure F45. Enr ^{235}U . LEU+HEU, M5-E68

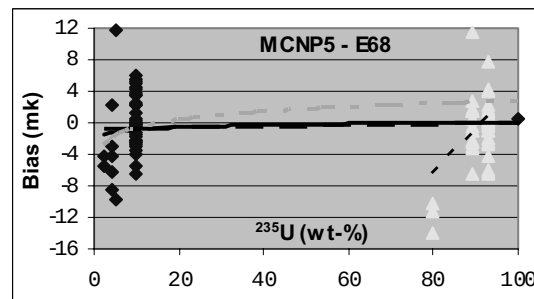


Figure F46. Enr ^{235}U . LEU, M5-E68

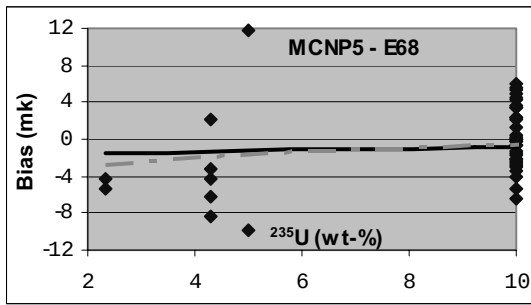


Figure F50. Enr ^{235}U . LEU, M5-F22

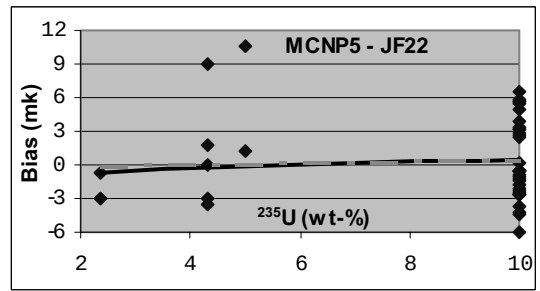


Figure F47. Enr ^{235}U . LEU+HEU, M5-E7P

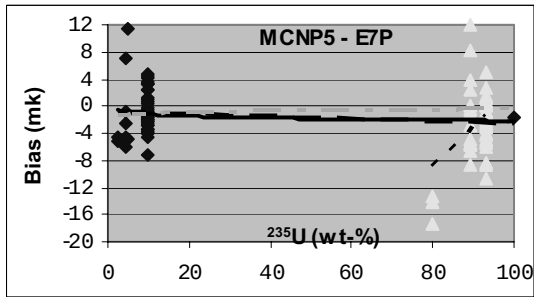


Figure F51. Enr ^{235}U . LEU+HEU, M5-F30

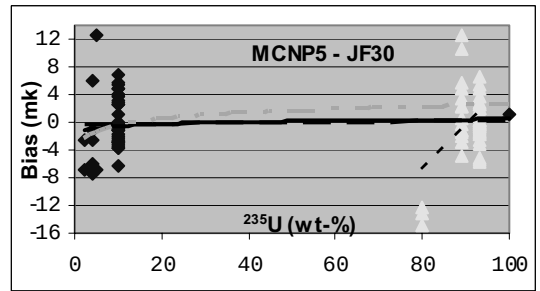


Figure F48. Enr ^{235}U . LEU, M5-E7P

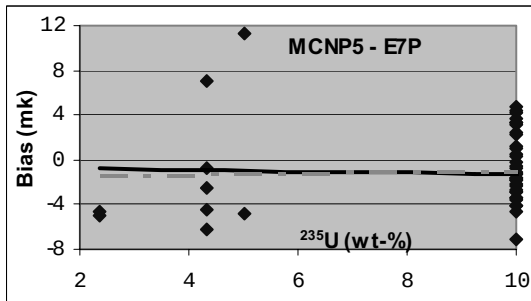


Figure F52. Enr ^{235}U . LEU, M5-F30

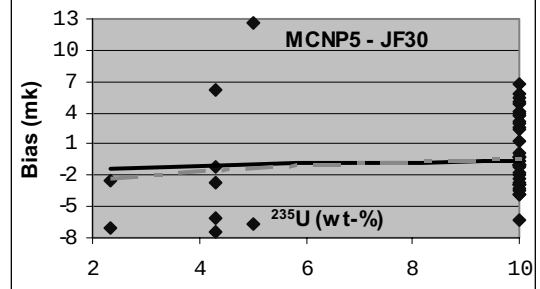


Figure F49. Enr ^{235}U . LEU+HEU, M5-F22

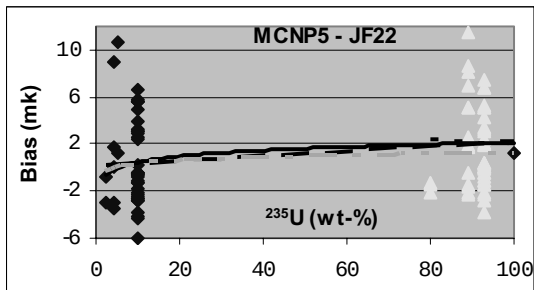


Figure F53. Enr ^{235}U . LEU+HEU, M5-J32

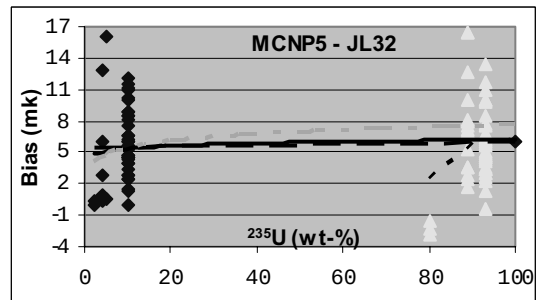


Figure F54. Enr ^{235}U . LEU, M5-J32

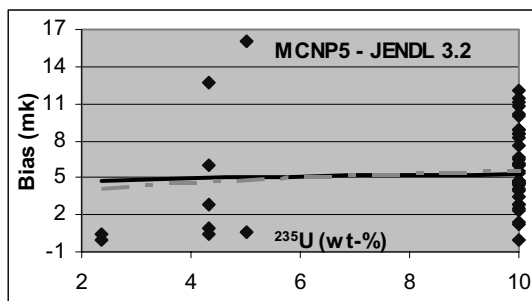


Figure F58. Enr ^{235}U . LEU, IPPE-04

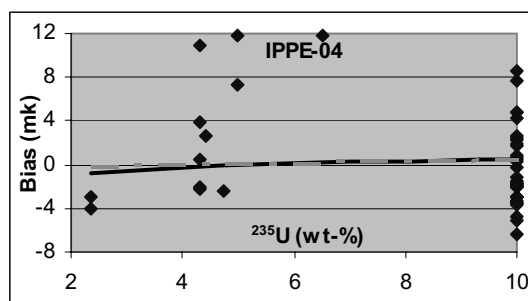


Figure F55. Enr ^{235}U . LEU+HEU, M5-J33

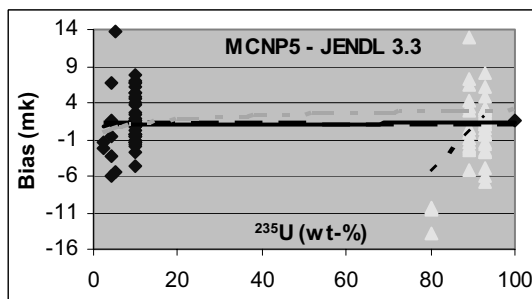


Figure F59. Legend for EALF trends

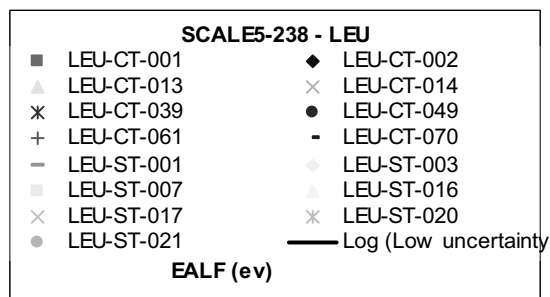


Figure F56. Enr ^{235}U . LEU, M5-J33

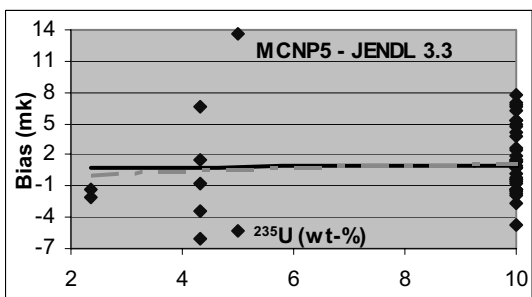


Figure F60. EALF. SCALE5+238 group

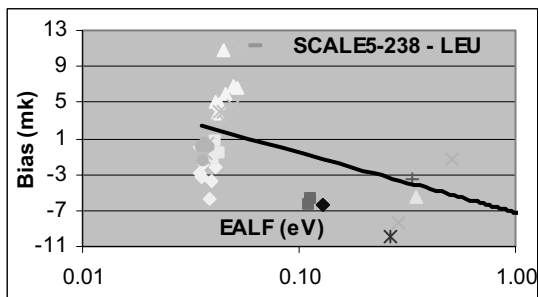


Figure F57. Enr ^{235}U . LEU+HEU, IPPE-04

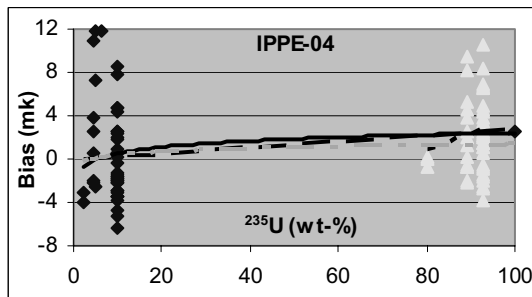


Figure F61. EALF. SCALE5+27 group

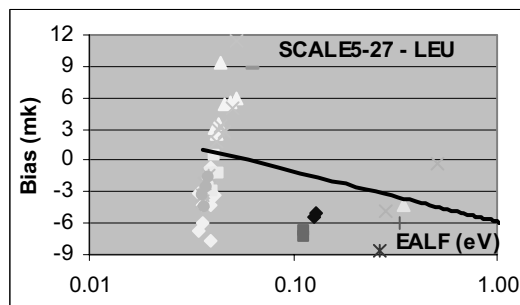


Figure F62. EALF. SCALE5+44 group

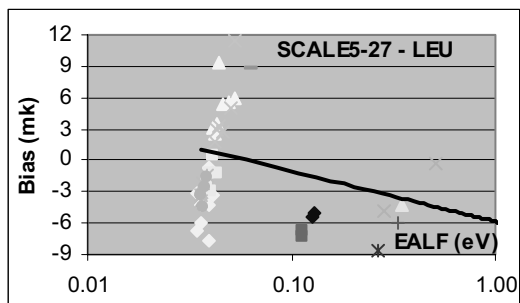


Figure F66. EALF. MCNP5+ENDF/B-68

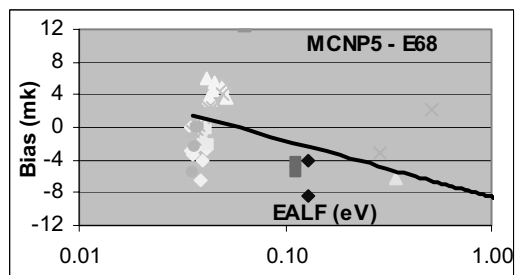


Figure F63. EALF. MCNP5+ENDF/B-50

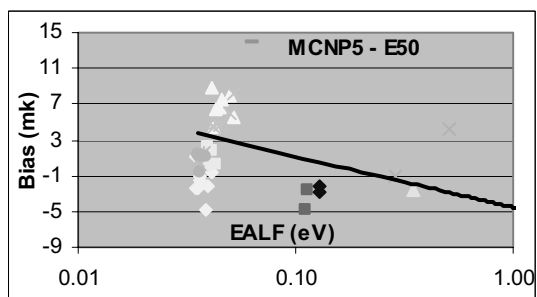


Figure F67. EALF. MCNP5+ENDF/B-7P

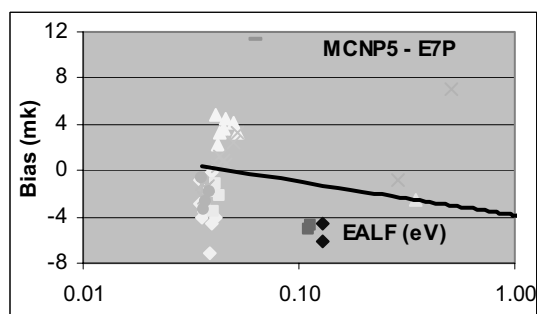


Figure F64. EALF. MCNP5+ENDF/B-62

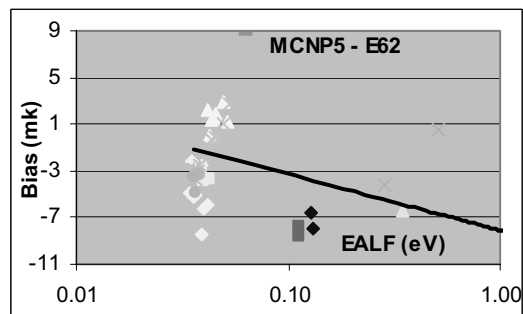


Figure F68. EALF. MCNP5+JEF 2.2

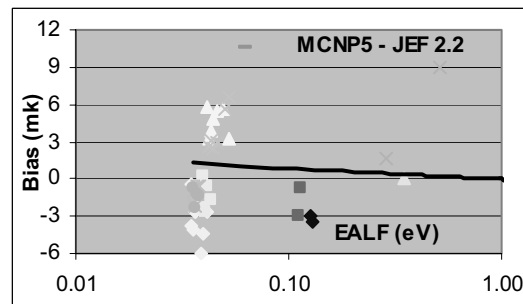


Figure F65. EALF. MCNP5+ENDF/B-66

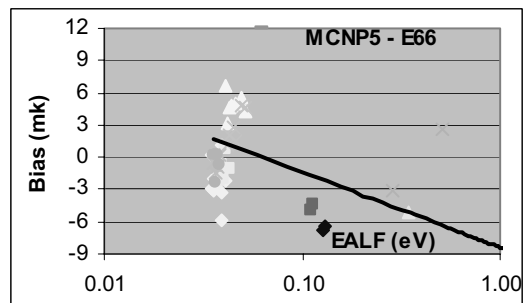


Figure F69. EALF. MCNP5+JEFF 3.0

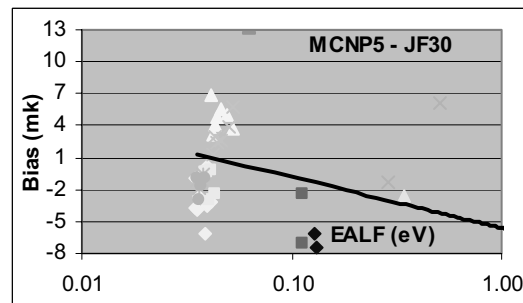


Figure F70. EALF. MCNP5+JENDL-3.2

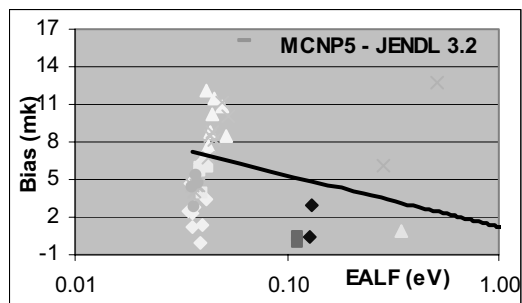


Figure F72. EALF. IPPE-04

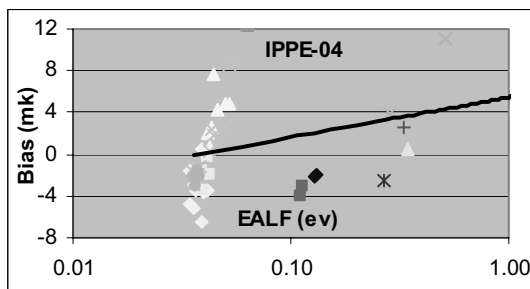


Figure F71. EALF. MCNP5+ JENDL-3.3

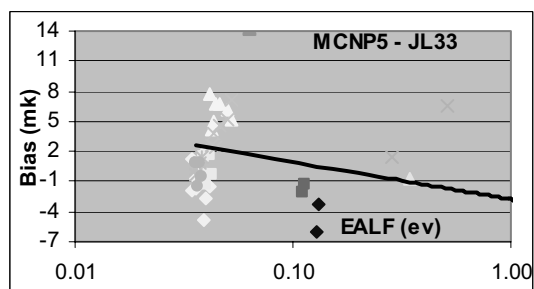


Figure F73. Legend: Chart with all results

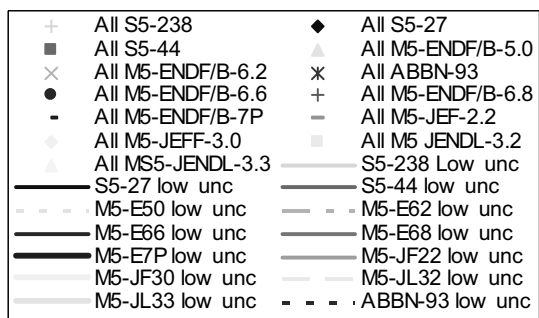


Figure F74. All results for LEU benchmarks (Note: EALF/3)

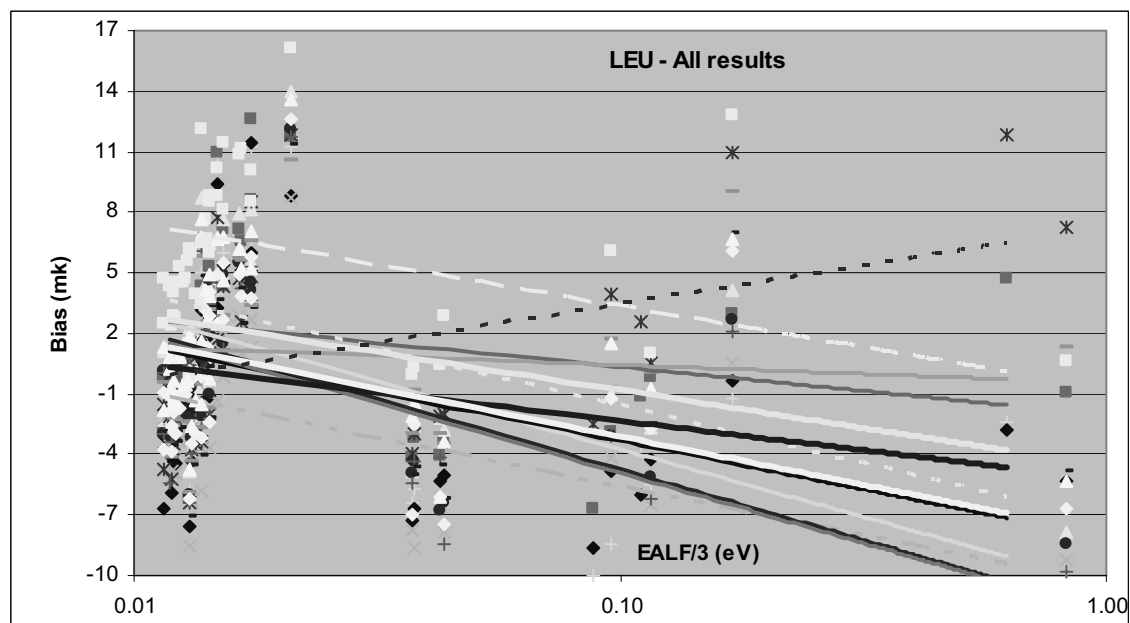


Table F70. LEU-CT-001 Case 01

ICSBEP benchmark	LEU-CT-001		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9998	0.0031		
EMS-S5-238	0.9941	0.0003	-0.0057	0.0985
EMS-S5-27	0.9931	0.0003	-0.0067	0.0747
EMS-S5-44	0.9966	0.0003	-0.0032	0.0961
EMS-M5-E50	0.9972	0.0010	-0.0026	0.1012
EMS-M5-E62	0.9912	0.0012	-0.0086	0.1023
EMS-M5-E66	0.9954	0.0011	-0.0044	0.0990
EMS-M5-E68	0.9955	0.0012	-0.0043	0.0992
EMS-M5-E7P	0.9951	0.0011	-0.0047	0.1010
EMS-M5-F22	0.9990	0.0010	-0.0008	0.1024
EMS-M5-F30	0.9973	0.0011	-0.0025	0.0988
EMS-M5-J32	1.0002	0.0010	0.0004	0.0988
EMS-M5-J33	0.9984	0.0011	-0.0014	0.1002
IPPE-ABBN93	0.9968	0.0003	-0.0030	

Table F71. LEU-CT-001 Case 02

ICSBEP benchmark	LEU-CT-001		Case 2	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9998	0.0031		
EMS-S5-238	0.9934	0.0003	-0.0064	0.0978
EMS-S5-27	0.9925	0.0003	-0.0073	0.0742
EMS-S5-44	0.9957	0.0003	-0.0041	0.0955
EMS-M5-E50	0.9950	0.0011	-0.0048	0.1009
EMS-M5-E62	0.9921	0.0011	-0.0077	0.1011
EMS-M5-E66	0.9949	0.0010	-0.0049	0.0985
EMS-M5-E68	0.9944	0.0011	-0.0054	0.0995
EMS-M5-E7P	0.9948	0.0011	-0.0050	0.0997
EMS-M5-F22	0.9969	0.0011	-0.0030	0.1020
EMS-M5-F30	0.9928	0.0011	-0.0070	0.0988
EMS-M5-J32	0.9997	0.0011	-0.0001	0.0991
EMS-M5-J33	0.9977	0.0011	-0.0021	0.0991
IPPE-ABBN93	0.9959	0.0003	-0.0040	

Table F72. LEU-CT-002 Case 01

ICSBEP benchmark	LEU-CT-002		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9997	0.002		
EMS-S5-238	0.9934	0.0004	-0.0063	0.1159
EMS-S5-27	0.9947	0.0004	-0.0050	0.0940
EMS-S5-44	0.9964	0.0004	-0.0033	0.1140
EMS-M5-E50	0.9970	0.0012	-0.0028	0.1182
EMS-M5-E62	0.9918	0.0012	-0.0079	0.1195
EMS-M5-E66	0.9933	0.0012	-0.0064	0.1170
EMS-M5-E68	0.9913	0.0012	-0.0084	0.1163
EMS-M5-E7P	0.9935	0.0013	-0.0062	0.1177
EMS-M5-F22	0.9963	0.0011	-0.0035	0.1190
EMS-M5-F30	0.9922	0.0014	-0.0075	0.1165
EMS-M5-J32	1.0026	0.0012	0.0029	0.1157
EMS-M5-J33	0.9964	0.0012	-0.0033	0.1167
IPPE-ABBN93	0.9977	0.0003	-0.0020	

Table F73. LEU-CT-002 Case 04

ICSBEP benchmark	LEU-CT-002		Case 4	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9997	0.002		
EMS-S5-238	0.9934	0.0004	-0.0063	0.1144
EMS-S5-27	0.9944	0.0004	-0.0053	0.0929
EMS-S5-44	0.9957	0.0004	-0.0040	0.1128
EMS-M5-E50	0.9975	0.0013	-0.0022	0.1180
EMS-M5-E62	0.9931	0.0011	-0.0066	0.1172
EMS-M5-E66	0.9930	0.0011	-0.0068	0.1158
EMS-M5-E68	0.9955	0.0012	-0.0042	0.1162
EMS-M5-E7P	0.9952	0.0012	-0.0045	0.1162
EMS-M5-F22	0.9967	0.0012	-0.0030	0.1184
EMS-M5-F30	0.9936	0.0012	-0.0061	0.1149
EMS-M5-J32	1.0001	0.0013	0.0004	0.1155
EMS-M5-J33	0.9936	0.0011	-0.0061	0.1158
IPPE-ABBN93	0.9976	0.0003	-0.0021	

Table F74. LEU-CT-013 Case 01

ICSBEP benchmark	LEU-CT-013		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0018		
EMS-S5-238	0.9945	0.0004	-0.0055	0.2995
EMS-S5-27	0.9957	0.0004	-0.0043	0.2487
EMS-S5-44	0.9998	0.0004	-0.0002	0.2946
EMS-M5-E50	0.9973	0.0006	-0.0027	0.3040
EMS-M5-E62	0.9936	0.0006	-0.0064	0.3039
EMS-M5-E66	0.9949	0.0006	-0.0051	0.2951
EMS-M5-E68	0.9938	0.0006	-0.0062	0.2964
EMS-M5-E7P	0.9975	0.0006	-0.0025	0.2979
EMS-M5-F22	1.0001	0.0006	0.0001	0.3029
EMS-M5-F30	0.9973	0.0006	-0.0027	0.2925
EMS-M5-J32	1.0010	0.0006	0.0010	0.1155
EMS-M5-J33	0.9993	0.0006	-0.0007	0.2948
IPPE-ABBN93	1.0005	0.0004	0.0005	

Table F75. LEU-CT-014 Case 01

ICSBEP benchmark	LEU-CT-014		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0019		
EMS-S5-238	0.9915	0.0004	-0.0085	0.2897
EMS-S5-27	0.9951	0.0004	-0.0049	0.2378
EMS-S5-44	0.9971	0.0004	-0.0029	0.2854
EMS-M5-E50	0.9989	0.0006	-0.0011	0.2921
EMS-M5-E62	0.9959	0.0006	-0.0041	0.2920
EMS-M5-E66	0.9969	0.0005	-0.0031	0.2846
EMS-M5-E68	0.9969	0.0006	-0.0031	0.2853
EMS-M5-E7P	0.9992	0.0006	-0.0008	0.2979
EMS-M5-F22	1.0017	0.0006	0.0017	0.2915
EMS-M5-F30	0.9988	0.0006	-0.0012	0.2815
EMS-M5-J32	1.0061	0.0005	0.0061	0.2810
EMS-M5-J33	1.0015	0.0006	0.0015	0.2810
IPPE-ABBN93	1.0039	0.0003	0.0039	

Table F76. LEU-CT-014 Case 06

ICSBEP benchmark	LEU-CT-014		Case 6	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0033		
EMS-S5-238	0.9988	0.0004	-0.0012	0.5247
EMS-S5-27	0.9997	0.0004	-0.0003	0.4379
EMS-S5-44	1.0029	0.0004	0.0029	0.5185
EMS-M5-E50	1.0042	0.0006	0.0042	0.5343
EMS-M5-E62	1.0006	0.0006	0.0006	0.5295
EMS-M5-E66	1.0027	0.0006	0.0027	0.5128
EMS-M5-E68	1.0021	0.0005	0.0021	0.5148
EMS-M5-E7P	1.0070	0.0006	0.0070	0.5125
EMS-M5-F22	1.0090	0.0006	0.0090	0.5242
EMS-M5-F30	1.0061	0.0006	0.0061	0.5056
EMS-M5-J32	1.0128	0.0006	0.0128	0.5025
EMS-M5-J33	1.0066	0.0006	0.0066	0.5073
IPPE-ABBN93	1.0110	0.0003	0.0110	

Table F77. LEU-CT-039 Case 01

ICSBEP benchmark	LEU-CT-039		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0014		
EMS-S5-238	0.9900	0.0004	-0.0100	0.2324
EMS-S5-27	0.9913	0.0004	-0.0087	0.1871
EMS-S5-44	0.9933	0.0004	-0.0067	0.2280
IPPE-ABBN93	0.9975	0.0004	-0.0025	

Table F78. LEU-CT-049 Case 01-Smpl

ICSBEP benchmark	LEU-CT-049		Case 1-Simple	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0034		
EMS-S5-238	0.9902	0.0004	-0.0098	2.1933
EMS-S5-27	0.9947	0.0004	-0.0053	1.7860
EMS-S5-44	0.9990	0.0004	-0.0010	2.1302
EMS-M5-E50	0.9922	0.0005	-0.0079	2.2153
EMS-M5-E62	0.9908	0.0005	-0.0092	2.1971
EMS-M5-E66	0.9915	0.0005	-0.0085	2.0886
EMS-M5-E68	0.9902	0.0006	-0.0098	2.0959
EMS-M5-E7P	0.9952	0.0005	-0.0048	2.0918
EMS-M5-F22	1.0013	0.0005	0.0013	2.1354
EMS-M5-F30	0.9933	0.0006	-0.0067	2.0425
EMS-M5-J32	1.0006	0.0006	0.0006	2.0115
EMS-M5-J33	0.9947	0.0006	-0.0053	2.0656
IPPE-ABBN93	1.0073	0.0003	0.0073	

Table F79. LEU-CT-061 Case 01

ICSBEP benchmark	LEU-CT-061		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0005	0.0023		
EMS-S5-238	0.9969	0.0006	-0.0036	0.2874
EMS-S5-27	0.9945	0.0005	-0.0060	0.2314
EMS-S5-44	0.9993	0.0006	-0.0012	0.2825
IPPE-ABBN93	1.0031	0.0004	0.0026	

Table F80. LEU-CT-070 Case 01

ICSBEP benchmark	LEU-CT-070		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0004	0.001		
EMS-S5-238	0.9980	0.0003	-0.0024	1.6229
EMS-S5-27	0.9976	0.0003	-0.0028	1.4031
EMS-S5-44	1.0051	0.0003	0.0047	1.5913
IPPE-ABBN93	1.0123	0.0003	0.0119	

Table F81. LEU-ST-00Q1 Case 01

ICSBEP benchmark	LEU-ST-001		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9991	0.0029		
EMS-S5-238	1.0103	0.0004	0.0112	0.0598
EMS-S5-27	1.0079	0.0004	0.0088	0.0425
EMS-S5-44	1.0109	0.0004	0.0118	0.0573
EMS-M5-E50	1.0131	0.0004	0.0140	0.0609
EMS-M5-E62	1.0078	0.0004	0.0087	0.0613
EMS-M5-E66	1.0112	0.0004	0.0121	0.0596
EMS-M5-E68	1.0108	0.0004	0.0117	0.0596
EMS-M5-E7P	1.0105	0.0004	0.0114	0.0599
EMS-M5-F22	1.0097	0.0004	0.0106	0.0624
EMS-M5-F30	1.0117	0.0004	0.0126	0.0596
EMS-M5-J32	1.0152	0.0004	0.0161	0.0606
EMS-M5-J33	1.0127	0.0004	0.0136	0.0598
IPPE-ABBN93	1.0109	0.0004	0.0118	

Table F82. LEU-ST-003 Case 01

ICSBEP benchmark	LEU-ST-003		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9997	0.0039		
EMS-S5-238	0.9976	0.0004	-0.0021	0.0410
EMS-S5-27	0.9964	0.0004	-0.0034	0.0284
EMS-S5-44	0.9977	0.0004	-0.0020	0.0391
EMS-M5-E50	0.9991	0.0003	-0.0006	0.0417
EMS-M5-E62	0.9939	0.0003	-0.0059	0.0419
EMS-M5-E66	0.9976	0.0003	-0.0021	0.0409
EMS-M5-E68	0.9970	0.0003	-0.0027	0.0409
EMS-M5-E7P	0.9956	0.0003	-0.0041	0.0410
EMS-M5-F22	0.9970	0.0003	-0.0027	0.0425
EMS-M5-F30	0.9965	0.0003	-0.0032	0.0409
EMS-M5-J32	1.0031	0.0003	0.0034	0.0416
EMS-M5-J33	0.9982	0.0003	-0.0015	0.0410
IPPE-ABBN93	0.9963	0.0003	-0.0034	

Table F83. LEU-ST-003 Case 02

ICSBEP benchmark	LEU-ST-003		Case 2	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9993	0.0042		
EMS-S5-238	0.9956	0.0003	-0.0037	0.0391
EMS-S5-27	0.9949	0.0003	-0.0044	0.0270
EMS-S5-44	0.9961	0.0004	-0.0032	0.0373
EMS-M5-E50	0.9972	0.0003	-0.0021	0.0398
EMS-M5-E62	0.9930	0.0003	-0.0063	0.0400
EMS-M5-E66	0.9961	0.0003	-0.0032	0.0391
EMS-M5-E68	0.9953	0.0003	-0.0040	0.0391
EMS-M5-E7P	0.9947	0.0003	-0.0046	0.0392
EMS-M5-F22	0.9950	0.0003	-0.0043	0.0406
EMS-M5-F30	0.9958	0.0003	-0.0035	0.0391
EMS-M5-J32	1.0007	0.0003	0.0014	0.0398
EMS-M5-J33	0.9967	0.0003	-0.0026	0.0391
IPPE-ABBN93	0.9956	0.0003	-0.0037	

Table F84. LEU-ST-003 Case 03

ICSBEP benchmark	LEU-ST-003		Case 3	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9995	0.0042		
EMS-S5-238	0.9995	0.0004	0.0000	0.0388
EMS-S5-27	0.9988	0.0004	-0.0007	0.0267
EMS-S5-44	1.0004	0.0004	0.0009	0.0370
EMS-M5-E50	1.0018	0.0003	0.0022	0.0394
EMS-M5-E62	0.9970	0.0003	-0.0025	0.0397
EMS-M5-E66	1.0006	0.0003	0.0011	0.0388
EMS-M5-E68	0.9999	0.0003	0.0004	0.0388
EMS-M5-E7P	0.9994	0.0003	-0.0001	0.0389
EMS-M5-F22	0.9990	0.0003	-0.0005	0.0403
EMS-M5-F30	0.9996	0.0003	0.0001	0.0388
EMS-M5-J32	1.0057	0.0003	0.0062	0.0394
EMS-M5-J33	1.0014	0.0003	0.0018	0.0389
IPPE-ABBN93	1.0001	0.0003	0.0006	

Table F85. LEU-ST-003 Case 04

ICSBEP benchmark	LEU-ST-003		Case 4	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9995	0.0042		
EMS-S5-238	0.9937	0.0003	-0.0058	0.0387
EMS-S5-27	0.9919	0.0004	-0.0076	0.0266
EMS-S5-44	0.9933	0.0004	-0.0062	0.0368
EMS-M5-E50	0.9947	0.0003	-0.0048	0.0393
EMS-M5-E62	0.9910	0.0003	-0.0085	0.0396
EMS-M5-E66	0.9935	0.0003	-0.0060	0.0386
EMS-M5-E68	0.9931	0.0003	-0.0064	0.0387
EMS-M5-E7P	0.9924	0.0003	-0.0071	0.0387
EMS-M5-F22	0.9936	0.0003	-0.0059	0.0401
EMS-M5-F30	0.9933	0.0003	-0.0062	0.0387
EMS-M5-J32	0.9994	0.0003	-0.0001	0.0392
EMS-M5-J33	0.9947	0.0003	-0.0048	0.0387
IPPE-ABBN93	0.9931	0.0003	-0.0064	

Table F86. LEU-ST-003 Case 05

ICSBEP benchmark	LEU-ST-003		Case 5	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9997	0.0048		
EMS-S5-238	0.9980	0.0003	-0.0017	0.0359
EMS-S5-27	0.9953	0.0003	-0.0044	0.0245
EMS-S5-44	0.9975	0.0003	-0.0022	0.0342
EMS-M5-E50	0.9983	0.0002	-0.0014	0.0366
EMS-M5-E62	0.9947	0.0002	-0.0050	0.0367
EMS-M5-E66	0.9972	0.0002	-0.0025	0.0359
EMS-M5-E68	0.9971	0.0002	-0.0026	0.0359
EMS-M5-E7P	0.9968	0.0002	-0.0029	0.0359
EMS-M5-F22	0.9971	0.0002	-0.0026	0.0373
EMS-M5-F30	0.9968	0.0002	-0.0029	0.0359
EMS-M5-J32	1.0025	0.0002	0.0028	0.0366
EMS-M5-J33	0.9985	0.0002	-0.0013	0.0360
IPPE-ABBN93	0.9963	0.0003	-0.0034	

Table F87. LEU-ST-003 Case 06

ICSBEP benchmark	LEU-ST-003		Case 6	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9999	0.0049		
EMS-S5-238	0.9985	0.0003	-0.0015	0.0356
EMS-S5-27	0.9957	0.0003	-0.0042	0.0243
EMS-S5-44	0.9983	0.0003	-0.0017	0.0339
EMS-M5-E50	0.9988	0.0002	-0.0011	0.0362
EMS-M5-E62	0.9951	0.0002	-0.0049	0.0364
EMS-M5-E66	0.9979	0.0002	-0.0020	0.0356
EMS-M5-E68	0.9977	0.0002	-0.0022	0.0357
EMS-M5-E7P	0.9963	0.0002	-0.0036	0.0357
EMS-M5-F22	0.9972	0.0002	-0.0027	0.0370
EMS-M5-F30	0.9973	0.0002	-0.0026	0.0357
EMS-M5-J32	1.0023	0.0002	0.0024	0.0363
EMS-M5-J33	0.9992	0.0002	-0.0007	0.0357
IPPE-ABBN93	0.9970	0.0002	-0.0029	

Table F88. LEU-ST-003 Case 07

ICSBEP benchmark	LEU-ST-003		Case 7	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9994	0.0049		
EMS-S5-238	0.9961	0.0003	-0.0033	0.0355
EMS-S5-27	0.9935	0.0003	-0.0059	0.0242
EMS-S5-44	0.9960	0.0003	-0.0034	0.0337
EMS-M5-E50	0.9971	0.0002	-0.0023	0.0361
EMS-M5-E62	0.9942	0.0002	-0.0052	0.0363
EMS-M5-E66	0.9962	0.0002	-0.0032	0.0354
EMS-M5-E68	0.9960	0.0002	-0.0034	0.0354
EMS-M5-E7P	0.9954	0.0002	-0.0040	0.0355
EMS-M5-F22	0.9952	0.0002	-0.0042	0.0368
EMS-M5-F30	0.9956	0.0002	-0.0038	0.0355
EMS-M5-J32	1.0006	0.0002	0.0012	0.0360
EMS-M5-J33	0.9978	0.0002	-0.0016	0.0355
IPPE-ABBN93	0.9942	0.0002	-0.0052	

Table F89. LEU-ST-003 Case 08

ICSBEP benchmark	LEU-ST-003		Case 8	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9993	0.0052		
EMS-S5-238	0.9992	0.0003	-0.0001	0.0344
EMS-S5-27	0.9962	0.0003	-0.0031	0.0234
EMS-S5-44	0.9991	0.0003	-0.0002	0.0327
EMS-M5-E50	1.0004	0.0002	0.0011	0.0350
EMS-M5-E62	0.9971	0.0002	-0.0022	0.0352
EMS-M5-E66	0.9994	0.0002	0.0001	0.0344
EMS-M5-E68	0.9993	0.0002	0.0000	0.0344
EMS-M5-E7P	0.9985	0.0002	-0.0008	0.0344
EMS-M5-F22	0.9988	0.0002	-0.0005	0.0357
EMS-M5-F30	0.9984	0.0002	-0.0009	0.0344
EMS-M5-J32	1.0040	0.0002	0.0047	0.0350
EMS-M5-J33	1.0006	0.0002	0.0013	0.0345
IPPE-ABBN93	0.9978	0.0002	-0.0015	

Table F90. LEU-ST-003 Case 09

ICSBEP benchmark	LEU-ST-003		Case 9	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9996	0.0052		
EMS-S5-238	0.9968	0.0003	-0.0028	0.0343
EMS-S5-27	0.9930	0.0003	-0.0066	0.0233
EMS-S5-44	0.9967	0.0003	-0.0029	0.0326
EMS-M5-E50	0.9973	0.0002	-0.0023	0.0349
EMS-M5-E62	0.9948	0.0002	-0.0049	0.0351
EMS-M5-E66	0.9966	0.0002	-0.0030	0.0343
EMS-M5-E68	0.9967	0.0002	-0.0029	0.0343
EMS-M5-E7P	0.9967	0.0002	-0.0029	0.0344
EMS-M5-F22	0.9959	0.0002	-0.0038	0.0356
EMS-M5-F30	0.9958	0.0002	-0.0038	0.0343
EMS-M5-J32	1.0020	0.0002	0.0024	0.0349
EMS-M5-J33	0.9977	0.0002	-0.0019	0.0343
IPPE-ABBN93	0.9949	0.0002	-0.0047	

Table F91. LEU-ST-007 Case 01

ICSBEP benchmark	LEU-ST-007		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9961	0.0009		
EMS-S5-238	0.9955	0.0004	-0.0006	0.0423
EMS-S5-27	0.9949	0.0003	-0.0012	0.0293
EMS-S5-44	0.9966	0.0003	0.0005	0.0404
EMS-M5-E50	0.9964	0.0005	0.0003	0.0434
EMS-M5-E62	0.9924	0.0005	-0.0037	0.0435
EMS-M5-E66	0.9950	0.0004	-0.0011	0.0424
EMS-M5-E68	0.9939	0.0004	-0.0022	0.0425
EMS-M5-E7P	0.9939	0.0004	-0.0022	0.0426
EMS-M5-F22	0.9943	0.0004	-0.0018	0.0441
EMS-M5-F30	0.9937	0.0004	-0.0024	0.0425
EMS-M5-J32	1.0021	0.0004	0.0060	0.0431
EMS-M5-J33	0.9958	0.0004	-0.0003	0.0425
IPPE-ABBN93	0.9941	0.0003	-0.0020	

Table F92. LEU-ST-007 Case 02

ICSBEP benchmark	LEU-ST-007		Case 2	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9973	0.0009		
EMS-S5-238	0.9979	0.0004	0.0006	0.0410
EMS-S5-27	0.9978	0.0004	0.0005	0.0283
EMS-S5-44	0.9988	0.0004	0.0015	0.0391
EMS-M5-E50	0.9992	0.0005	0.0019	0.0419
EMS-M5-E62	0.9937	0.0005	-0.0036	0.0420
EMS-M5-E66	0.9981	0.0005	0.0008	0.0412
EMS-M5-E68	0.9970	0.0005	-0.0003	0.0411
EMS-M5-E7P	0.9961	0.0005	-0.0012	0.0412
EMS-M5-F22	0.9968	0.0005	-0.0005	0.0428
EMS-M5-F30	0.9972	0.0005	-0.0001	0.0411
EMS-M5-J32	1.0038	0.0003	0.0065	0.0417
EMS-M5-J33	0.9989	0.0005	0.0016	0.0410
IPPE-ABBN93	0.9970	0.0003	-0.0003	

Table F93. LEU-ST-007 Case 03

ICSBEP benchmark	LEU-ST-007		Case 3	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9985	0.001		
EMS-S5-238	0.9971	0.0003	-0.0014	0.0397
EMS-S5-27	0.9956	0.0003	-0.0029	0.0273
EMS-S5-44	0.9968	0.0004	-0.0017	0.0378
EMS-M5-E50	0.9988	0.0004	0.0003	0.0406
EMS-M5-E62	0.9946	0.0005	-0.0039	0.0407
EMS-M5-E66	0.9965	0.0005	-0.0020	0.0398
EMS-M5-E68	0.9967	0.0005	-0.0018	0.0399
EMS-M5-E7P	0.9950	0.0005	-0.0035	0.0399
EMS-M5-F22	0.9958	0.0005	-0.0027	0.0414
EMS-M5-F30	0.9955	0.0005	-0.0030	0.0398
EMS-M5-J32	1.0024	0.0005	0.0039	0.0405
EMS-M5-J33	0.9972	0.0005	-0.0013	0.0398
IPPE-ABBN93	0.9950	0.0003	-0.0035	

Table F94. LEU-ST-007 Case 04

ICSBEP benchmark	LEU-ST-007		Case 4	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9988	0.0011		
EMS-S5-238	0.9990	0.0003	0.0002	0.0389
EMS-S5-27	0.9976	0.0004	-0.0012	0.0267
EMS-S5-44	0.9998	0.0004	0.0010	0.0370
EMS-M5-E50	1.0010	0.0005	0.0022	0.0397
EMS-M5-E62	0.9962	0.0005	-0.0027	0.0400
EMS-M5-E66	0.9982	0.0005	-0.0006	0.0391
EMS-M5-E68	0.9983	0.0005	-0.0005	0.0390
EMS-M5-E7P	0.9969	0.0005	-0.0019	0.0391
EMS-M5-F22	0.9990	0.0005	0.0002	0.0406
EMS-M5-F30	0.9985	0.0005	-0.0003	0.0389
EMS-M5-J32	1.0048	0.0005	0.0060	0.0397
EMS-M5-J33	1.0003	0.0005	0.0015	0.0391
IPPE-ABBN93	0.9972	0.0003	-0.0016	

Table F95. LEU-ST-007 Case 05

ICSBEP benchmark	LEU-ST-007		Case 5	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9983	0.0011		
EMS-S5-238	0.9977	0.0003	-0.0006	0.0383
EMS-S5-27	0.9961	0.0003	-0.0022	0.0262
EMS-S5-44	0.9977	0.0003	-0.0006	0.0364
EMS-M5-E50	0.9982	0.0005	-0.0001	0.0391
EMS-M5-E62	0.9954	0.0005	-0.0029	0.0392
EMS-M5-E66	0.9961	0.0005	-0.0022	0.0384
EMS-M5-E68	0.9971	0.0004	-0.0012	0.0384
EMS-M5-E7P	0.9967	0.0005	-0.0016	0.0385
EMS-M5-F22	0.9959	0.0005	-0.0024	0.0400
EMS-M5-F30	0.9980	0.0004	-0.0003	0.0384
EMS-M5-J32	1.0039	0.0005	0.0056	0.0391
EMS-M5-J33	0.9980	0.0004	-0.0003	0.0384
IPPE-ABBN93	0.9965	0.0003	-0.0018	

Table F96. LEU-ST-016 Case 01

ICSBEP benchmark	LEU-ST-016		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9996	0.0013		
EMS-S5-238	1.0063	0.0004	0.0067	0.0515
EMS-S5-27	1.0056	0.0004	0.0059	0.0365
EMS-S5-44	1.0082	0.0004	0.0086	0.0493
EMS-M5-E50	1.0051	0.0003	0.0055	0.0418
EMS-M5-E62	1.0009	0.0003	0.0013	0.0420
EMS-M5-E66	1.0038	0.0003	0.0042	0.0410
EMS-M5-E68	1.0033	0.0003	0.0037	0.0410
EMS-M5-E7P	1.0028	0.0003	0.0032	0.0410
EMS-M5-F22	1.0029	0.0003	0.0033	0.0426
EMS-M5-F30	1.0033	0.0003	0.0037	0.0410
EMS-M5-J32	1.0081	0.0003	0.0085	0.0417
EMS-M5-J33	1.0048	0.0003	0.0052	0.0410
IPPE-ABBN93	1.0044	0.0003	0.0048	

Table F97. LEU-ST-016 Case 02

ICSBEP benchmark	LEU-ST-016		Case 2	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9999	0.0013		
EMS-S5-238	1.0068	0.0004	0.0069	0.0490
EMS-S5-27	1.0055	0.0004	0.0056	0.0345
EMS-S5-44	1.0071	0.0004	0.0072	0.0469
EMS-M5-E50	1.0079	0.0004	0.0080	0.0498
EMS-M5-E62	1.0028	0.0004	0.0029	0.0502
EMS-M5-E66	1.0054	0.0004	0.0055	0.0488
EMS-M5-E68	1.0049	0.0004	0.0050	0.0488
EMS-M5-E7P	1.0041	0.0004	0.0042	0.0489
EMS-M5-F22	1.0056	0.0004	0.0057	0.0509
EMS-M5-F30	1.0049	0.0004	0.0050	0.0488
EMS-M5-J32	1.0108	0.0004	0.0109	0.0496
EMS-M5-J33	1.0061	0.0004	0.0062	0.0489
IPPE-ABBN93	1.0047	0.0003	0.0048	

Table F98. LEU-ST-016 Case 03

ICSBEP benchmark	LEU-ST-016		Case 3	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9994	0.0014		
EMS-S5-238	1.0054	0.0004	0.0060	0.0452
EMS-S5-27	1.0048	0.0004	0.0054	0.0316
EMS-S5-44	1.0066	0.0004	0.0072	0.0432
EMS-M5-E50	1.0070	0.0004	0.0076	0.0460
EMS-M5-E62	1.0013	0.0004	0.0019	0.0462
EMS-M5-E66	1.0044	0.0004	0.0050	0.0450
EMS-M5-E68	1.0049	0.0004	0.0055	0.0450
EMS-M5-E7P	1.0038	0.0004	0.0044	0.0452
EMS-M5-F22	1.0049	0.0004	0.0055	0.0470
EMS-M5-F30	1.0049	0.0004	0.0055	0.0450
EMS-M5-J32	1.0109	0.0004	0.0115	0.0458
EMS-M5-J33	1.0062	0.0004	0.0068	0.0452
IPPE-ABBN93	1.0037	0.0003	0.0043	

Table F99. LEU-ST-016 Case 04

ICSBEP benchmark	LEU-ST-016		Case 4	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9996	0.0014		
EMS-S5-238	1.0103	0.0004	0.0107	0.0439
EMS-S5-27	1.0090	0.0003	0.0094	0.0306
EMS-S5-44	1.0106	0.0004	0.0110	0.0419
EMS-M5-E50	1.0063	0.0004	0.0067	0.0446
EMS-M5-E62	1.0012	0.0004	0.0016	0.0449
EMS-M5-E66	1.0043	0.0004	0.0047	0.0438
EMS-M5-E68	1.0041	0.0004	0.0045	0.0437
EMS-M5-E7P	1.0033	0.0004	0.0037	0.0439
EMS-M5-F22	1.0045	0.0004	0.0049	0.0456
EMS-M5-F30	1.0045	0.0003	0.0049	0.0438
EMS-M5-J32	1.0098	0.0004	0.0102	0.0445
EMS-M5-J33	1.0063	0.0004	0.0067	0.0438
IPPE-ABBN93	1.0073	0.0003	0.0077	

Table F100. LEU-ST-016 Case 05

ICSBEP benchmark	LEU-ST-016		Case 5	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9995	0.0014		
EMS-S5-238	1.0044	0.0004	0.0049	0.0426
EMS-S5-27	1.0031	0.0004	0.0036	0.0296
EMS-S5-44	1.0049	0.0004	0.0053	0.0407
EMS-M5-E50	1.0060	0.0003	0.0065	0.0434
EMS-M5-E62	1.0008	0.0004	0.0013	0.0436
EMS-M5-E66	1.0041	0.0003	0.0046	0.0425
EMS-M5-E68	1.0030	0.0003	0.0035	0.0425
EMS-M5-E7P	1.0028	0.0003	0.0033	0.0426
EMS-M5-F22	1.0034	0.0003	0.0039	0.0442
EMS-M5-F30	1.0036	0.0004	0.0040	0.0425
EMS-M5-J32	1.0083	0.0004	0.0088	0.0432
EMS-M5-J33	1.0044	0.0003	0.0049	0.0426
IPPE-ABBN93	1.0020	0.0003	0.0025	

Table F101. LEU-ST-016 Case 06

ICSBEP benchmark	LEU-ST-016		Case 6	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9992	0.0015		
EMS-S5-238	1.0031	0.0003	0.0039	0.0417
EMS-S5-27	1.0017	0.0003	0.0025	0.0290
EMS-S5-44	1.0025	0.0003	0.0033	0.0398
EMS-M5-E50	1.0037	0.0003	0.0045	0.0425
EMS-M5-E62	0.9992	0.0003	0.0000	0.0427
EMS-M5-E66	1.0024	0.0003	0.0032	0.0416
EMS-M5-E68	1.0027	0.0003	0.0035	0.0416
EMS-M5-E7P	1.0015	0.0003	0.0023	0.0417
EMS-M5-F22	1.0024	0.0003	0.0032	0.0433
EMS-M5-F30	1.0024	0.0003	0.0032	0.0417
EMS-M5-J32	1.0068	0.0003	0.0076	0.0424
EMS-M5-J33	1.0033	0.0003	0.0041	0.0417
IPPE-ABBN93	0.9998	0.0003	0.0006	

Table F102. LEU-ST-016 Case 07

ICSBEP benchmark	LEU-ST-016		Case 7	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9994	0.0015		
EMS-S5-238	1.0044	0.0003	0.0050	0.0411
EMS-S5-27	1.0026	0.0004	0.0032	0.0285
EMS-S5-44	1.0037	0.0004	0.0043	0.0392
EMS-M5-E50	1.0081	0.0004	0.0087	0.0524
EMS-M5-E62	1.0017	0.0004	0.0023	0.0527
EMS-M5-E66	1.0061	0.0004	0.0067	0.0513
EMS-M5-E68	1.0055	0.0004	0.0061	0.0512
EMS-M5-E7P	1.0042	0.0004	0.0048	0.0516
EMS-M5-F22	1.0052	0.0004	0.0058	0.0535
EMS-M5-F30	1.0062	0.0004	0.0068	0.0513
EMS-M5-J32	1.0115	0.0004	0.0121	0.0522
EMS-M5-J33	1.0071	0.0004	0.0077	0.0515
IPPE-ABBN93	1.0013	0.0003	0.0019	

Table F103. LEU-ST-017 Case 01

ICSBEP benchmark	LEU-ST-017		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9981	0.0013		
EMS-S5-238	1.0094	0.0004	0.0113	0.0516
EMS-S5-27	1.0095	0.0004	0.0114	0.0365
EMS-S5-44	1.0107	0.0004	0.0126	0.0494
EMS-M5-E50	1.0062	0.0006	0.0081	0.0527
EMS-M5-E62	1.0008	0.0006	0.0027	0.0529
EMS-M5-E66	1.0026	0.0006	0.0045	0.0515
EMS-M5-E68	1.0034	0.0006	0.0053	0.0513
EMS-M5-E7P	1.0014	0.0006	0.0033	0.0516
EMS-M5-F22	1.0047	0.0006	0.0066	0.0536
EMS-M5-F30	1.0039	0.0006	0.0058	0.0513
EMS-M5-J32	1.0081	0.0006	0.0100	0.0522
EMS-M5-J33	1.0052	0.0006	0.0071	0.0516
IPPE-ABBN93	1.0066	0.0004	0.0085	

Table F104. LEU-ST-017 Case 02

ICSBEP benchmark	LEU-ST-017		Case 2	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9986	0.0013		
EMS-S5-238	1.0031	0.0003	0.0045	0.0493
EMS-S5-27	1.0037	0.0004	0.0051	0.0347
EMS-S5-44	1.0052	0.0004	0.0066	0.0472
EMS-M5-E50	1.0047	0.0006	0.0061	0.0500
EMS-M5-E62	0.9996	0.0006	0.0010	0.0506
EMS-M5-E66	1.0035	0.0006	0.0048	0.0491
EMS-M5-E68	1.0028	0.0006	0.0042	0.0491
EMS-M5-E7P	1.0011	0.0006	0.0025	0.0493
EMS-M5-F22	1.0042	0.0006	0.0056	0.0512
EMS-M5-F30	1.0025	0.0006	0.0039	0.0493
EMS-M5-J32	1.0097	0.0006	0.0111	0.0499
EMS-M5-J33	1.0039	0.0006	0.0052	0.0492
IPPE-ABBN93	1.0012	0.0003	0.0026	

Table F105. LEU-ST-017 Case 03

ICSBEP benchmark	LEU-ST-017		Case 3	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9989	0.0014		
EMS-S5-238	1.0019	0.0004	0.0030	0.0452
EMS-S5-27	1.0016	0.0004	0.0027	0.0316
EMS-S5-44	1.0032	0.0004	0.0043	0.0432
EMS-M5-E50	1.0039	0.0005	0.0050	0.0460
EMS-M5-E62	0.9987	0.0005	-0.0002	0.0461
EMS-M5-E66	1.0004	0.0006	0.0015	0.0449
EMS-M5-E68	1.0001	0.0006	0.0012	0.0451
EMS-M5-E7P	0.9995	0.0005	0.0006	0.0452
EMS-M5-F22	1.0018	0.0005	0.0029	0.0469
EMS-M5-F30	1.0016	0.0005	0.0027	0.0450
EMS-M5-J32	1.0071	0.0006	0.0082	0.0457
EMS-M5-J33	1.0035	0.0006	0.0046	0.0451
IPPE-ABBN93	0.9998	0.0003	0.0009	

Table F106. LEU-ST-017 Case 04

ICSBEP benchmark	LEU-ST-017		Case 4	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9992	0.0014		
EMS-S5-238	1.0031	0.0004	0.0039	0.0439
EMS-S5-27	1.0025	0.0003	0.0033	0.0306
EMS-S5-44	1.0039	0.0004	0.0047	0.0420
EMS-M5-E50	1.0039	0.0005	0.0047	0.0447
EMS-M5-E62	0.9979	0.0005	-0.0013	0.0450
EMS-M5-E66	1.0020	0.0005	0.0028	0.0438
EMS-M5-E68	1.0016	0.0005	0.0023	0.0438
EMS-M5-E7P	1.0002	0.0005	0.0010	0.0440
EMS-M5-F22	1.0016	0.0005	0.0024	0.0457
EMS-M5-F30	1.0017	0.0005	0.0025	0.0439
EMS-M5-J32	1.0081	0.0005	0.0089	0.0446
EMS-M5-J33	1.0017	0.0005	0.0025	0.0439
IPPE-ABBN93	1.0009	0.0003	0.0017	

Table F107. LEU-ST-017 Case 05

ICSBEP benchmark	LEU-ST-017		Case 5	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9987	0.0015		
EMS-S5-238	1.0026	0.0003	0.0039	0.0427
EMS-S5-27	1.0017	0.0003	0.0030	0.0296
EMS-S5-44	1.0031	0.0004	0.0044	0.0407
EMS-M5-E50	1.0035	0.0005	0.0048	0.0434
EMS-M5-E62	0.9984	0.0005	-0.0003	0.0436
EMS-M5-E66	1.0007	0.0005	0.0020	0.0433
EMS-M5-E68	1.0009	0.0005	0.0022	0.0426
EMS-M5-E7P	0.9999	0.0006	0.0012	0.0427
EMS-M5-F22	1.0018	0.0005	0.0031	0.0443
EMS-M5-F30	1.0016	0.0005	0.0029	0.0426
EMS-M5-J32	1.0072	0.0005	0.0085	0.0432
EMS-M5-J33	1.0025	0.0005	0.0038	0.0425
IPPE-ABBN93	1.0010	0.0003	0.0023	

Table F108. LEU-ST-017 Case 06

ICSBEP benchmark	LEU-ST-017		Case 6	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9996	0.0015		
EMS-S5-238	1.0020	0.0004	0.0024	0.0420
EMS-S5-27	1.0014	0.0003	0.0018	0.0291
EMS-S5-44	1.0019	0.0003	0.0023	0.0401
EMS-M5-E50	1.0040	0.0005	0.0044	0.0427
EMS-M5-E62	0.9986	0.0005	-0.0010	0.0430
EMS-M5-E66	1.0007	0.0005	0.0011	0.0426
EMS-M5-E68	1.0020	0.0005	0.0024	0.0419
EMS-M5-E7P	0.9999	0.0005	0.0003	0.0420
EMS-M5-F22	1.0022	0.0005	0.0026	0.0437
EMS-M5-F30	1.0009	0.0005	0.0013	0.0419
EMS-M5-J32	1.0063	0.0005	0.0067	0.0427
EMS-M5-J33	1.0022	0.0005	0.0026	0.0419
IPPE-ABBN93	0.9998	0.0003	0.0002	

Table F109. LEU-ST-020 Case 01

ICSBEP benchmark	LEU-ST-020		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9995	0.001		
EMS-S5-238	1.0000	0.0003	0.0005	0.0378
EMS-S5-27	0.9980	0.0004	-0.0015	0.0259
EMS-S5-44	0.9997	0.0003	0.0002	0.0360
EMS-M5-E50	1.0010	0.0002	0.0015	0.0384
EMS-M5-E62	0.9971	0.0002	-0.0025	0.0386
EMS-M5-E66	0.9997	0.0002	0.0002	0.0377
EMS-M5-E68	0.9998	0.0002	0.0003	0.0377
EMS-M5-E7P	0.9982	0.0002	-0.0014	0.0378
EMS-M5-F22	0.9990	0.0002	-0.0005	0.0392
EMS-M5-F30	0.9989	0.0002	-0.0007	0.0377
EMS-M5-J32	1.0040	0.0002	0.0045	0.0384
EMS-M5-J33	1.0009	0.0002	0.0014	0.0378
IPPE-ABBN93	0.9983	0.0002	-0.0012	

Table F110. LEU-ST-020 Case 02

ICSBEP benchmark	LEU-ST-020		Case 2	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9996	0.001		
EMS-S5-238	0.9989	0.0004	-0.0007	0.0369
EMS-S5-27	0.9974	0.0003	-0.0022	0.0253
EMS-S5-44	0.9993	0.0003	-0.0003	0.0351
EMS-M5-E50	1.0009	0.0002	0.0013	0.0375
EMS-M5-E62	0.9965	0.0002	-0.0031	0.0377
EMS-M5-E66	0.9987	0.0002	-0.0009	0.0369
EMS-M5-E68	0.9995	0.0002	-0.0001	0.0369
EMS-M5-E7P	0.9981	0.0002	-0.0016	0.0369
EMS-M5-F22	0.9991	0.0002	-0.0005	0.0383
EMS-M5-F30	0.9985	0.0002	-0.0011	0.0369
EMS-M5-J32	1.0042	0.0002	0.0046	0.0375
EMS-M5-J33	1.0004	0.0002	0.0008	0.0369
IPPE-ABBN93	0.9977	0.0002	-0.0019	

Table F111. LEU-ST-020 Case 03

ICSBEP benchmark	LEU-ST-020		Case 3	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9997	0.0012		
EMS-S5-238	0.9986	0.0003	-0.0011	0.0359
EMS-S5-27	0.9957	0.0003	-0.0040	0.0245
EMS-S5-44	0.9987	0.0003	-0.0011	0.0342
EMS-M5-E50	1.0000	0.0002	0.0003	0.0365
EMS-M5-E62	0.9960	0.0002	-0.0037	0.0368
EMS-M5-E66	0.9982	0.0002	-0.0015	0.0359
EMS-M5-E68	0.9983	0.0002	-0.0014	0.0359
EMS-M5-E7P	0.9974	0.0002	-0.0023	0.0360
EMS-M5-F22	0.9975	0.0002	-0.0022	0.0373
EMS-M5-F30	0.9978	0.0002	-0.0019	0.0359
EMS-M5-J32	1.0037	0.0002	0.0040	0.0365
EMS-M5-J33	0.9994	0.0002	-0.0004	0.0359
IPPE-ABBN93	0.9968	0.0002	-0.0029	

Table F112. LEU-ST-020 Case 04

ICSBEP benchmark	LEU-ST-020		Case 4	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9998	0.0012		
EMS-S5-238	0.9988	0.0003	-0.0010	0.0354
EMS-S5-27	0.9965	0.0003	-0.0034	0.0241
EMS-S5-44	0.9991	0.0003	-0.0007	0.0337
EMS-M5-E50	1.0005	0.0002	0.0007	0.0360
EMS-M5-E62	0.9970	0.0002	-0.0028	0.0362
EMS-M5-E66	0.9994	0.0002	-0.0004	0.0354
EMS-M5-E68	0.9992	0.0002	-0.0006	0.0354
EMS-M5-E7P	0.9987	0.0002	-0.0011	0.0354
EMS-M5-F22	0.9987	0.0002	-0.0011	0.0367
EMS-M5-F30	0.9987	0.0002	-0.0011	0.0353
EMS-M5-J32	1.0043	0.0002	0.0045	0.0360
EMS-M5-J33	1.0001	0.0003	0.0003	0.0354
IPPE-ABBN93	0.9980	0.0002	-0.0018	

Table F113. LEU-ST-021 Case 01

ICSBEP benchmark	LEU-ST-021		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9983	0.0009		
EMS-S5-238	0.9984	0.0003	0.0001	0.0380
EMS-S5-27	0.9967	0.0003	-0.0016	0.0261
EMS-S5-44	0.9983	0.0003	0.0000	0.0362
EMS-M5-E50	0.9994	0.0004	0.0011	0.0386
EMS-M5-E62	0.9949	0.0004	-0.0034	0.0388
EMS-M5-E66	0.9976	0.0005	-0.0007	0.0380
EMS-M5-E68	0.9984	0.0005	0.0001	0.0379
EMS-M5-E7P	0.9965	0.0005	-0.0019	0.0380
EMS-M5-F22	0.9970	0.0005	-0.0013	0.0393
EMS-M5-F30	0.9973	0.0005	-0.0010	0.0379
EMS-M5-J32	1.0031	0.0004	0.0048	0.0385
EMS-M5-J33	0.9978	0.0005	-0.0005	0.0379
IPPE-ABBN93	0.9962	0.0002	-0.0021	

Table F114. LEU-ST-021 Case 02

ICSBEP benchmark	LEU-ST-021		Case 2	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9985	0.001		
EMS-S5-238	0.9989	0.0004	0.0004	0.0371
EMS-S5-27	0.9959	0.0003	-0.0027	0.0254
EMS-S5-44	0.9982	0.0003	-0.0003	0.0353
EMS-M5-E50	0.9996	0.0004	0.0011	0.0377
EMS-M5-E62	0.9951	0.0004	-0.0034	0.0379
EMS-M5-E66	0.9987	0.0004	0.0002	0.0370
EMS-M5-E68	0.9985	0.0004	0.0000	0.0370
EMS-M5-E7P	0.9958	0.0004	-0.0027	0.0371
EMS-M5-F22	0.9972	0.0004	-0.0013	0.0384
EMS-M5-F30	0.9968	0.0004	-0.0017	0.0371
EMS-M5-J32	1.0038	0.0004	0.0053	0.0377
EMS-M5-J33	0.9994	0.0004	0.0009	0.0371
IPPE-ABBN93	0.9969	0.0002	-0.0016	

Table F115. LEU-ST-021 Case 03

ICSBEP benchmark	LEU-ST-021		Case 3	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9989	0.0011		
EMS-S5-238	0.9973	0.0003	-0.0016	0.0360
EMS-S5-27	0.9945	0.0003	-0.0045	0.0246
EMS-S5-44	0.9970	0.0003	-0.0020	0.0343
EMS-M5-E50	0.9983	0.0004	-0.0006	0.0366
EMS-M5-E62	0.9939	0.0004	-0.0050	0.0369
EMS-M5-E66	0.9965	0.0004	-0.0024	0.0361
EMS-M5-E68	0.9965	0.0004	-0.0024	0.0361
EMS-M5-E7P	0.9956	0.0004	-0.0033	0.0361
EMS-M5-F22	0.9966	0.0004	-0.0023	0.0374
EMS-M5-F30	0.9960	0.0004	-0.0029	0.0361
EMS-M5-J32	1.0017	0.0004	0.0028	0.0366
EMS-M5-J33	0.9975	0.0004	-0.0014	0.0359
IPPE-ABBN93	0.9959	0.0002	-0.0030	

Table F116. LEU-ST-021 Case 04

ICSBEP benchmark	LEU-ST-021		Case 4	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9993	0.0012		
EMS-S5-238	0.9992	0.0003	-0.0001	0.0355
EMS-S5-27	0.9960	0.0003	-0.0033	0.0242
EMS-S5-44	0.9988	0.0003	-0.0005	0.0338
EMS-M5-E50	1.0006	0.0004	0.0013	0.0361
EMS-M5-E62	0.9958	0.0004	-0.0035	0.0363
EMS-M5-E66	0.9995	0.0004	0.0002	0.0355
EMS-M5-E68	0.9938	0.0004	-0.0055	0.0355
EMS-M5-E7P	0.9987	0.0004	-0.0006	0.0355
EMS-M5-F22	0.9985	0.0004	-0.0008	0.0369
EMS-M5-F30	0.9983	0.0004	-0.0010	0.0355
EMS-M5-J32	1.0037	0.0004	0.0044	0.0361
EMS-M5-J33	1.0001	0.0004	0.0008	0.0355
IPPE-ABBN93	0.9972	0.0002	-0.0021	

Fast plutonium system validation results

The plutonium benchmarks selected are too few to get a reasonable statistical base for evaluation. The applications are water-reflected, while most of the benchmarks are bare. Benchmark PuMT011 is a water-reflected system that seems very similar to some applications. Further, the uncertainty is low. Concerning the plutonium isotope distribution, benchmarks PuMT001 and PuMT002 are of special interest. They are similar, except that the isotope distribution in PuMT002 is unusual in the benchmarks (“reactor-grade” plutonium) but of interest in the applications. The difference between the MCNP5 calculations with ENDF/B5 cross sections is that -50 refers to use of only “.50c” cross sections while -5F (Final) refers to use of “.55c” cross-sections for ^{239}Pu . The EALF values are determined from MCNP5 calculations using ENDF/B-7P, JEFF-3.0 and JENDL3.3, not DICE.

Figure F75. Legend for fast Pu

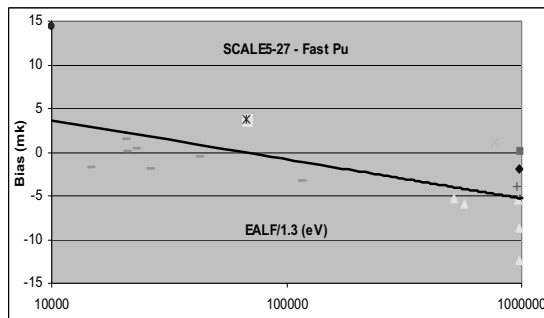


Figure F78. Fast Pu. SCALE5+44 grp

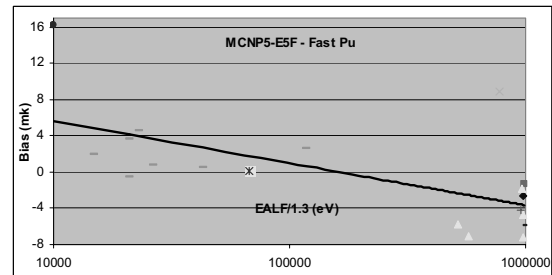


Figure F76. Fast Pu. SCALE5+238 grp



Figure F79. Fast Pu. MCNP5+ENDF/B-5.0

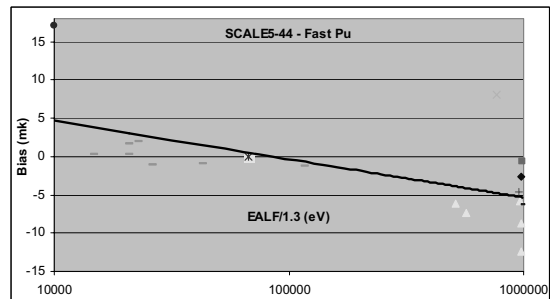


Figure F77. Fast Pu. SCALE5+27 grp

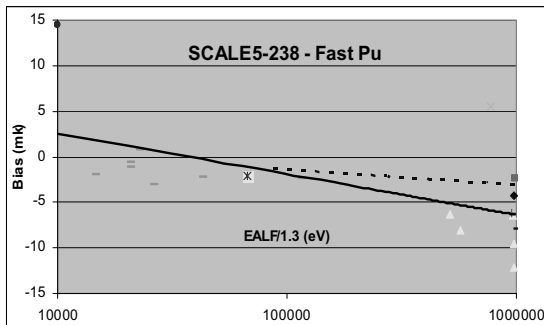


Figure F80. Fast Pu. MCNP5+ENDF/B-5F

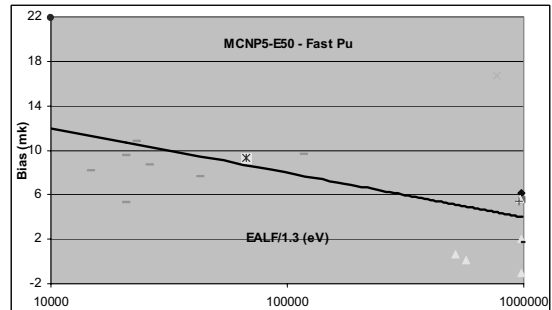


Figure F81. Fast Pu. MCNP5+ENDF/B-6.2

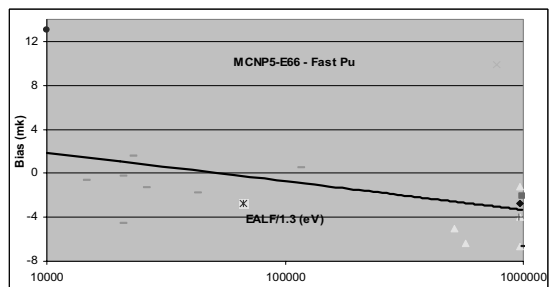


Figure F85. Fast Pu. MCNP5+JEF-2.2

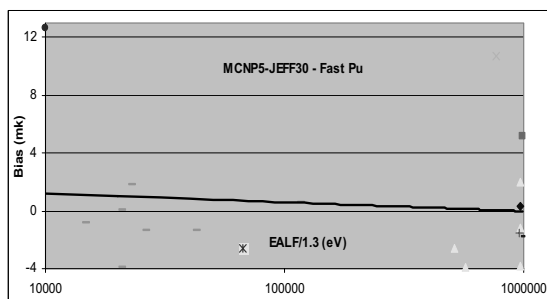


Figure F82. Fast Pu. MCNP5+ENDF/B-6.6

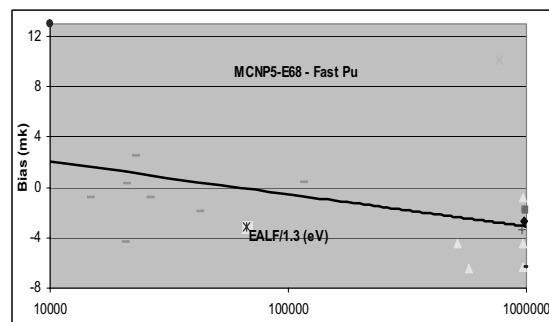


Figure F86. Fast Pu. MCNP5+JEFF-3.0

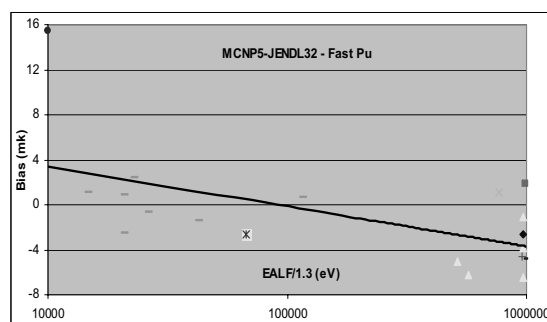


Figure F83. Fast Pu. MCNP5+ENDF/B-6.8

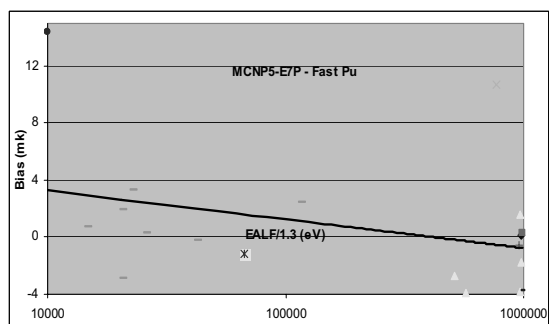


Figure F87. Fast Pu. MCNP5+JENDL-3.2

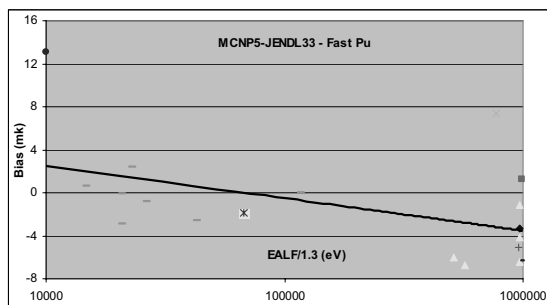


Figure F84. Fast Pu. MCNP5+ENDF/B-7P

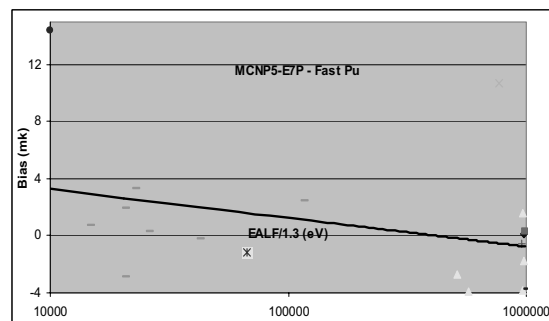


Figure F88. Fast Pu. MCNP5+JENDL-3.3

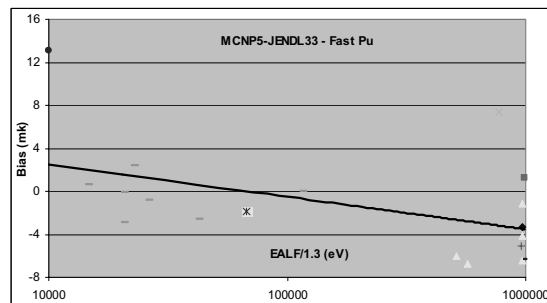


Figure F89. Fast Pu.ABBN-93

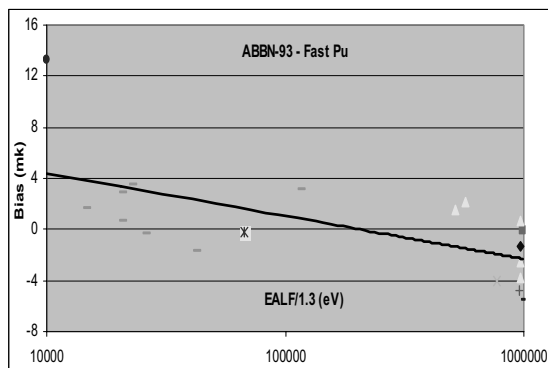


Figure F90. Legend for all methods chart

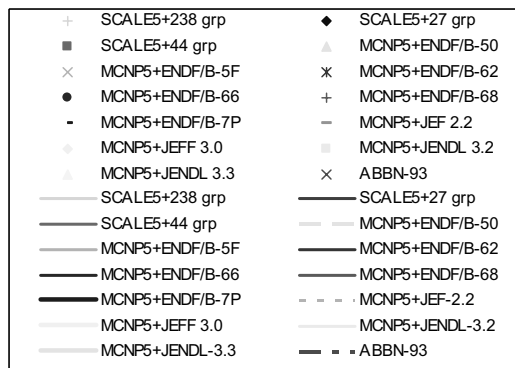


Figure F91. Fast Pu.All methods

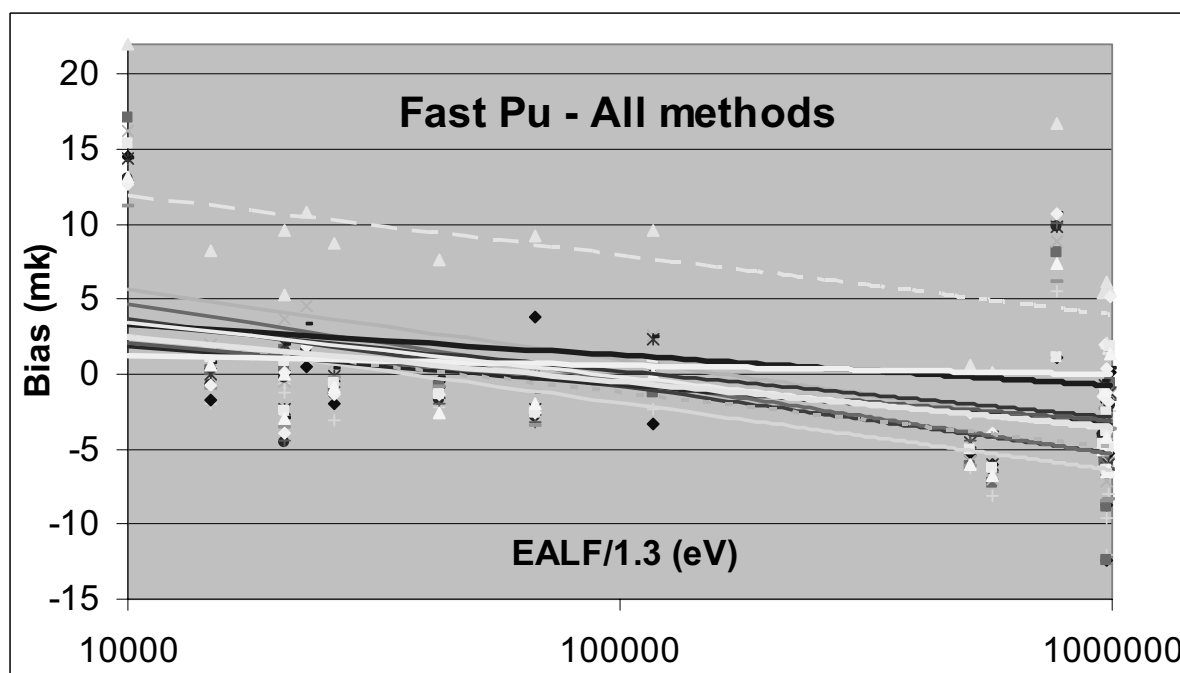


Table F117. Pu-MF-001 Case 01

ICSBEP benchmark	Pu-MF-001		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0020		
EMS-S5-238	0.9958		-0.0042	1239000
EMS-S5-27	0.9981		-0.0019	1154000
EMS-S5-44	0.9973		-0.0027	1196000
EMS-M5-E50	1.0062	0.0002	0.0062	1206000
EMS-M5-E5F	0.9974	0.0002	-0.0026	1256300
EMS-M5-E62	0.9980	0.0002	-0.0021	1256800
EMS-M5-E66	0.9973	0.0002	-0.0028	1254300
EMS-M5-E68	0.9973	0.0002	-0.0027	1254500
EMS-M5-E7P	1.0002	0.0002	0.0002	1255200
EMS-M5-F22	0.9959	0.0002	-0.0041	1204000
EMS-M5-F30	1.0003	0.0002	0.0003	1284300
EMS-M5-J32	0.9974	0.0002	-0.0026	1296000
EMS-M5-J33	0.9967	0.0002	-0.0033	1256000
IPPE-ABBN93	0.9986	0.0006	-0.0014	

Table F118. Pu-MF-002 Case 01

ICSBEP benchmark	Pu-MF-001		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0020		
EMS-S5-238	0.9958		-0.0042	1239000
EMS-S5-27	0.9981		-0.0019	1154000
EMS-S5-44	0.9973		-0.0027	1196000
EMS-M5-E50	1.0062	0.0002	0.0062	1206000
EMS-M5-E5F	0.9974	0.0002	-0.0026	1256300
EMS-M5-E62	0.9980	0.0002	-0.0021	1256800
EMS-M5-E66	0.9973	0.0002	-0.0028	1254300
EMS-M5-E68	0.9973	0.0002	-0.0027	1254500
EMS-M5-E7P	1.0002	0.0002	0.0002	1255200
EMS-M5-F22	0.9959	0.0002	-0.0041	1204000
EMS-M5-F30	1.0003	0.0002	0.0003	1284300
EMS-M5-J32	0.9974	0.0002	-0.0026	1296000
EMS-M5-J33	0.9967	0.0002	-0.0033	1256000
IPPE-ABBN93	0.9986	0.0006	-0.0014	

Table F119. Pu-MF-003 Case 01

ICSBEP benchmark	Pu-MF-003		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0030		
EMS-S5-238	0.9936	0.0003	-0.0064	1241530
EMS-S5-27	0.9945	0.0003	-0.0055	1153320
EMS-S5-44	0.9942	0.0003	-0.0058	1201370
EMS-M5-E50	1.0056	0.0002	0.0056	1203300
EMS-M5-E5F	0.9982	0.0002	-0.0018	1254400
EMS-M5-E62	0.9993	0.0002	-0.0007	1254200
EMS-M5-E66	0.9988	0.0002	-0.0012	1249800
EMS-M5-E68	0.9992	0.0002	-0.0008	1249000
EMS-M5-E7P	1.0016	0.0002	0.0016	1250000
EMS-M5-F22	0.9977	0.0002	-0.0023	1197800
EMS-M5-F30	1.0020	0.0002	0.0019	1281400
EMS-M5-J32	0.9989	0.0002	-0.0011	1285100
EMS-M5-J33	0.9988	0.0002	-0.0012	1252600
IPPE-ABBN93	1.0006	0.0009	0.0006	

Table F120. Pu-MF-003 Case 02

ICSBEP benchmark	Pu-MF-003		Case 2	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0030		
EMS-S5-238	0.9919	0.0003	-0.0081	690457
EMS-S5-27	0.9940	0.0003	-0.0060	628874
EMS-S5-44	0.9927	0.0003	-0.0073	671241
EMS-M5-E50	1.0001	0.0002	0.0001	705430
EMS-M5-E5F	0.9930	0.0002	-0.0071	739530
EMS-M5-E62	0.9939	0.0002	-0.0061	738570
EMS-M5-E66	0.9937	0.0002	-0.0063	733200
EMS-M5-E68	0.9935	0.0002	-0.0065	731120
EMS-M5-E7P	0.9961	0.0002	-0.0040	735400
EMS-M5-F22	0.9928	0.0002	-0.0072	698460
EMS-M5-F30	0.9961	0.0002	-0.0039	757330
EMS-M5-J32	0.9938	0.0002	-0.0062	757330
EMS-M5-J33	0.9932	0.0002	-0.0068	737010
IPPE-ABBN93	1.0021	0.0009	0.0021	

Table F121. Pu-MF-003 Case 03

ICSBEP benchmark	Pu-MF-003		Case 3	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0030		
EMS-S5-238	0.9879	0.0003	-0.0121	1242910
EMS-S5-27	0.9876	0.0003	-0.0124	1155850
EMS-S5-44	0.9876	0.0003	-0.0124	1204260
EMS-M5-E50	0.9989	0.0002	-0.0011	1205700
EMS-M5-E5F	0.9928	0.0002	-0.0072	1256100
EMS-M5-E62	0.9937	0.0002	-0.0063	1256200
EMS-M5-E66	0.9933	0.0002	-0.0067	1251400
EMS-M5-E68	0.9937	0.0002	-0.0063	1250500
EMS-M5-E7P	0.9962	0.0002	-0.0038	1253100
EMS-M5-F22	0.9915	0.0002	-0.0085	1200300
EMS-M5-F30	0.9962	0.0002	-0.0038	1282800
EMS-M5-J32	0.9936	0.0002	-0.0064	1287400
EMS-M5-J33	0.9935	0.0002	-0.0065	1255100
IPPE-ABBN93	0.9962	0.0009	-0.0038	

Table F122. Pu-MF-003 Case 04

ICSBEP benchmark	Pu-MF-003		Case 4	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0030		
EMS-S5-238	0.9937	0.0003	-0.0063	624264
EMS-S5-27	0.9946	0.0003	-0.0054	570784
EMS-S5-44	0.9939	0.0003	-0.0061	607997
EMS-M5-E50	1.0006	0.0002	0.0006	633420
EMS-M5-E5F	0.9942	0.0002	-0.0058	664500
EMS-M5-E62	0.9954	0.0002	-0.0046	661470
EMS-M5-E66	0.9950	0.0002	-0.0050	659210
EMS-M5-E68	0.9955	0.0002	-0.0045	656410
EMS-M5-E7P	0.9973	0.0002	-0.0027	660770
EMS-M5-F22	0.9938	0.0002	-0.0062	627910
EMS-M5-F30	0.9974	0.0002	-0.0026	683210
EMS-M5-J32	0.9950	0.0002	-0.0050	682370
EMS-M5-J33	0.9940	0.0002	-0.0060	663240
IPPE-ABBN93	1.0015	0.0009	0.0015	

Table F123. Pu-MF-003 Case 05

ICSBEP benchmark	Pu-MF-003		Case 5	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0030		
EMS-S5-238	0.9905	0.0003	-0.0095	1244370
EMS-S5-27	0.9913	0.0003	-0.0087	1155970
EMS-S5-44	0.9912	0.0003	-0.0088	1204140
EMS-M5-E50	1.0021	0.0002	0.0021	1206800
EMS-M5-E5F	0.9953	0.0002	-0.0047	1256900
EMS-M5-E62	0.9963	0.0002	-0.0037	1257600
EMS-M5-E66	0.9960	0.0002	-0.0040	1253400
EMS-M5-E68	0.9956	0.0002	-0.0044	1252300
EMS-M5-E7P	0.9983	0.0002	-0.0018	1254600
EMS-M5-F22	0.9947	0.0002	-0.0053	1200900
EMS-M5-F30	0.9988	0.0002	-0.0012	1284500
EMS-M5-J32	0.9961	0.0002	-0.0039	1289400
EMS-M5-J33	0.9958	0.0002	-0.0042	1255800
IPPE-ABBN93	0.9974	0.0009	-0.0026	

Table F124. Pu-MF-005 Case 01

ICSBEP benchmark	Pu-MF-005		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0013		
EMS-S5-238	1.0055		0.0055	980200
EMS-S5-27	1.0011		0.0011	937300
EMS-S5-44	1.0081		0.0080	943000
EMS-M5-E50	1.0168	0.0003	0.0168	955720
EMS-M5-E5F	1.0089	0.0003	0.0089	986750
EMS-M5-E62	1.0099	0.0003	0.0099	984260
EMS-M5-E66	1.0099	0.0003	0.0099	984260
EMS-M5-E68	1.0101	0.0003	0.0101	981110
EMS-M5-E7P	1.0107	0.0003	0.0107	1011000
EMS-M5-F22	1.0062	0.0003	0.0062	950030
EMS-M5-F30	1.0107	0.0003	0.0107	1011000
EMS-M5-J32	1.0011	0.0003	0.0011	1039700
EMS-M5-J33	1.0074	0.0003	0.0074	985130
IPPE-ABBN93	0.9959	0.0009	-0.0041	

Table F125. Pu-MF-011 Case 01

ICSBEP benchmark	Pu-MF-011		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0010		
EMS-S5-238	0.9979		-0.0021	83240
EMS-S5-27	1.0038		0.0038	72220
EMS-S5-44	0.9999		-0.0001	79590
EMS-M5-E50	1.0093	0.0002	0.0093	81268
EMS-M5-E5F	1.0001	0.0002	0.0001	86292
EMS-M5-E62	0.9976	0.0002	0.0002	85354
EMS-M5-E66	0.9972	0.0002	-0.0028	84928
EMS-M5-E68	0.9968	0.0002	-0.0032	85258
EMS-M5-E7P	0.9988	0.0002	-0.0012	86137
EMS-M5-F22	0.9965	0.0002	-0.0035	81241
EMS-M5-F30	0.9974	0.0002	-0.0026	89784
EMS-M5-J32	0.9974	0.0002	-0.0026	90067
EMS-M5-J33	0.9981	0.0002	-0.0019	85905
IPPE-ABBN93	0.9998	0.0009	-0.0002	

Table F126. Pu-MF-016 Case 01

ICSBEP benchmark	Pu-MF-016		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9974	0.0042		
EMS-S5-238	1.0118	0.0003	0.0144	11601
EMS-S5-27	1.0119	0.0003	0.0145	10271
EMS-S5-44	1.0145	0.0003	0.0171	11121
EMS-M5-E50	1.0193	0.0003	0.0219	11478
EMS-M5-E5F	1.0136	0.0002	0.0162	12090
EMS-M5-E62	1.0118	0.0003	0.0118	12062
EMS-M5-E66	1.0105	0.0003	0.0131	12096
EMS-M5-E68	1.0104	0.0003	0.0130	12132
EMS-M5-E7P	1.0118	0.0003	0.0144	12212
EMS-M5-F22	1.0086	0.0002	0.0112	11799
EMS-M5-F30	1.0101	0.0003	0.0127	12658
EMS-M5-J32	1.0128	0.0003	0.0154	12335
EMS-M5-J33	1.0105	0.0003	0.0131	12369
IPPE-ABBN93	1.0107	0.0009	0.0133	

Table F127. Pu-MF-022 Case 01

ICSBEP benchmark	Pu-MF-022		Case 1 - Simple	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0021		
EMS-S5-238	0.9939	0.0003	-0.0061	1218630
EMS-S5-27	0.9960	0.0003	-0.0040	1136820
EMS-S5-44	0.9955	0.0003	-0.0046	1176250
EMS-M5-E50	1.0054	0.0003	0.0054	1187500
EMS-M5-E5F	0.9958	0.0003	-0.0042	1237200
EMS-M5-E62	0.9964	0.0003	-0.0036	1236900
EMS-M5-E66	0.9960	0.0003	-0.0040	1235100
EMS-M5-E68	0.9967	0.0003	-0.0033	1233200
EMS-M5-E7P	0.9995	0.0003	-0.0006	1237600
EMS-M5-F22	0.9947	0.0003	-0.0053	1184900
EMS-M5-F30	0.9985	0.0003	-0.0015	1263600
EMS-M5-J32	0.9954	0.0003	-0.0046	1276300
EMS-M5-J33	0.9949	0.0003	-0.0051	1235500
IPPE-ABBN93	0.9953	0.0006	-0.0047	

Table F128. Pu-MF-029 Case 01

ICSBEP benchmark	Pu-MF-029		Case 1-Simple	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0020		
EMS-S5-238	0.9920		-0.0080	1246000
EMS-S5-27	0.9947		-0.0053	1158000
EMS-S5-44	0.9937		-0.0063	1203000
EMS-M5-E50	1.0018	0.0003	0.0017	1214600
EMS-M5-E5F	0.9940	0.0003	-0.0060	1262100
EMS-M5-E62	0.9940	0.0003	-0.0060	1262900
EMS-M5-E66	0.9933	0.0003	-0.0067	1259900
EMS-M5-E68	0.9937	0.0003	-0.0063	1259200
EMS-M5-E7P	0.9963	0.0003	-0.0037	1261800
EMS-M5-F22	0.9916	0.0003	-0.0084	1212600
EMS-M5-F30	0.9982	0.0003	-0.0018	1294000
EMS-M5-J32	0.9951	0.0003	-0.0049	1301100
EMS-M5-J33	0.9937	0.0003	-0.0063	1269100
IPPE-ABBN93	0.9945	0.0006	-0.0055	

Table F129. Pu-MF-037 Case 01

ICSBEP benchmark	Pu-MF-037		Case 01	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0044		
EMS-S5-238	0.9977	0.0003	-0.0023	145614
EMS-S5-27	0.9967	0.0016	-0.0033	129393
EMS-S5-44	0.9988	0.0003	-0.0012	140239
EMS-M5-E50	1.0096	0.0004	0.0096	141570
EMS-M5-E5F	1.0026	0.0008	0.0026	150920
EMS-M5-E62	1.0023	0.0004	0.0023	148100
EMS-M5-E66	1.0005	0.0004	0.0005	149400
EMS-M5-E68	1.0004	0.0004	0.0004	149030
EMS-M5-E7P	1.0024	0.0004	0.0024	150460
EMS-M5-F22	1.0006	0.0004	0.0006	140200
EMS-M5-F30	1.0006	0.0004	0.0006	155570
EMS-M5-J32	1.0007	0.0004	0.0007	153780
EMS-M5-J33	1.0000	0.0004	0.0000	150570
IPPE-ABBN93	1.0031	0.0009	0.0031	

Table F130. Pu-MF-037 Case 05

ICSBEP benchmark	Pu-MF-037		Case 05	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0037		
EMS-S5-238	0.9978	0.0003	-0.0022	51362
EMS-S5-27	0.9995	0.0003	-0.0005	45436
EMS-S5-44	0.9991	0.0003	-0.0009	49751
EMS-M5-E50	1.0076	0.0002	0.0076	51963
EMS-M5-E5F	1.0006	0.0002	0.0006	55082
EMS-M5-E62	0.9988	0.0002	-0.0012	54813
EMS-M5-E66	0.9982	0.0004	-0.0018	54360
EMS-M5-E68	0.9803	0.0002	-0.0197	54716
EMS-M5-E7P	0.9998	0.0004	-0.0002	54865
EMS-M5-F22	0.9992	0.0004	-0.0008	51333
EMS-M5-F30	0.9986	0.0004	-0.0014	56785
EMS-M5-J32	0.9986	0.0002	-0.0014	56157
EMS-M5-J33	0.9974	0.0004	-0.0026	55557
IPPE-ABBN93	0.9984	0.0009	-0.0016	

Table F131. Pu-MF-037 Case 07

ICSBEP benchmark	Pu-MF-037		Case 07	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0038		
EMS-S5-238	0.9969	0.0003	-0.0031	33165
EMS-S5-27	0.9981	0.0003	-0.0019	29194
EMS-S5-44	0.9989	0.0003	-0.0011	32067
EMS-M5-E50	1.0087	0.0004	0.0087	32115
EMS-M5-E5F	1.0008	0.0004	0.0008	33980
EMS-M5-E62	0.9999	0.0004	-0.0001	33674
EMS-M5-E66	0.9987	0.0004	-0.0013	33617
EMS-M5-E68	0.9991	0.0004	-0.0009	33472
EMS-M5-E7P	1.0003	0.0004	0.0003	33683
EMS-M5-F22	0.9998	0.0004	-0.0002	31594
EMS-M5-F30	0.9987	0.0004	-0.0013	35080
EMS-M5-J32	0.9994	0.0004	-0.0007	34699
EMS-M5-J33	0.9991	0.0004	-0.0009	33880
IPPE-ABBN93	0.9997	0.0009	-0.0003	

Table F132. Pu-MF-037 Case 10

ICSBEP benchmark	Pu-MF-037		Case 10	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0034		
EMS-S5-238	0.9988	0.0003	-0.0012	25970
EMS-S5-27	1.0000	0.0003	0.0000	23120
EMS-S5-44	1.0003	0.0003	0.0003	25238
EMS-M5-E50	1.0095	0.0004	0.0095	25512
EMS-M5-E5F	1.0037	0.0004	0.0037	26814
EMS-M5-E62	1.0019	0.0004	0.0019	26828
EMS-M5-E66	0.9997	0.0004	-0.0003	26496
EMS-M5-E68	1.0003	0.0004	0.0003	26579
EMS-M5-E7P	1.0019	0.0004	0.0019	26952
EMS-M5-F22	1.0010	0.0004	0.0010	25153
EMS-M5-F30	1.0001	0.0004	0.0001	27684
EMS-M5-J32	1.0009	0.0004	0.0009	27435
EMS-M5-J33	0.9999	0.0004	-0.0001	26881
IPPE-ABBN93	1.0029	0.0009	0.0029	

Table F133. Pu-MF-037 Case 12

ICSBEP benchmark	Pu-MF-037		Case 12	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0040		
EMS-S5-238	0.9994	0.0003	-0.0006	23516
EMS-S5-27	1.0015	0.0003	0.0015	20910
EMS-S5-44	1.0016	0.0003	0.0016	22617
EMS-M5-E50	1.0053	0.0004	0.0053	25621
EMS-M5-E5F	0.9995	0.0004	-0.0005	26849
EMS-M5-E62	0.9977	0.0004	-0.0023	26498
EMS-M5-E66	0.9955	0.0004	-0.0045	26565
EMS-M5-E68	0.9956	0.0004	-0.0044	26631
EMS-M5-E7P	0.9971	0.0004	-0.0029	26776
EMS-M5-F22	0.9964	0.0004	-0.0036	25324
EMS-M5-F30	0.9961	0.0004	-0.0039	27815
EMS-M5-J32	0.9975	0.0004	-0.0025	27224
EMS-M5-J33	0.9971	0.0004	-0.0029	26850
IPPE-ABBN93	1.0007	0.0008	0.0007	

Table F134. Pu-MF-037 Case 15

ICSBEP benchmark	Pu-MF-037		Case 15	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0033		
EMS-S5-238	0.9980	0.0003	-0.0020	18213
EMS-S5-27	0.9983	0.0003	-0.0017	16231
EMS-S5-44	1.0003	0.0003	0.0003	17611
EMS-M5-E50	1.0082	0.0004	0.0082	18108
EMS-M5-E5F	1.0019	0.0004	0.0019	18874
EMS-M5-E62	1.0000	0.0004	0.0000	18790
EMS-M5-E66	0.9993	0.0004	-0.0007	18696
EMS-M5-E68	0.9992	0.0004	-0.0008	18618
EMS-M5-E7P	1.0007	0.0004	0.0007	19026
EMS-M5-F22	0.9990	0.0004	-0.0010	17888
EMS-M5-F30	0.9992	0.0004	-0.0008	19511
EMS-M5-J32	1.0011	0.0004	0.0011	19122
EMS-M5-J33	1.0006	0.0004	0.0006	19023
IPPE-ABBN93	1.0017	0.0008	0.0016	

Table F135. Pu-MF-037 Case 16

ICSBEP benchmark	Pu-MF-037		Case 16	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0039		
EMS-S5-238	1.0007	0.0003	0.0007	28363
EMS-S5-27	1.0005	0.0003	0.0005	25431
EMS-S5-44	1.0020	0.0003	0.0020	27458
EMS-M5-E50	1.0108	0.0004	0.0108	29420
EMS-M5-E5F	1.0045	0.0004	0.0045	29610
EMS-M5-E62	1.0022	0.0004	0.0022	29420
EMS-M5-E66	1.0016	0.0004	0.0015	29352
EMS-M5-E68	1.0025	0.0004	0.0025	29279
EMS-M5-E7P	1.0033	0.0004	0.0033	29595
EMS-M5-F22	1.0020	0.0004	0.0020	27970
EMS-M5-F30	1.0018	0.0004	0.0018	30428
EMS-M5-J32	1.0025	0.0004	0.0025	29958
EMS-M5-J33	1.0024	0.0004	0.0024	29634
IPPE-ABBN93	1.0035	0.0009	0.0035	

Thermal plutonium system validation results

The uncertainties for these benchmarks are in general quite high. The only benchmarks with a lower standard deviation than 3 mk (0.003 in k_{eff}) are in the PuST022 series. This series is preliminary chosen as the basis for validation. Other benchmarks and similarity tests will be used to determine if this is a reasonable procedure. The PuST025 series of benchmarks is also of extra interest. The uncertainties are large but the systems are similar to some of the applications. The range of EALF covered is larger than in series PuST22. Unlike the fast plutonium benchmarks selected, the thermal plutonium benchmarks include several with reactor-grade plutonium isotope distributions. PuST022 contains reactor-grade plutonium. PuST025 and PuST026 each contain a wide range of isotope distributions. The large differences seen for fast plutonium systems using MCNP5 with the two ENDF/B-5 sets of ^{239}Pu cross-section are not seen for thermal plutonium systems.

The published ICSBEP 2004 sample input and results for the first nine benchmarks in Pu-ST-022, as calculated using MCNP4 and ENDF/B-V cross sections, are incorrect (about 1 %). Unfortunately, the older input on the CD-ROM contains other errors. The biases due to these errors have not been investigated.

Figure F92. Thermal Pu. Legend

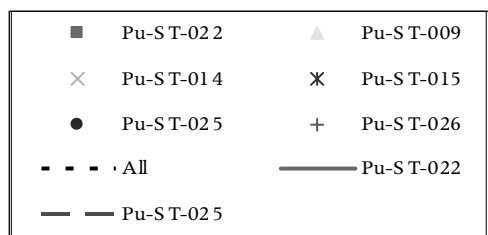


Figure F95. Thermal Pu. S5-44 grp

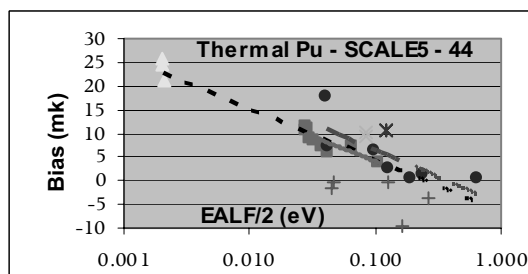


Figure F93. Thermal Pu. S5-238 grp

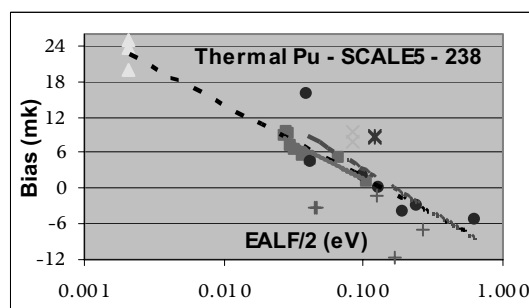


Figure F96. Thermal Pu. M5-E50

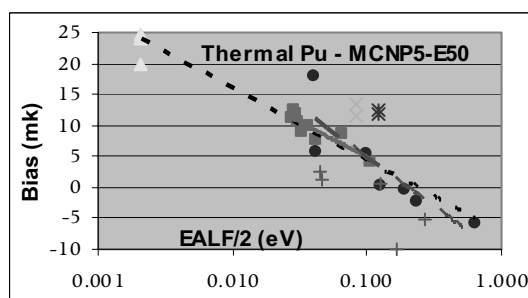


Figure F94. Thermal Pu. S5-27 grp

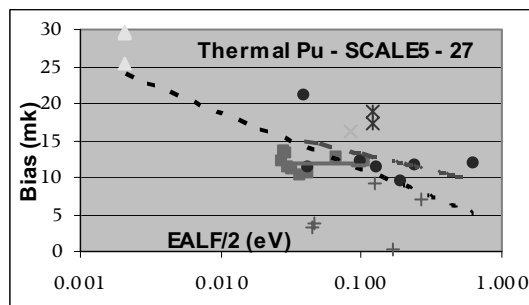


Figure F97. Thermal Pu. M5-E5F

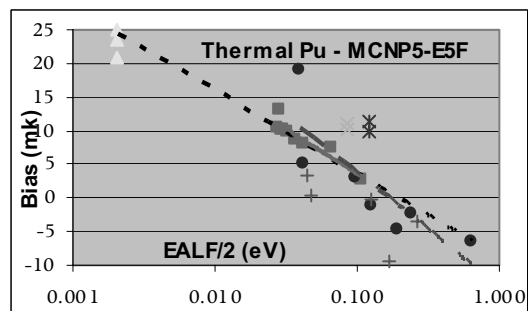


Figure F98. Thermal Pu. M5-E62

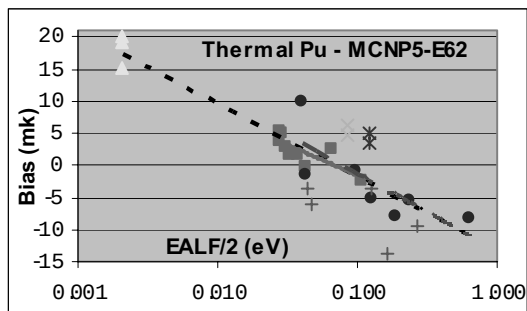


Figure F102. Thermal Pu. M5-JF22

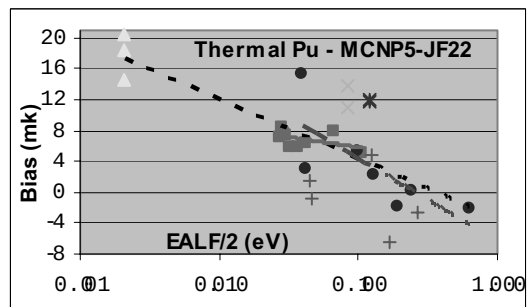


Figure F99. Thermal Pu. M5-E66

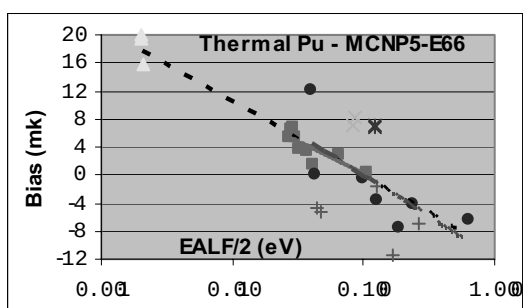


Figure F103. Thermal Pu. M5-JF30

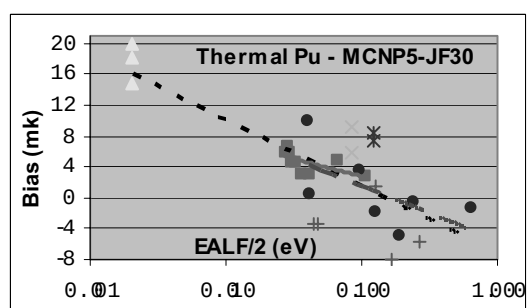


Figure F100. Thermal Pu. M5-E68

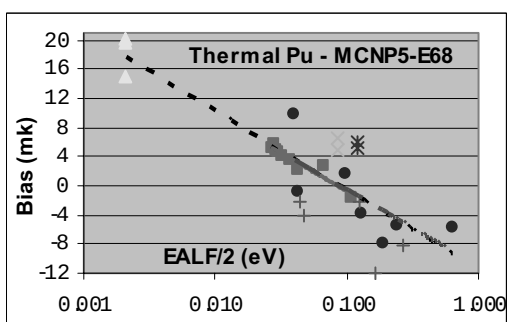


Figure F104. Thermal Pu. M5-JL32

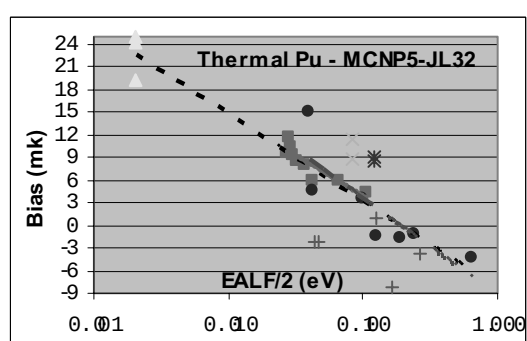


Figure F101. Thermal Pu. M5-E7P

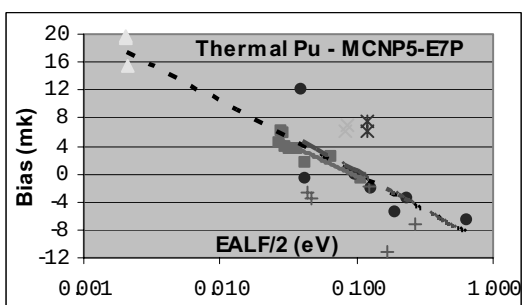


Figure F105. Thermal Pu. M5-JL33

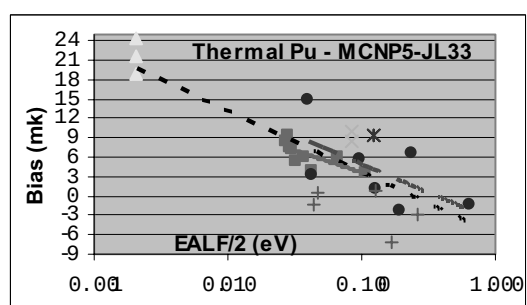


Figure F106. Thermal Pu. ABBN-93

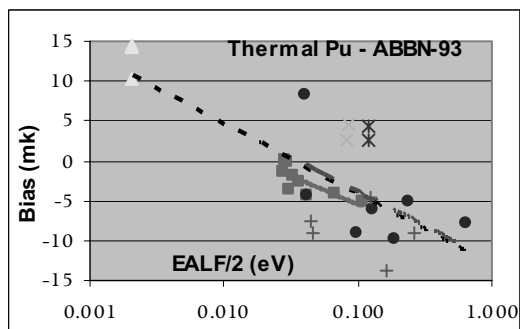


Figure F107. Legend. Thermal Pu. All

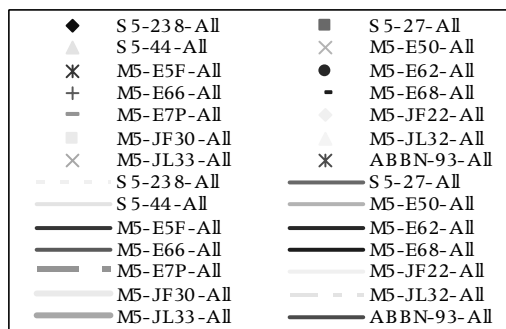


Figure F108. Thermal Pu. All

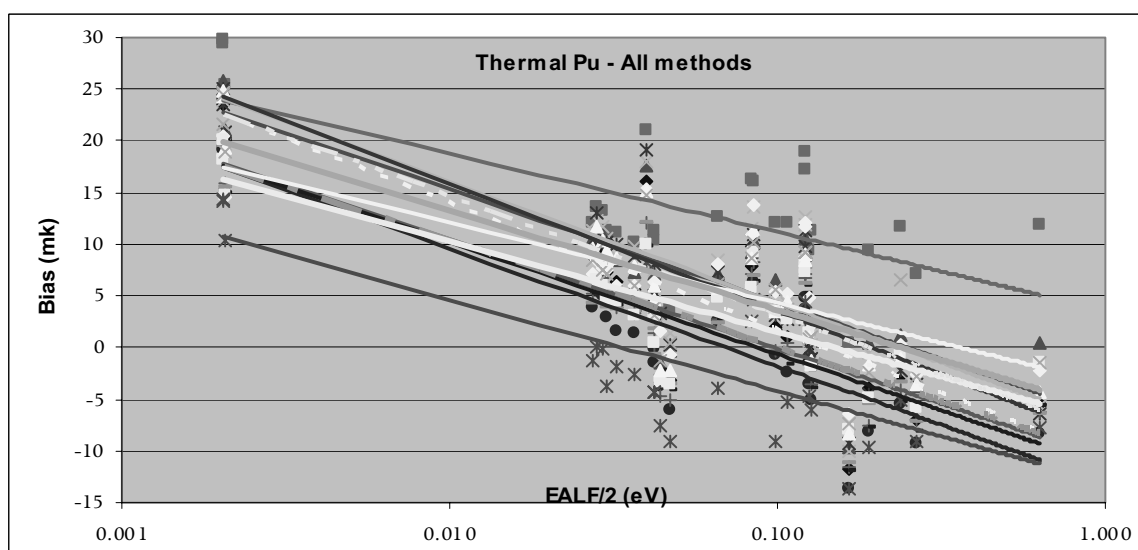


Table F136. Pu-ST-009 Case 1

ICSBEP benchmark	Pu-ST-009		Case 1	
Method		σ	Bias	EALF (eV)
Benchmark	1.0000	0.0033		
EMS-S5-238	1.0200	0.0003	0.0200	0.0411
EMS-S5-27	1.0254	0.0003	0.0254	0.0313
EMS-S5-44	1.0211	0.0003	0.0211	0.0397
EMS-M5-E50	1.0197	0.0004	0.0197	0.0418
EMS-M5-E5F	1.0208	0.0004	0.0208	0.0417
EMS-M5-E62	1.0152	0.0004	0.0152	0.0418
EMS-M5-E66	1.0158	0.0004	0.0158	0.0412
EMS-M5-E68	1.0149	0.0004	0.0149	0.0412
EMS-M5-E7P	1.0155	0.0004	0.0155	0.0412
EMS-M5-F22	1.0146	0.0004	0.0146	0.0422
EMS-M5-F30	1.0148	0.0004	0.0148	0.0412
EMS-M5-J32	1.0193	0.0004	0.0193	0.0415
EMS-M5-J33	1.0190	0.0004	0.0190	0.0414
IPPE-ABBN93	1.0103	0.0005	0.0103	

Table F137. Pu-ST-009 Case 2

ICSBEP benchmark	Pu-ST-009		Case 2	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0033		
EMS-S5-238	1.0251	0.0003	0.0251	0.0407
EMS-S5-27	1.0298	0.0003	0.0298	0.0310
EMS-S5-44	1.0257	0.0003	0.0257	0.0393
EMS-M5-E50	1.0247	0.0004	0.0247	0.0412
EMS-M5-E5F	1.0250	0.0004	0.0250	0.0413
EMS-M5-E62	1.0200	0.0004	0.0200	0.0415
EMS-M5-E66	1.0195	0.0004	0.0195	0.0408
EMS-M5-E68	1.0198	0.0004	0.0197	0.0408
EMS-M5-E7P	1.0198	0.0004	0.0198	0.0409
EMS-M5-F22	1.0204	0.0004	0.0204	0.0417
EMS-M5-F30	1.0201	0.0004	0.0201	0.0408
EMS-M5-J32	1.0249	0.0004	0.0249	0.0412
EMS-M5-J33	1.0244	0.0004	0.0244	0.0409
IPPE-ABBN93	1.0142	0.0004	0.0142	

Table F138. Pu-ST-009 Case 3

ICSBEP benchmark	Pu-ST-009		Case 3	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0033		
EMS-S5-238	1.0235	0.0003	0.0235	0.0406
EMS-S5-27	1.0293	0.0003	0.0293	0.0309
EMS-S5-44	1.0246	0.0003	0.0246	0.0392
EMS-M5-E50	1.0240	0.0004	0.0240	0.0413
EMS-M5-E5F	1.0235	0.0003	0.0235	0.0412
EMS-M5-E62	1.0192	0.0004	0.0192	0.0414
EMS-M5-E66	1.0200	0.0004	0.0200	0.0408
EMS-M5-E68	1.0201	0.0004	0.0201	0.0408
EMS-M5-E7P	1.0195	0.0004	0.0195	0.0408
EMS-M5-F22	1.0186	0.0004	0.0186	0.0416
EMS-M5-F30	1.0182	0.0004	0.0182	0.0408
EMS-M5-J32	1.0243	0.0004	0.0243	0.0412
EMS-M5-J33	1.0217	0.0004	0.0217	0.0406
IPPE-ABBN93	1.0144	0.0004	0.0144	

Table F139. Pu-ST-014 Case 1

ICSBEP benchmark	Pu-ST-014		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9980	0.0032		
EMS-S5-238	1.0077	0.0004	0.0097	0.1676
EMS-S5-27	1.0142	0.0005	0.0162	0.1415
EMS-S5-44	1.0084	0.0005	0.0104	0.1655
EMS-M5-E50	1.0116	0.0009	0.0136	0.1692
EMS-M5-E5F	1.0090	0.0009	0.0110	0.1697
EMS-M5-E62	1.0044	0.0009	0.0064	0.1696
EMS-M5-E66	1.0064	0.0004	0.0084	0.1661
EMS-M5-E68	1.0045	0.0010	0.0065	0.1664
EMS-M5-E7P	1.0049	0.0009	0.0069	0.1660
EMS-M5-F22	1.0117	0.0009	0.0137	0.1684
EMS-M5-F30	1.0072	0.0009	0.0092	0.1655
EMS-M5-J32	1.0093	0.0009	0.0113	0.1671
EMS-M5-J33	1.0081	0.0009	0.0101	0.1659
IPPE-ABBN93	1.0026	0.0010	0.0046	

Table F140. Pu-ST-014 Case 2

ICSBEP benchmark	Pu-ST-014		Case 2	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9980	0.0032		
EMS-S5-238	1.0058	0.0005	0.0078	0.1675
EMS-S5-27	1.0143	0.0005	0.0163	0.1414
EMS-S5-44	1.0072	0.0005	0.0092	0.1653
EMS-M5-E50	1.0094	0.0009	0.0114	0.1698
EMS-M5-E5F	1.0083	0.0009	0.0103	0.1695
EMS-M5-E62	1.0026	0.0009	0.0046	0.1692
EMS-M5-E66	1.0051	0.0009	0.0071	0.1658
EMS-M5-E68	1.0028	0.0009	0.0048	0.1661
EMS-M5-E7P	1.0041	0.0009	0.0061	0.1660
EMS-M5-F22	1.0089	0.0009	0.0109	0.1693
EMS-M5-F30	1.0038	0.0009	0.0058	0.1660
EMS-M5-J32	1.0067	0.0009	0.0087	0.1667
EMS-M5-J33	1.0066	0.0009	0.0086	0.1661
IPPE-ABBN93	1.0005	0.0010	0.0025	

Table F141. Pu-ST-015 Case 1

ICSBEP benchmark	Pu-ST-015		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9980	0.0038		
EMS-S5-238	1.0067	0.0005	0.0087	0.2374
EMS-S5-27	1.0170	0.0004	0.0190	0.2042
EMS-S5-44	1.0085	0.0005	0.0105	0.2349
EMS-M5-E50	1.0099	0.0007	0.0119	0.2414
EMS-M5-E5F	1.0093	0.0007	0.0113	0.2409
EMS-M5-E62	1.0016	0.0007	0.0036	0.2403
EMS-M5-E66	1.0052	0.0007	0.0072	0.2348
EMS-M5-E68	1.0040	0.0007	0.0060	0.2359
EMS-M5-E7P	1.0042	0.0007	0.0062	0.2354
EMS-M5-F22	1.0101	0.0007	0.0121	0.2389
EMS-M5-F30	1.0063	0.0007	0.0083	0.2351
EMS-M5-J32	1.0065	0.0007	0.0085	0.2378
EMS-M5-J33	1.0072	0.0007	0.0092	0.2356
IPPE-ABBN93	1.0025	0.0010	0.0045	

Table F142. Pu-ST-015 Case 2

ICSBEP benchmark	Pu-ST-015		Case 2	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9980	0.0038		
EMS-S5-238	1.0064	0.0005	0.0084	0.2372
EMS-S5-27	1.0152	0.0004	0.0172	0.2040
EMS-S5-44	1.0086	0.0005	0.0106	0.2349
EMS-M5-E50	1.0106	0.0007	0.0126	0.2403
EMS-M5-E5F	1.0078	0.0007	0.0098	0.2407
EMS-M5-E62	1.0029	0.0007	0.0049	0.2399
EMS-M5-E66	1.0047	0.0007	0.0067	0.2344
EMS-M5-E68	1.0031	0.0007	0.0051	0.2352
EMS-M5-E7P	1.0056	0.0007	0.0076	0.2362
EMS-M5-F22	1.0096	0.0007	0.0116	0.2394
EMS-M5-F30	1.0054	0.0007	0.0073	0.2350
EMS-M5-J32	1.0070	0.0007	0.0090	0.2376
EMS-M5-J33	1.0072	0.0007	0.0092	0.2357
IPPE-ABBN93	1.0006	0.0010	0.0026	

Table F142. Pu-ST-015 Case 2

ICSBEP benchmark	Pu-ST-015		Case 2	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	0.9980	0.0038		
EMS-S5-238	1.0064	0.0005	0.0084	0.2372
EMS-S5-27	1.0152	0.0004	0.0172	0.2040
EMS-S5-44	1.0086	0.0005	0.0106	0.2349
EMS-M5-E50	1.0106	0.0007	0.0126	0.2403
EMS-M5-E5F	1.0078	0.0007	0.0098	0.2407
EMS-M5-E62	1.0029	0.0007	0.0049	0.2399
EMS-M5-E66	1.0047	0.0007	0.0067	0.2344
EMS-M5-E68	1.0031	0.0007	0.0051	0.2352
EMS-M5-E7P	1.0056	0.0007	0.0076	0.2362
EMS-M5-F22	1.0096	0.0007	0.0116	0.2394
EMS-M5-F30	1.0054	0.0007	0.0073	0.2350
EMS-M5-J32	1.0070	0.0007	0.0090	0.2376
EMS-M5-J33	1.0072	0.0007	0.0092	0.2357
IPPE-ABBN93	1.0006	0.0010	0.0026	

Table F143. Pu-ST-022 Case 1

ICSBEP benchmark	Pu-ST-022		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0021		
EMS-S5-238	1.0011	0.0005	0.0011	0.2099
EMS-S5-27	1.0120	0.0004	0.0120	0.1789
EMS-S5-44	1.0041	0.0004	0.0041	0.2073
EMS-M5-E50	1.0042	0.0007	0.0042	0.2131
EMS-M5-E5F	1.0027	0.0007	0.0027	0.2127
EMS-M5-E62	0.9976	0.0007	-0.0024	0.2118
EMS-M5-E66	1.0004	0.0006	0.0004	0.2072
EMS-M5-E68	0.9983	0.0006	-0.0017	0.2077
EMS-M5-E7P	0.9993	0.0007	-0.0008	0.2085
EMS-M5-F22	1.0052	0.0006	0.0052	0.2115
EMS-M5-F30	1.0028	0.0006	0.0028	0.2073
EMS-M5-J32	1.0044	0.0007	0.0044	0.2092
EMS-M5-J33	1.0037	0.0006	0.0037	0.2076
IPPE-ABBN93	0.9948	0.0009	-0.0052	

The published ICSBEP 2004 sample input and results for the first nine benchmarks in Pu-ST-022, as calculated using MCNP4 and ENDF/B-V cross sections, are incorrect (about 1 %). Unfortunately, the older input on the CD-ROM contains other errors. The biases due to these errors have not been investigated.

Table F144. Pu-ST-022 Case 2

ICSBEP benchmark	Pu-ST-022		Case 2	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0018		
EMS-S5-238	1.0051	0.0005	0.0051	0.1311
EMS-S5-27	1.0126	0.0004	0.0126	0.1091
EMS-S5-44	1.0071	0.0004	0.0071	0.1292
EMS-M5-E50	1.0085	0.0006	0.0085	0.1332
EMS-M5-E5F	1.0074	0.0007	0.0074	0.1327
EMS-M5-E62	1.0026	0.0006	0.0026	0.1329
EMS-M5-E66	1.0028	0.0006	0.0028	0.1297
EMS-M5-E68	1.0027	0.0006	0.0027	0.1297
EMS-M5-E7P	1.0024	0.0007	0.0024	0.1302
EMS-M5-F22	1.0080	0.0006	0.0080	0.1329
EMS-M5-F30	1.0048	0.0007	0.0048	0.1299
EMS-M5-J32	1.0059	0.0007	0.0058	0.1311
EMS-M5-J33	1.0061	0.0006	0.0061	0.1301
IPPE-ABBN93	0.9960	0.0008	-0.0040	

Table F145. Pu-ST-022 Case 3

ICSBEP benchmark	Pu-ST-022		Case 3	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0017		
EMS-S5-238	1.0048	0.0004	0.0048	0.0840
EMS-S5-27	1.0104	0.0004	0.0104	0.0676
EMS-S5-44	1.0059	0.0004	0.0059	0.0821
EMS-M5-E50	1.0076	0.0006	0.0076	0.0848
EMS-M5-E5F	1.0081	0.0006	0.0081	0.0849
EMS-M5-E62	0.9999	0.0006	-0.0001	0.0849
EMS-M5-E66	1.0014	0.0006	0.0014	0.0832
EMS-M5-E68	1.0023	0.0006	0.0023	0.0830
EMS-M5-E7P	1.0017	0.0006	0.0017	0.0833
EMS-M5-F22	1.0064	0.0006	0.0064	0.0852
EMS-M5-F30	1.0030	0.0006	0.0030	0.0831
EMS-M5-J32	1.0060	0.0006	0.0060	0.0837
EMS-M5-J33	1.0039	0.0006	0.0038	0.0830
IPPE-ABBN93	0.9956	0.0008	-0.0044	

Table F146. Pu-ST-022 Case 4

ICSBEP benchmark	Pu-ST-022		Case 4	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0018		
EMS-S5-238	1.0055	0.0004	0.0055	0.0739
EMS-S5-27	1.0102	0.0004	0.0102	0.0589
EMS-S5-44	1.0074	0.0004	0.0074	0.0720
EMS-M5-E50	1.0098	0.0006	0.0098	0.0745
EMS-M5-E5F	1.0088	0.0006	0.0088	0.0744
EMS-M5-E62	1.0015	0.0006	0.0015	0.0746
EMS-M5-E66	1.0033	0.0006	0.0033	0.0730
EMS-M5-E68	1.0034	0.0006	0.0034	0.0731
EMS-M5-E7P	1.0035	0.0006	0.0035	0.0733
EMS-M5-F22	1.0059	0.0006	0.0059	0.0750
EMS-M5-F30	1.0031	0.0006	0.0031	0.0729
EMS-M5-J32	1.0079	0.0006	0.0079	0.0736
EMS-M5-J33	1.0060	0.0006	0.0060	0.0731
IPPE-ABBN93	0.9973	0.0008	-0.0027	

Table F147. Pu-ST-022 Case 5

ICSBEP benchmark	Pu-ST-022		Case 5	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0020		
EMS-S5-238	1.0064	0.0004	0.0064	0.0651
EMS-S5-27	1.0111	0.0004	0.0111	0.0514
EMS-S5-44	1.0084	0.0004	0.0084	0.0633
EMS-M5-E50	1.0089	0.0005	0.0089	0.0656
EMS-M5-E5F	1.0099	0.0006	0.0099	0.0653
EMS-M5-E62	1.0016	0.0006	0.0015	0.0657
EMS-M5-E66	1.0038	0.0006	0.0038	0.0643
EMS-M5-E68	1.0040	0.0006	0.0040	0.0643
EMS-M5-E7P	1.0037	0.0006	0.0037	0.0645
EMS-M5-F22	1.0059	0.0006	0.0059	0.0662
EMS-M5-F30	1.0045	0.0006	0.0045	0.0643
EMS-M5-J32	1.0086	0.0006	0.0086	0.0649
EMS-M5-J33	1.0055	0.0006	0.0055	0.0643
IPPE-ABBN93	0.9981	0.0007	-0.0019	

Table F148. Pu-ST-022 Case 6

ICSBEP benchmark	Pu-ST-022		Case 6	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0022		
EMS-S5-238	1.0073	0.0004	0.0072	0.0610
EMS-S5-27	1.0114	0.0003	0.0114	0.0480
EMS-S5-44	1.0091	0.0004	0.0091	0.0594
EMS-M5-E50	1.0105	0.0006	0.0105	0.0614
EMS-M5-E5F	1.0102	0.0005	0.0102	0.0613
EMS-M5-E62	1.0029	0.0006	0.0029	0.0616
EMS-M5-E66	1.0054	0.0006	0.0054	0.0604
EMS-M5-E68	1.0046	0.0005	0.0046	0.0604
EMS-M5-E7P	1.0038	0.0005	0.0038	0.0605
EMS-M5-F22	1.0074	0.0005	0.0074	0.0620
EMS-M5-F30	1.0046	0.0006	0.0046	0.0603
EMS-M5-J32	1.0093	0.0005	0.0093	0.0610
EMS-M5-J33	1.0071	0.0006	0.0071	0.0603
IPPE-ABBN93	0.9963	0.0007	-0.0037	

Table F149. Pu-ST-022 Case 7

ICSBEP benchmark	Pu-ST-022		Case 7	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0023		
EMS-S5-238	1.0092	0.0004	0.0092	0.0587
EMS-S5-27	1.0133	0.0004	0.0133	0.0460
EMS-S5-44	1.0109	0.0003	0.0109	0.0570
EMS-M5-E50	1.0118	0.0005	0.0117	0.0590
EMS-M5-E5F	1.0100	0.0005	0.0100	0.0591
EMS-M5-E62	1.0050	0.0006	0.0050	0.0593
EMS-M5-E66	1.0068	0.0005	0.0068	0.0578
EMS-M5-E68	1.0050	0.0005	0.0050	0.0581
EMS-M5-E7P	1.0057	0.0005	0.0057	0.0580
EMS-M5-F22	1.0077	0.0005	0.0077	0.0595
EMS-M5-F30	1.0059	0.0005	0.0059	0.0581
EMS-M5-J32	1.0104	0.0006	0.0104	0.0585
EMS-M5-J33	1.0074	0.0005	0.0074	0.0581
IPPE-ABBN93	0.9999	0.0007	-0.0001	

Table F150. Pu-ST-022 Case 8

ICSBEP benchmark	Pu-ST-022		Case 8	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0024		
EMS-S5-238	1.0095	0.0004	0.0095	0.0568
EMS-S5-27	1.0136	0.0003	0.0136	0.0444
EMS-S5-44	1.0113	0.0003	0.0113	0.0551
EMS-M5-E50	1.0124	0.0005	0.0124	0.0570
EMS-M5-E5F	1.0131	0.0005	0.0131	0.0571
EMS-M5-E62	1.0053	0.0005	0.0053	0.0572
EMS-M5-E66	1.0065	0.0005	0.0065	0.0563
EMS-M5-E68	1.0057	0.0005	0.0057	0.0563
EMS-M5-E7P	1.0062	0.0005	0.0062	0.0561
EMS-M5-F22	1.0085	0.0005	0.0085	0.0575
EMS-M5-F30	1.0066	0.0005	0.0066	0.0561
EMS-M5-J32	1.0117	0.0005	0.0117	0.0565
EMS-M5-J33	1.0095	0.0005	0.0095	0.0563
IPPE-ABBN93	1.0001	0.0007	0.0001	

Table F151. Pu-ST-022 Case 9

ICSBEP benchmark	Pu-ST-022		Case 9	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0025		
EMS-S5-238	1.0089	0.0004	0.0089	0.0552
EMS-S5-27	1.0121	0.0003	0.0121	0.0431
EMS-S5-44	1.0105	0.0003	0.0105	0.0536
EMS-M5-E50	1.0113	0.0005	0.0113	0.0556
EMS-M5-E5F	1.0103	0.0005	0.0103	0.0554
EMS-M5-E62	1.0038	0.0005	0.0038	0.0558
EMS-M5-E66	1.0053	0.0005	0.0053	0.0547
EMS-M5-E68	1.0052	0.0007	0.0052	0.0548
EMS-M5-E7P	1.0043	0.0005	0.0043	0.0547
EMS-M5-F22	1.0071	0.0006	0.0071	0.0559
EMS-M5-F30	1.0060	0.0005	0.0060	0.0547
EMS-M5-J32	1.0096	0.0005	0.0096	0.0550
EMS-M5-J33	1.0084	0.0005	0.0084	0.0546
IPPE-ABBN93	0.9987	0.0007	-0.0013	

Table F152. Pu-ST-025 Case 1

ICSBEP benchmark	Pu-ST-025		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0039		
EMS-S5-238	1.0160	0.0005	0.0160	0.0794
EMS-S5-27	1.0210	0.0005	0.0210	0.0641
EMS-S5-44	1.0176	0.0004	0.0176	0.0776
EMS-M5-E50	1.0181	0.0006	0.0181	0.0799
EMS-M5-E5F	1.0192	0.0006	0.0192	0.0801
EMS-M5-E62	1.0100	0.0006	0.0100	0.0803
EMS-M5-E66	1.0121	0.0006	0.0121	0.0788
EMS-M5-E68	1.0099	0.0006	0.0099	0.0790
EMS-M5-E7P	1.0120	0.0006	0.0120	0.0792
EMS-M5-F22	1.0153	0.0006	0.0153	0.0808
EMS-M5-F30	1.0100	0.0006	0.0000	0.0789
EMS-M5-J32	1.0150	0.0006	0.0150	0.0792
EMS-M5-J33	1.0148	0.0006	0.0148	0.0789
IPPE-ABBN93	1.0082	0.0008	0.0082	

Table F153. Pu-ST-025 Case 7

ICSBEP benchmark	Pu-ST-025		Case 7	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0038		
EMS-S5-238	1.0045	0.0004	0.0045	0.0844
EMS-S5-27	1.0113	0.0004	0.0113	0.0681
EMS-S5-44	1.0071	0.0004	0.0071	0.0824
EMS-M5-E50	1.0056	0.0006	0.0056	0.0854
EMS-M5-E5F	1.0050	0.0006	0.0050	0.0853
EMS-M5-E62	0.9986	0.0006	-0.0014	0.0853
EMS-M5-E66	1.0001	0.0006	0.0001	0.0837
EMS-M5-E68	0.9991	0.0006	-0.0009	0.0839
EMS-M5-E7P	0.9992	0.0006	-0.0008	0.0838
EMS-M5-F22	1.0029	0.0006	0.0029	0.0859
EMS-M5-F30	1.0004	0.0006	0.0000	0.0836
EMS-M5-J32	1.0047	0.0006	0.0047	0.0841
EMS-M5-J33	1.0032	0.0006	0.0032	0.0836
IPPE-ABBN93	0.9957	0.0008	-0.0043	

Table F154. Pu-ST-025 Case 14

ICSBEP benchmark	Pu-ST-025		Case 14	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0040		
EMS-S5-238	1.0020	0.0005	0.0020	0.1912
EMS-S5-27	1.0122	0.0004	0.0122	0.1629
EMS-S5-44	1.0066	0.0004	0.0066	0.1886
EMS-M5-E50	1.0055	0.0006	0.0055	0.1942
EMS-M5-E5F	1.0031	0.0006	0.0031	0.1948
EMS-M5-E62	0.9993	0.0006	-0.0007	0.1927
EMS-M5-E66	0.9996	0.0007	-0.0004	0.1898
EMS-M5-E68	1.0016	0.0007	0.0016	0.1891
EMS-M5-E7P	0.9999	0.0006	-0.0001	0.1898
EMS-M5-F22	1.0054	0.0006	0.0053	0.1929
EMS-M5-F30	1.0035	0.0006	0.0000	0.1895
EMS-M5-J32	1.0035	0.0006	0.0035	0.1903
EMS-M5-J33	1.0056	0.0006	0.0055	0.1894
IPPE-ABBN93	0.9910	0.0009	-0.0090	

Table F155. Pu-ST-025 Case 21

ICSBEP benchmark	Pu-ST-025		Case 21	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0044		
EMS-S5-238	1.0002	0.0004	0.0002	0.2463
EMS-S5-27	1.0113	0.0004	0.0113	0.2117
EMS-S5-44	1.0026	0.0004	0.0026	0.2434
EMS-M5-E50	1.0002	0.0006	0.0002	0.2505
EMS-M5-E5F	0.9989	0.0006	-0.0011	0.2512
EMS-M5-E62	0.9950	0.0006	-0.0051	0.2496
EMS-M5-E66	0.9964	0.0006	-0.0036	0.2447
EMS-M5-E68	0.9961	0.0006	-0.0039	0.2450
EMS-M5-E7P	0.9979	0.0006	-0.0021	0.2448
EMS-M5-F22	1.0022	0.0006	0.0022	0.2487
EMS-M5-F30	0.9981	0.0007	0.0000	0.2437
EMS-M5-J32	0.9987	0.0006	-0.0013	0.2461
EMS-M5-J33	1.0011	0.0006	0.0011	0.2455
IPPE-ABBN93	0.9940	0.0009	-0.0060	

Table F156. Pu-ST-025 Case 28

ICSBEP benchmark	Pu-ST-025		Case 28	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0048		
EMS-S5-238	0.9961	0.0005	-0.0039	0.3594
EMS-S5-27	1.0094	0.0004	0.0094	0.3152
EMS-S5-44	1.0004	0.0004	0.0004	0.3560
EMS-M5-E50	0.9996	0.0006	-0.0004	0.3673
EMS-M5-E5F	0.9954	0.0006	-0.0046	0.3688
EMS-M5-E62	0.9919	0.0006	-0.0081	0.3642
EMS-M5-E66	0.9924	0.0006	-0.0076	0.3567
EMS-M5-E68	0.9922	0.0006	-0.0078	0.3574
EMS-M5-E7P	0.9946	0.0006	-0.0054	0.3598
EMS-M5-F22	0.9982	0.0006	-0.0018	0.3632
EMS-M5-F30	0.9952	0.0006	0.0000	0.3559
EMS-M5-J32	0.9983	0.0006	-0.0017	0.3601
EMS-M5-J33	0.9976	0.0006	-0.0024	0.3588
IPPE-ABBN93	0.9903	0.0008	-0.0097	

Table F157. Pu-ST-025 Case 34

ICSBEP benchmark	Pu-ST-025		Case 34	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0049		
EMS-S5-238	0.9972	0.0005	-0.0028	0.4482
EMS-S5-27	1.0117	0.0004	0.0117	0.3933
EMS-S5-44	1.0012	0.0004	0.0012	0.4437
EMS-M5-E50	0.9977	0.0003	-0.0023	0.4577
EMS-M5-E5F	0.9977	0.0006	-0.0023	0.4586
EMS-M5-E62	0.9946	0.0006	-0.0054	0.4523
EMS-M5-E66	0.9958	0.0007	-0.0042	0.4468
EMS-M5-E68	0.9947	0.0006	-0.0053	0.4453
EMS-M5-E7P	0.9966	0.0007	-0.0034	0.4433
EMS-M5-F22	1.0002	0.0006	0.0002	0.4491
EMS-M5-F30	0.9994	0.0006	0.0000	0.4439
EMS-M5-J32	0.9989	0.0007	-0.0011	0.4490
EMS-M5-J33	1.0065	0.0006	0.0065	0.4457
IPPE-ABBN93	0.9949	0.0008	-0.0051	

Table F158. Pu-ST-025 Case 39

ICSBEP benchmark	Pu-ST-025		Case 39	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0060		
EMS-S5-238	0.9946	0.0004	-0.0054	1.1367
EMS-S5-27	1.0118	0.0004	0.0118	1.0226
EMS-S5-44	1.0005	0.0004	0.0005	1.1238
EMS-M5-E50	0.9943	0.0006	-0.0057	1.1717
EMS-M5-E5F	0.9937	0.0006	-0.0063	1.1727
EMS-M5-E62	0.9917	0.0006	-0.0083	1.1438
EMS-M5-E66	0.9937	0.0006	-0.0063	1.1289
EMS-M5-E68	0.9943	0.0006	-0.0057	1.1328
EMS-M5-E7P	0.9935	0.0006	-0.0065	1.1311
EMS-M5-F22	0.9979	0.0006	-0.0021	1.1322
EMS-M5-F30	0.9986	0.0006	0.0000	1.1289
EMS-M5-J32	0.9956	0.0006	-0.0044	1.1331
EMS-M5-J33	0.9986	0.0006	-0.0014	1.1289
IPPE-ABBN93	0.9923	0.0008	-0.0078	

Table F159. Pu-ST-026 Case 1

ICSBEP benchmark	Pu-ST-026		Case 1	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0052		
EMS-S5-238	0.9967	0.0006	-0.0033	0.0890
EMS-S5-27	1.0033	0.0005	0.0033	0.0721
EMS-S5-44	0.9985	0.0005	-0.0015	0.0871
EMS-M5-E50	1.0026	0.0007	0.0026	0.0897
EMS-M5-E5F	1.0032	0.0007	0.0032	0.0897
EMS-M5-E62	0.9963	0.0007	-0.0037	0.0900
EMS-M5-E66	0.9953	0.0007	-0.0047	0.0881
EMS-M5-E68	0.9977	0.0007	-0.0023	0.0882
EMS-M5-E7P	0.9972	0.0006	-0.0028	0.0884
EMS-M5-F22	1.0015	0.0007	0.0015	0.0901
EMS-M5-F30	0.9966	0.0007	0.0000	0.0882
EMS-M5-J32	0.9977	0.0007	-0.0023	0.0888
EMS-M5-J33	0.9988	0.0007	-0.0012	0.0880
IPPE-ABBN93	0.9924	0.0004	-0.0076	

Table F160. Pu-ST-026 Case 4

ICSBEP benchmark	Pu-ST-026		Case 4	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0045		
EMS-S5-238	0.9969	0.0005	-0.0031	0.0941
EMS-S5-27	1.0037	0.0005	0.0037	0.0761
EMS-S5-44	0.9997	0.0004	-0.0003	0.0920
EMS-M5-E50	1.0014	0.0006	0.0014	0.0949
EMS-M5-E5F	1.0003	0.0006	0.0003	0.0949
EMS-M5-E62	0.9939	0.0007	-0.0061	0.0950
EMS-M5-E66	0.9948	0.0007	-0.0052	0.0931
EMS-M5-E68	0.9959	0.0006	-0.0041	0.0933
EMS-M5-E7P	0.9965	0.0006	-0.0035	0.0933
EMS-M5-F22	0.9993	0.0007	-0.0007	0.0953
EMS-M5-F30	0.9965	0.0007	0.0000	0.0930
EMS-M5-J32	0.9978	0.0007	-0.0022	0.0935
EMS-M5-J33	1.0005	0.0006	0.0005	0.0931
IPPE-ABBN93	0.9909	0.0004	-0.0091	

Table F161. Pu-ST-026 Case 9

ICSBEP benchmark	Pu-ST-026		Case 9	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0049		
EMS-S5-238	0.9987	0.0005	-0.0013	0.2478
EMS-S5-27	1.0093	0.0005	0.0093	0.2120
EMS-S5-44	0.9996	0.0004	-0.0004	0.2451
EMS-M5-E50	1.0007	0.0007	0.0007	0.2509
EMS-M5-E5F	0.9999	0.0007	-0.0001	0.2515
EMS-M5-E62	0.9964	0.0006	-0.0036	0.2490
EMS-M5-E66	0.9983	0.0007	-0.0017	0.2443
EMS-M5-E68	0.9977	0.0007	-0.0023	0.2444
EMS-M5-E7P	0.9983	0.0007	-0.0017	0.2444
EMS-M5-F22	1.0049	0.0007	0.0049	0.2478
EMS-M5-F30	1.0014	0.0007	0.0000	0.2438
EMS-M5-J32	1.0010	0.0007	0.0010	0.2463
EMS-M5-J33	1.0008	0.0007	0.0008	0.2457
IPPE-ABBN93	0.9953	0.0004	-0.0047	

Table F162. Pu-ST-026 Case 15

ICSBEP benchmark	Pu-ST-026		Case 15	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0046		
EMS-S5-238	0.9883	0.0005	-0.0117	0.3252
EMS-S5-27	1.0004	0.0004	0.0004	0.2809
EMS-S5-44	0.9903	0.0004	-0.0097	0.3221
EMS-M5-E50	0.9899	0.0007	-0.0101	0.3304
EMS-M5-E5F	0.9907	0.0007	-0.0093	0.3308
EMS-M5-E62	0.9863	0.0007	-0.0137	0.3279
EMS-M5-E66	0.9885	0.0007	-0.0115	0.3220
EMS-M5-E68	0.9880	0.0007	-0.0120	0.3199
EMS-M5-E7P	0.9888	0.0007	-0.0112	0.3208
EMS-M5-F22	0.9936	0.0007	-0.0064	0.3235
EMS-M5-F30	0.9920	0.0007	0.0000	0.3204
EMS-M5-J32	0.9917	0.0007	-0.0083	0.3231
EMS-M5-J33	0.9927	0.0007	-0.0073	0.3215
IPPE-ABBN93	0.9863	0.0004	-0.0137	

Table F163. Pu-ST-026 Case 17

ICSBEP benchmark	Pu-ST-026		Case 17	
Method	k_{eff}	σ	Bias	EALF (eV)
Benchmark	1.0000	0.0050		
EMS-S5-238	0.9930	0.0005	-0.0070	0.5252
EMS-S5-27	1.0070	0.0005	0.0070	0.4611
EMS-S5-44	0.9962	0.0004	-0.0038	0.5205
EMS-M5-E50	0.9948	0.0007	-0.0052	0.5356
EMS-M5-E5F	0.9964	0.0007	-0.0036	0.5338
EMS-M5-E62	0.9906	0.0007	-0.0094	0.5292
EMS-M5-E66	0.9930	0.0007	-0.0070	0.5171
EMS-M5-E68	0.9919	0.0007	-0.0081	0.5162
EMS-M5-E7P	0.9929	0.0007	-0.0071	0.5165
EMS-M5-F22	0.9974	0.0007	-0.0026	0.5209
EMS-M5-F30	0.9942	0.0007	0.0000	0.5147
EMS-M5-J32	0.9964	0.0007	-0.0037	0.5224
EMS-M5-J33	0.9972	0.0007	-0.0028	0.5206
IPPE-ABBN93	0.9909	0.0004	-0.0091	

Appendix G

REFERENCE VALUES FOR UO₂, UNH, PUO₂ AND UNH

The 132 reference values (30 UO₂, 30 UNH, 36 PuO₂ and 36 PuNH) selected by the Expert Group include minimum critical values for mass, volume, cylinder diameter, slab thickness and fissionable element (uranium and plutonium) concentration as well as the maximum critical values for moderation. Water is the only moderation (besides the fissionable material itself) and reflection material to be considered.

The chemical materials are uranium dioxide (UO₂), uranium nitrate (UNH), plutonium dioxide (PuO₂) and plutonium nitrate (PuNH). The nitrates are crystals with water molecules included. The addition of water to the nitrates is assumed to lead to solutions and mixtures (above the saturation point for solutions). The oxides are not soluble in water and mixtures are assumed. All mixtures and solutions are homogeneous and uniform.

The uranium isotopes are ²³⁵U and ²³⁸U. The considered isotopic distributions are specified with the mass percentage of ²³⁵U in total uranium in the form U(X) where X is 100, 20, 5, 4 and 3.

The plutonium isotopes considered are ²³⁹Pu, ²⁴⁰Pu, ²⁴¹Pu and ²⁴²Pu. The considered isotopic distributions are specified with the mass percentages of each isotope in total plutonium in the form Pu(P9/P0/P1/P2). P9/P0/P1/P2 were selected as 100/0/0/0, 95/5/0/0, 80/10/10/0, 90/10/0/0, 80/15/5/0 and 71/17/11/1. Trailing zeros in the isotope distribution may be dropped, e.g. 95/5.

The fissile properties determine the order of the reference values in the tables in this report. All plutonium isotopes can support criticality on their own, but only ²³⁹Pu and ²⁴¹Pu are fissile. Since ²⁴¹Pu is “more” fissile than ²³⁹Pu, applications with the distribution 80/10/10/0 come before those with the distribution 90/10/0/0. In one case, for slabs, the 80/10/10/0 distribution gives a smaller critical thickness than the distribution 95/5/0/0.

The charts follow a similar format. Two groups of values are plotted individually for each method. One group (blue diamonds) contains the raw data while the other group contains bias-corrected results (purple), when available. There are further 4 average values (lines): the “Major 6” (or “Major 5”) best estimate bias-corrected average (purple line), the “Major 6” average for the raw data from the methods used in the best-estimate evaluation (dashed black line), the bias-corrected average (green dashed/dotted line) and the raw data average (black dotted line). The best-estimate methods are normally selected from the “major 6”: EMSM5E7P(or E68 when E7P results are not available), EMSM5F30, EMSM5J33, EMSS5K238, Serco-Mk8-F22 and IPPE-ABBN93 (or IPPE-ABBN93).

◆	Raw data
■	Best estimate
—	Major 5 - Best
- - -	Major 5 - Raw
.....	Raw mean
- . . . -	Best mean

Consideration of other results is taken, including raw data from IRSN. SERCO results will sometimes be weighted higher, sometimes lower than the MCNP results. If the selection of benchmarks is particularly questionable, all the EMS results will be weighted lower. This includes the plutonium systems since there was no effort in separating the Pu isotopic distribution influence. The SCALE 5 results using XSDRNPM are not included in the averages; the KENOv results are preferable (almost identical). The EMS-S4X-238 (EMS-S4X-238) individual results are shown but they are not included in the best-estimate average.

The charts for the critical moderation contain very few values. They may be added during final editing of the report. From an evaluation point of view, they are not different than the concentration evaluation. The mean value only contains one of the SCALE results when two such values were submitted.

Some common notes for the tables follow:

1. It is pointed out that the bias-corrections involve codes and cross-sections only. Other important input data such as atomic number densities and optimum moderation are not validated and the results are not bias-corrected for such errors. Some of the agreement between the many EMS methods must be attributed to the fact that the same atomic number densities and optimum moderation values were used. A simple statistical treatment of the reported values is thus not sufficient. The values are correlated. However, there is a significant benefit in this; the influence of different cross-sections can be identified clearly.
2. For plutonium reference values, the Pu isotopic distributions probably cause different bias trends. In the EMS evaluations of benchmarks, there was no effort to identify such trends. At least some methods seem to give significant differences (seen by comparisons of benchmarks PuMF001 and PuST002). This would be an important task for a continued study.
3. Both Monte Carlo (KENOv) and deterministic (XSDRNPM) codes from SCALE 5 were used to calculate reference values and critical experiment benchmarks. The same cross-section libraries were used and, even though the codes may treat them differently, the results show that with proper convergence, mesh and angular quadrature, the results are essentially identical. However, the bias corrections are mostly based on KENOv calculations. Since the KENOv statistical uncertainty is assumed to be less significant than the additional XSDRNPM “accuracy” bias (due to default or other input specifications), the KENOv results are considered slightly more reliable when there are differences.
4. The EMS-S4X-238 calculation biases were based on an ORNL report intended for criticality safety application. Those biases are lumped together without weighting of benchmark accuracy and correlation between benchmarks. The new biases, determined with SCALE5 and the same cross-section library, are considered more appropriate for the determination of reference values. Further, the input specifications for SCALE5 calculations lead to better accuracy.

5. The EMS-S4X-238 calculation uncertainties were based on the same ORNL report as the biases. The very wide coverage of different experiments in each group causes large uncertainties. Those uncertainties are not representative for the final reference values in this report.
6. Six methods are high-lighted (3 yellow for MCNP with the latest cross-section library releases), 1 blue for SCALE5 with 238 group cross-sections, one red for Serco-Mk8-F22 MONK calculations and green for IPPE-ABBN93). The 238-group library is old but the results are important since the validation process was different than from MCNP5 and MONK calculations. These six methods will be given almost full weighting to determine best-estimate reference values. Some of the MONK results are deviating significantly from other results. In such cases, they will not be included in the average. As long as the reasons for the deviations are not evaluated and understood, the odd results can't be rejected with full confidence if the application concerns safety.
7. The JAERI results are bias-corrected and the k_{eff} biases are given in the Japanese Handbook. It would however require too much time to recreate calculated values based on the biases. There often seems to be problems with the Japanese handbook bias-corrected results. A known reason is that the JAERI Handbook results are based on validation with benchmarks that were not as well documented as in the ICSBEP Handbook. The biases in the benchmarks, as known today, were not considered.
8. The JAERI results sometimes agree with the bias-corrected EMS-S4X-238 results, while being far off from other results. This is interesting. Both the JAERI and the EMS-S4X-238 (borrowed from the ORNL report that also ORNL refers to for its validation) validations are based on a very large number of different types of benchmarks. In both cases, the purpose of the validations is application to criticality safety, not determination of physical constants (the objective of the Expert Group study). This confirms the conclusion that the selection of benchmarks is very important for getting accurate results.
9. The maximum critical moderation H/X where X is a fissile element (U or Pu) was requested and some results are reported. The calculations are identical to those for minimum critical concentration. During the final evaluation it was considered less important to calculate those values since the information is already there (in the concentration results), indirectly. Otherwise the H/X ratio is more interesting than the concentration since it is not density dependent.
10. It is very likely that significant editorial mistakes are contributing to discrepancies. Time and resources do not allow for a check of each deviation, but some discrepancies were resolved during the evaluation.
11. Different selections of benchmarks for validation lead to different biases, even for identical methods. The validation processes for different methods need further comparison and evaluation.

12. Different fissile systems for the same reference value may be caused by different atomic number density calculation methods, in particular for solutions at high fissile densities, and by differences in the optimisations of moderation.
13. SCALE 4 and SCALE 5 have been used in several methods. Three of them (ORNL, EMS-S4X-238 and EMS-S5X-238) use the 238-group cross section library and the XSDRNPM deterministic code in SCALE. The ORNL and EMS-S4X-238 results are usually very similar. The convergence criteria in SCALE 4.4 were used in EMS-S4X-238 but were improved in ORNL and in EMS SCALE 5 calculations. A discrepancy for U(3)O₂ mass was explained through the use of different optimisation approaches. The ORNL result is based on the nearest calculation value while the EMS-S4X-238 result is based on a “curved” interpolation. The ORNL report containing the data shows that the EMS-S4X-238 result is better optimised. A separate calculation during this evaluation confirmed this conclusion. The EMS-S5X-238 results sometimes differ from the EMS-S4X-238 and ORNL results for other reasons. A major reason is that the angular quadrature was increased in many cases (particularly important for spheres of fast systems). Another major reason is that the number of mesh points was increased (particularly important for slabs in fast systems). Monte Carlo calculations with KENOv, as reported for the methods EMS-S5K-238, -27 and -44 confirmed that the new XSDRNPM results are much better.
14. The number of significant digits for the reference values has been determined from the target of having a precision corresponding to a reactivity of 1 mk (0.001 in keff). Values reported by participants that have more significant digits have been rounded.
15. IRSN and ORNL results are reported in the “raw” data column. It is pointed out that these methods are very well validated for criticality safety application. The IRSN results for many systems are more accurate than the bias-corrected results from some other methods.
16. The EMS-S4X-238 uncertainties are based on actual calculations corresponding to the reported biases in k_{eff} . This explains why the positive and negative reference value biases are different even though the k_{eff} biases are identical. The relationships between keff and the reference parameters are not linear (“curved”). These uncertainties could be compared with the more crude linear bias-corrections used for other methods. A future study should determine the bias-corrections either from a direct calculation at the critical point, or from a curve that correctly ties k_{eff} to each reference parameter.
17. For low-density fissionable element systems, the differences between oxide and nitrate results should be small and the differences between methods should be consistent. Above the solution saturation points, more investigation is needed.
18. The MCNP5 release 1.30 includes preliminary ENDF/B-VII cross-sections for some nuclides. Of the Pu isotopes only ²³⁹Pu is included. For this reason, the reference values for other Pu distributions than the pure ²³⁹Pu were not calculated with this library. It would have been meaningful, but more complicated to evaluate such calculations. The most

recent ENDF/B-VI cross-section release available will then be 8. The yellow marking for EMSM5E7P will be taken over by EMSM5E68 in those tables.

19. The MCNP5 calculations with ENDF/B-V cross sections were first carried out using the .50c set for ^{239}Pu . During the evaluation, it was noticed that the ICSBEP evaluations for the Handbook often (not always) used the .55c set for ^{239}Pu , keeping the .50c sets for other fissionable nuclides. Comparisons showed that the differences were very large for fast systems. A decision was made to add calculations for this combination (.55c for ^{239}Pu and .50c for all other nuclides). It is referred to as EMS-M5-E5F (Final). Russ Mosteller at LANL kindly explained that the .50c set for ^{239}Pu was an interim set, while the .55c was the final. This is obvious to experienced users of MCNP with ENDF/B-V cross sections. For SCALE cross-section libraries based on ENDF/B-V (238-group and 44-group) there is no option for choosing between these two ^{239}Pu sets.
20. Some of the large deviations from the average for bias-corrected values may depend on large corrections, for which the linear corrections are not valid.

UO₂ reference values

Figure G1. U(100)O₂ – Mass

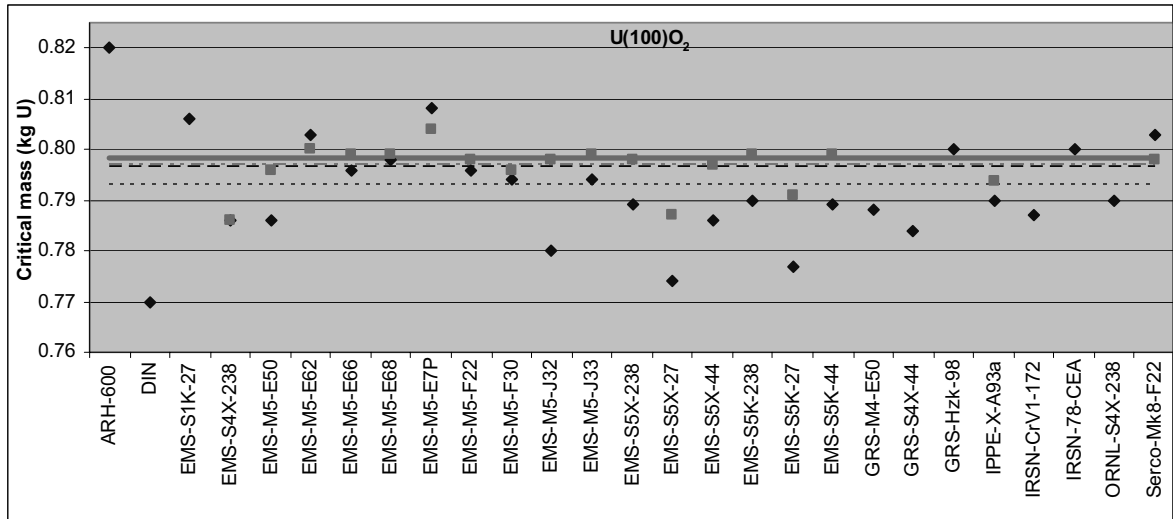


Figure G2. U(100)O₂ – Volume

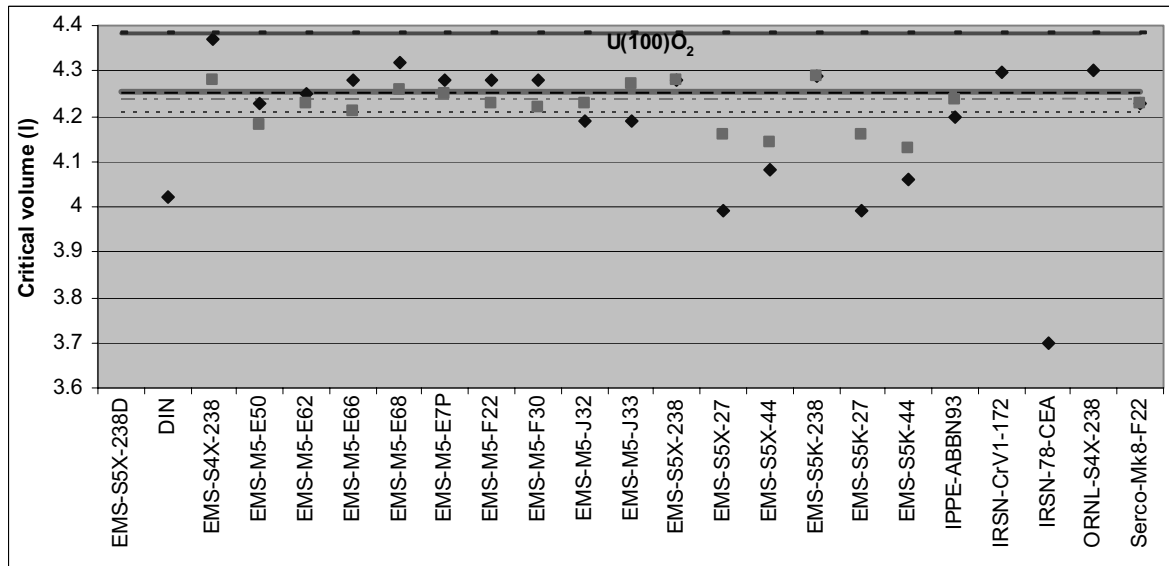


Table G1. Mass – U(100)O₂

Critical mass for H ₂ O-reflected U(100)O ₂ + H ₂ O systems			
EALF = 0.0413	Mass (kg U)		
Source	Raw data	Best-estimate	2 σ
ARH-600	0.82		
DIN	0.77		
EMS-S4X-238	0.786	0.786)	+0.075/-0.067)
EMS-M5-E50	0.786	0.796	
EMS-M5-E62	0.803	0.800	
EMS-M5-E66	0.796	0.799	
EMS-M5-E68	0.798	0.799	
EMS-M5-E7P	0.808	0.804	
EMS-M5-F22	0.796	0.798	
EMS-M5-F30	0.794	0.796	
EMS-M5-J32	0.780	0.798	
EMS-M5-J33	0.794	0.799	
EMS-S5X-238	0.789	0.798	
EMS-S5X-27	0.774	0.787	
EMS-S5X-44	0.786	0.797	
EMS-S5K-238	0.790	0.799	
EMS-S5K-27	0.777	0.791	
EMS-S5K-44	0.789	0.799	
GRS-M4-E50	0.788		
GRS-S4X-44	0.784		
GRS-HzK-98	0.8		
IPPE-ABBN93	0.790	0.794	
IRSN-CrV1-172	0.787		
IRSN-78-CEA	0.80*		
ORNL-S4X-238	0.79		
Serco-Mk8-F22	0.803	0.798	1.8%

Table G2. Volume for U(100)O₂

Critical volume for H ₂ O-reflected U(100)O ₂ + H ₂ O systems			
EALF = 11153	Volume (l)		
Source	Raw data	Best-estimate	2 σ
DIN	4.02		
EMS-S4X-238	4.37	4.28)	+0.19/-0.18)
EMS-M5-E50	4.23	4.18	
EMS-M5-E62	4.25	4.23	
EMS-M5-E66	4.28	4.21	
EMS-M5-E68	4.32	4.26	
EMS-M5-E7P	4.28	4.25	
EMS-M5-F22	4.28	4.23	
EMS-M5-F30	4.28	4.22	
EMS-M5-J32	4.19	4.23	
EMS-M5-J33	4.19	4.27	
EMS-S5X-238	4.28	4.28	
EMS-S5X-27	3.99	4.16	
EMS-S5X-44	4.08	4.14	
EMS-S5K-238	4.29	4.29	
EMS-S5K-27	3.99	4.16	
EMS-S5K-44	4.06	4.13	
IPPE-ABBN93	4.2	4.24	
IRSN-CrV1-172	4.30		
IRSN-78-CEA	3.7*		
ORNL-S4X-238	4.3		
Serco-Mk8-F22	4.23	4.23	0.6%

* Extrapolation in Figure U.1

* Extrapolation in Figure U-2

Figure G3. U(100)O₂ – Cylinder diameter

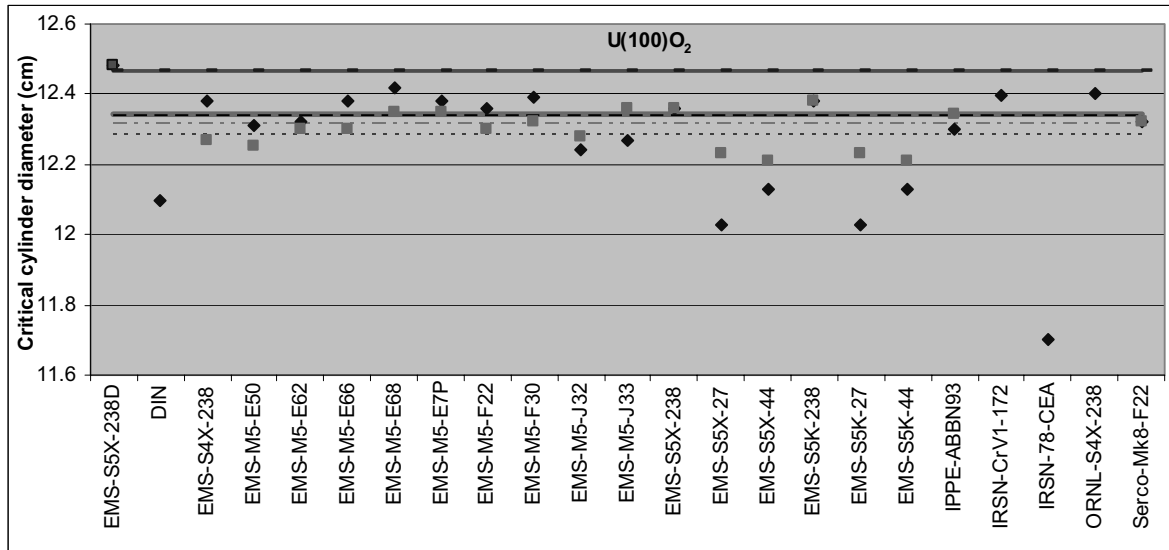


Figure G4. U(100)O₂ – Slab thickness

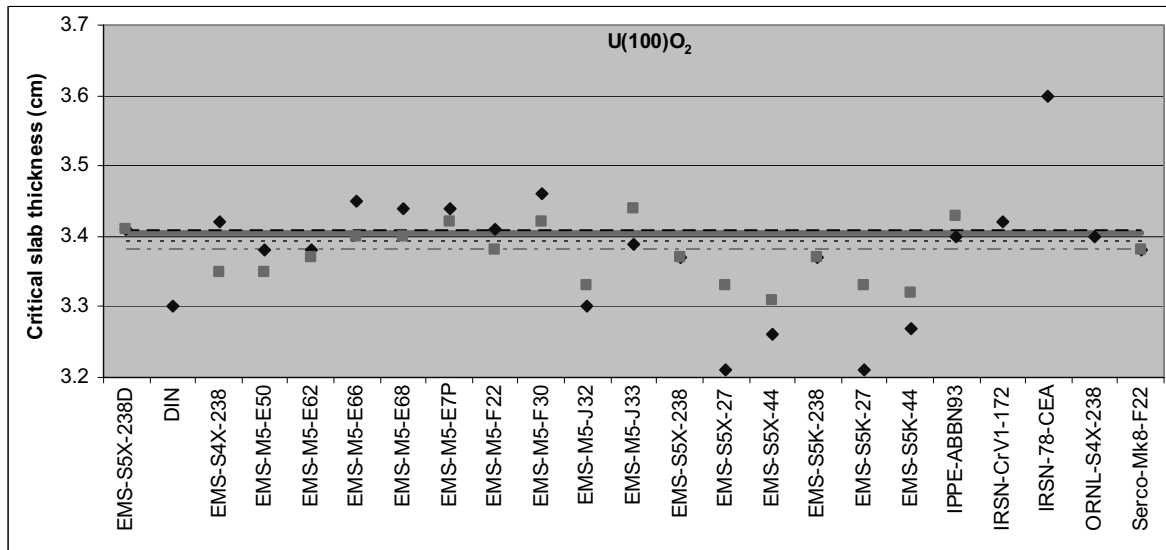


Table G3. Cylinder diameter U(100)O₂

Critical cylinder diameter for H ₂ O-reflected U(100)O ₂ + H ₂ O systems			
EALF = 4599	Cylinder diameter (cm)		
Source	Raw data	Best-estimate	2 σ
DIN	12.1		
EMS-S4X-238	12.38	12.27)	+0.22/-0.22
EMS-M5-E50	12.31	12.25	
EMS-M5-E62	12.32	12.30	
EMS-M5-E66	12.38	12.30	
EMS-M5-E68	12.42	12.35	
EMS-M5-E7P	12.38	12.35	
EMS-M5-F22	12.36	12.30	
EMS-M5-F30	12.39	12.32	
EMS-M5-J32	12.24	12.28	
EMS-M5-J33	12.27	12.36	
EMS-S5X-238	12.36	12.36	
EMS-S5X-27	12.03	12.23	
EMS-S5X-44	12.13	12.21	
EMS-S5K-238	12.38	12.38	
EMS-S5K-27	12.03	12.23	
EMS-S5K-44	12.13	12.21	
IPPE-ABBN93	12.3	12.34	
IRSN-CrV1-172	12.40		
IRSN-78-CEA	11.7*		
ORNL-S4X-238	12.4		
Serco-Mk8-F22	12.32	12.32	0.2%

Table G4. Slab thickness U(100)O₂

Critical slab thickness for H ₂ O-reflected U(100)O ₂ + H ₂ O systems			
EALF = 385	Slab thickness (cm)		
Source	Raw data	Best-estimate	2 σ
DIN	3.3		
EMS-S4X-238	3.42	3.35)	+0.14/-0.13
EMS-M5-E50	3.38	3.35	
EMS-M5-E62	3.38	3.37	
EMS-M5-E66	3.45	3.40	
EMS-M5-E68	3.44	3.40	
EMS-M5-E7P	3.44	3.42	
EMS-M5-F22	3.41	3.38	
EMS-M5-F30	3.46	3.42	
EMS-M5-J32	3.30	3.33	
EMS-M5-J33	3.39	3.44	
EMS-S5X-238	3.37	3.37	
EMS-S5X-27	3.21	3.33	
EMS-S5X-44	3.26	3.31	
EMS-S5K-238	3.37	3.37	
EMS-S5K-27	3.21	3.33	
EMS-S5K-44	3.27	3.32	
IPPE-ABBN93	3.4	3.43	
IRSN-CrV1-172	3.42		
IRSN-78-CEA	3.6*		
ORNL-S4X-238	3.4		
Serco-Mk8-F22	3.38	3.38	0.4%

* Extrapolation in Figure U-3

* Extrapolation in Figure U-4

Figure G5. $U(100)O_2$ – Concentration

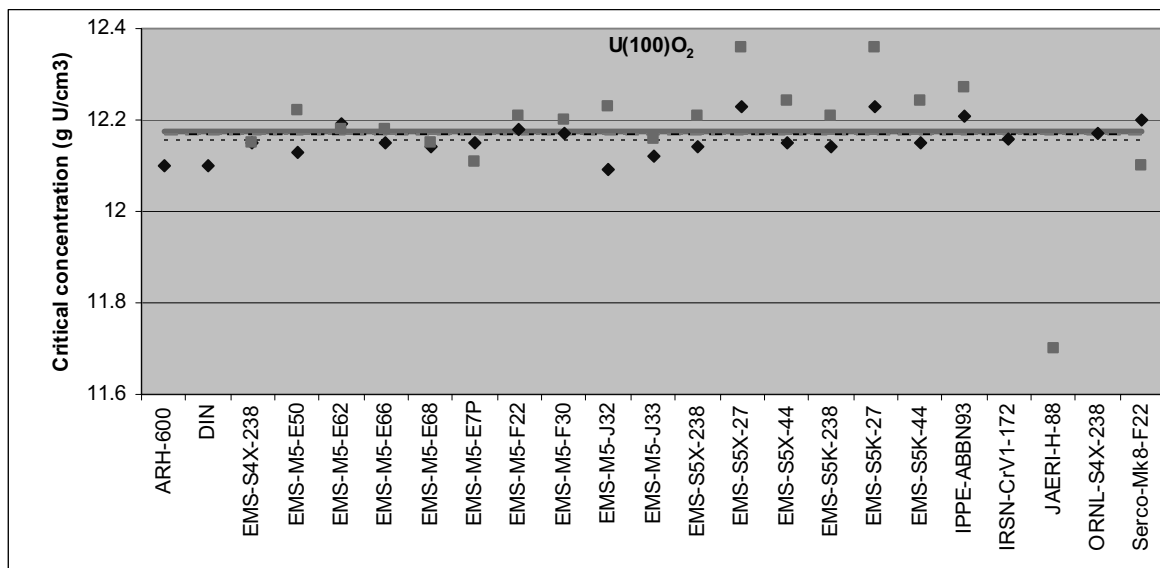


Figure G6. $U(100)O_2$ – Moderation H/U

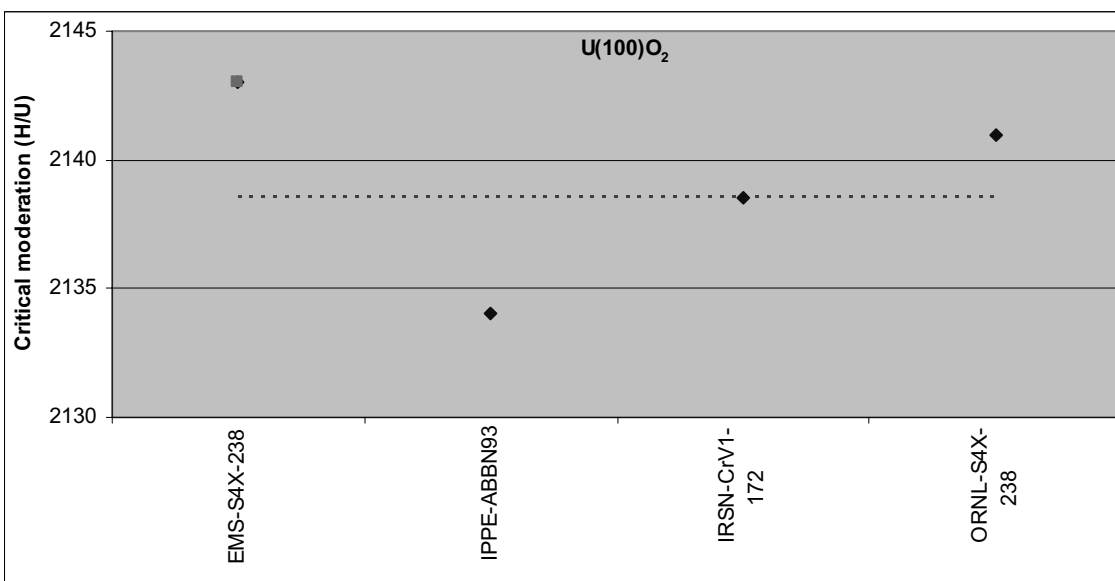


Table G5. Concentration – U(100)O₂

Critical concentration for H₂O-reflected U(100)O₂ + H₂O systems			
EALF = 0.0305	U concentration (g/cm ³)		
Source	Raw data	Best- estimate	2 σ
ARH-600	12.1		
DIN	12.1		
EMS-S4X-238	12.15	12.15)	+0.48/-0.47
EMS-M5-E50	12.13	12.22	
EMS-M5-E62	12.19	12.18	
EMS-M5-E66	12.15	12.18	
EMS-M5-E68	12.14	12.15	
EMS-M5-E7P	12.15	12.11	
EMS-M5-F22	12.18	12.21	
EMS-M5-F30	12.17	12.20	
EMS-M5-J32	12.09	12.23	
EMS-M5-J33	12.12	12.16	
EMS-S5X-238	12.14	12.21	
EMS-S5X-27	12.23	12.36	
EMS-S5X-44	12.15	12.24	
EMS-S5K-238	12.14	12.21	
EMS-S5K-27	12.23	12.36	
EMS-S5K-44	12.15	12.24	
IPPE-ABBN93	12.21	12.27	
IRSN-CrV1-172	12.16		
JAERI-H-88		11.7	
ORNL-S4X-238	12.17		
Serco-Mk8-F22	12.2	12.1	0.8%

Table G6. Moderation U(100)O₂

Critical moderation for H₂O-reflected U(100)O₂ + H₂O systems			
EALF = 0.0305	Moderation (H/U)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	2143	2143)	-82/ +85
IPPE-ABBN93	2134		
IRSN-CrV1-172	2139		
ORNL-S4X-238	2141		

Figure G7. $U(20)O_2$ – Mass

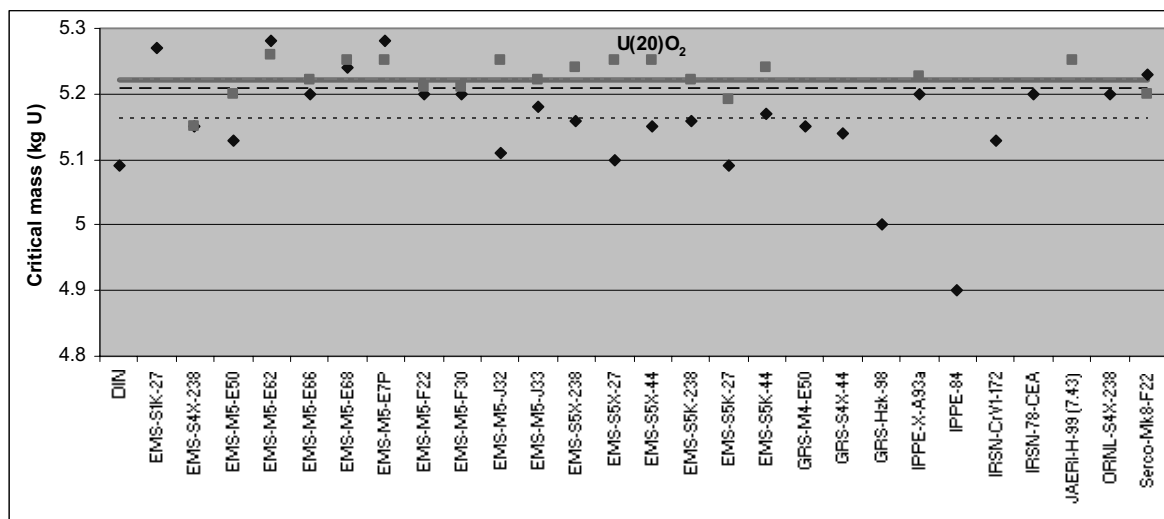


Figure G8. $U(20)O_2$ – Volume

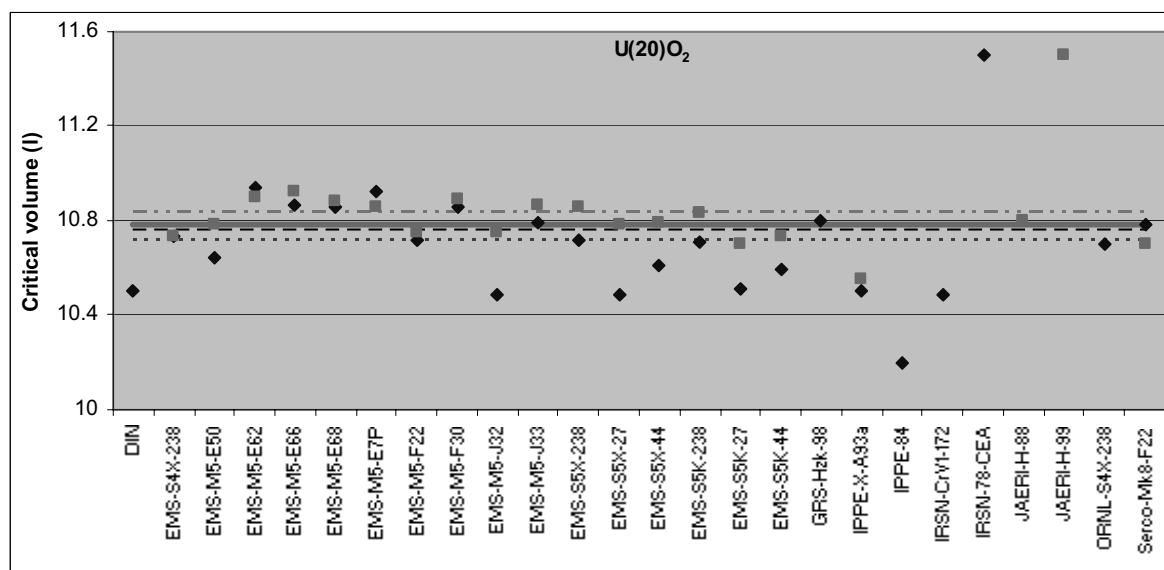


Table G7. Uranium mass – U(20)O₂

Critical mass for H ₂ O-reflected U(20)O ₂ + H ₂ O systems			
EALF = 0.0434	Mass (kg U)		
Source	Raw data	Best-estimate	2 σ
DIN	5.09		
EMS-S1K-27	5.27		
EMS-S4X-238	5.15	5.15)	+0.55/-0.49
EMS-M5-E50	5.13	5.20	
EMS-M5-E62	5.28	5.26	
EMS-M5-E66	5.20	5.22	
EMS-M5-E68	5.24	5.25	
EMS-M5-E7P	5.28	5.25	
EMS-M5-F22	5.20	5.21	
EMS-M5-F30	5.20	5.21	
EMS-M5-J32	5.11	5.25	
EMS-M5-J33	5.18	5.22	
EMS-S5X-238	5.16	5.24	
EMS-S5X-27	5.10	5.25	
EMS-S5X-44	5.15	5.25	
EMS-S5K-238	5.16	5.22	
EMS-S5K-27	5.09	5.19	
EMS-S5K-44	5.17	5.24	
GRS-M4-E50	5.15		
GRS-S4X-44	5.14		
GRS-HzK-98	5.0		
IPPE-ABBN93	5.2	5.23	
IPPE-84	4.9		
IRSN-CrV1-172	5.13		
IRSN-78-CEA	5.2		
IRSN-96-2	4.95		
JAERI-H-99		7.43!!!	Error!
JAERI-2004		5.25	See [48]
ORNL-S4X-238	5.2		
Serco-Mk8-F22	5.23	5.20	1.8%

Table G8. Volume for U(20)O₂

Critical volume for H ₂ O-reflected U(20)O ₂ + H ₂ O systems			
EALF = 0.129	Volume (l)		
Source	Raw data	Best-estimate	2 σ
DIN	10.5		
EMS-S4X-238	10.73	10.73	+1.06/-0.95
EMS-M5-E50	10.64	10.78	
EMS-M5-E62	10.94	10.90	
EMS-M5-E66	10.87	10.92	
EMS-M5-E68	10.86	10.88	
EMS-M5-E7P	10.92	10.86	
EMS-M5-F22	10.72	10.75	
EMS-M5-F30	10.86	10.89	
EMS-M5-J32	10.49	10.75	
EMS-M5-J33	10.79	10.87	
EMS-S5X-238	10.72	10.86	
EMS-S5X-27	10.49	10.78	
EMS-S5X-44	10.61	10.79	
EMS-S5K-238	10.71	10.83	
EMS-S5K-27	10.51	10.70	
EMS-S5K-44	10.59	10.73	
GRS-HzK-98	10.8		
IPPE-ABBN93	10.5	10.55	
IPPE-84	10.2		
IRSN-CrV1-172	10.49		
IRSN-78-CEA	11.5		
JAERI-H-88		10.2	
JAERI-H-99		11.5	
ORNL-S4X-238	10.7		
Serco-Mk8-F22	10.78	10.7	1.8%

Figure G9. $U(20)O_2$ – Cylinder diameter

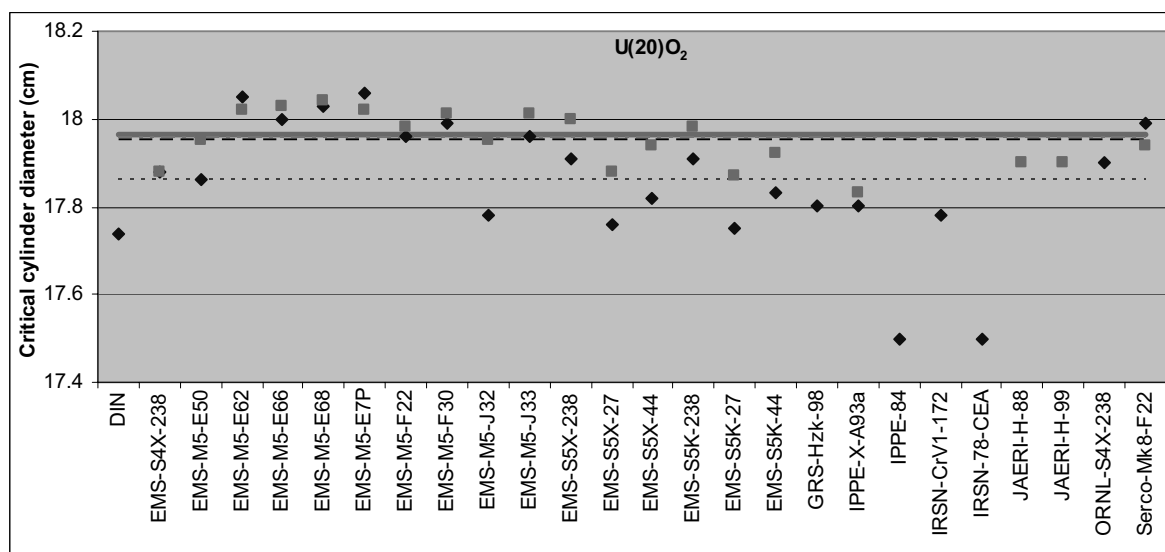


Figure G10. $U(20)O_2$ – Slab thickness

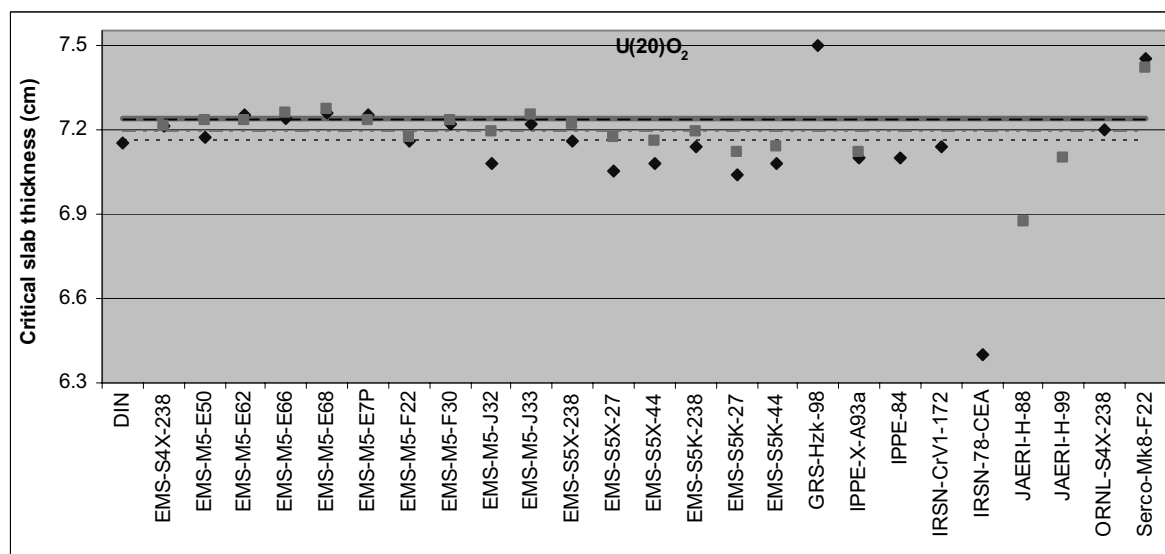


Table G9. Cylinder diameter U(20)O₂

Critical cylinder diameter for H ₂ O-reflected U(20)O ₂ + H ₂ O systems			
EALF = 0.133	Cylinder diameter (cm)		
Source	Raw data	Best-estimate	2 σ
DIN	17.74		
EMS-S4X-238	17.88	(17.88)	+0.66/-0.64
EMS-M5-E50	17.86	17.95	
EMS-M5-E62	18.05	18.02	
EMS-M5-E66	18.00	18.03	
EMS-M5-E68	18.03	18.04	
EMS-M5-E7P	18.06	18.02	
EMS-M5-F22	17.96	17.98	
EMS-M5-F30	17.99	18.01	
EMS-M5-J32	17.78	17.95	
EMS-M5-J33	17.96	18.01	
EMS-S5X-238	17.91	18.00	
EMS-S5X-27	17.76	17.94	
EMS-S5X-44	17.82	17.94	
EMS-S5K-238	17.91	17.98	
EMS-S5K-27	17.75	17.87	
EMS-S5K-44	17.83	17.92	
GRS-Hzk-98	17.8		
IPPE-ABBN93	17.8	17.83	
IPPE-84	17.5		
IRSN-CrV1-172	17.78		
IRSN-78-CEA	17.5		
JAERI-H-88		17.9	
JAERI-H-99		17.9	
ORNL-S4X-238	17.9		
Serco-Mk8-F22	17.99	17.94	0.6%

Table G10. Slab thickness U(20)O₂

Critical slab thickness for H ₂ O-reflected U(20)O ₂ + H ₂ O systems			
EALF = 0.162	Slab thickness (cm)		
Source	Raw data	Best-estimate	2 σ
DIN	7.15		
EMS-S4X-238	7.21	7.21	+0.44/-0.42
EMS-M5-E50	7.17	7.23	
EMS-M5-E62	7.25	7.23	
EMS-M5-E66	7.24	7.26	
EMS-M5-E68	7.26	7.27	
EMS-M5-E7P	7.25	7.23	
EMS-M5-F22	7.16	7.17	
EMS-M5-F30	7.22	7.23	
EMS-M5-J32	7.08	7.19	
EMS-M5-J33	7.22	7.25	
EMS-S5X-238	7.16	7.22	
EMS-S5X-27	7.05	7.17	
EMS-S5X-44	7.08	7.16	
EMS-S5K-238	7.14	7.19	
EMS-S5K-27	7.04	7.12	
EMS-S5K-44	7.08	7.14	
GRS-Hzk-98	7.5		
IPPE-ABBN93	7.1	7.12	
IPPE-84	7.1		
IRSN-CrV1-172	7.14		
IRSN-78-CEA	6.4		
JAERI-H-88		6.87	
JAERI-H-99		7.1	
ORNL-S4X-238	7.2		
Serco-Mk8-F22	7.45	7.42	1.0%

Figure G11. $U(20)O_2$ – Uranium concentration

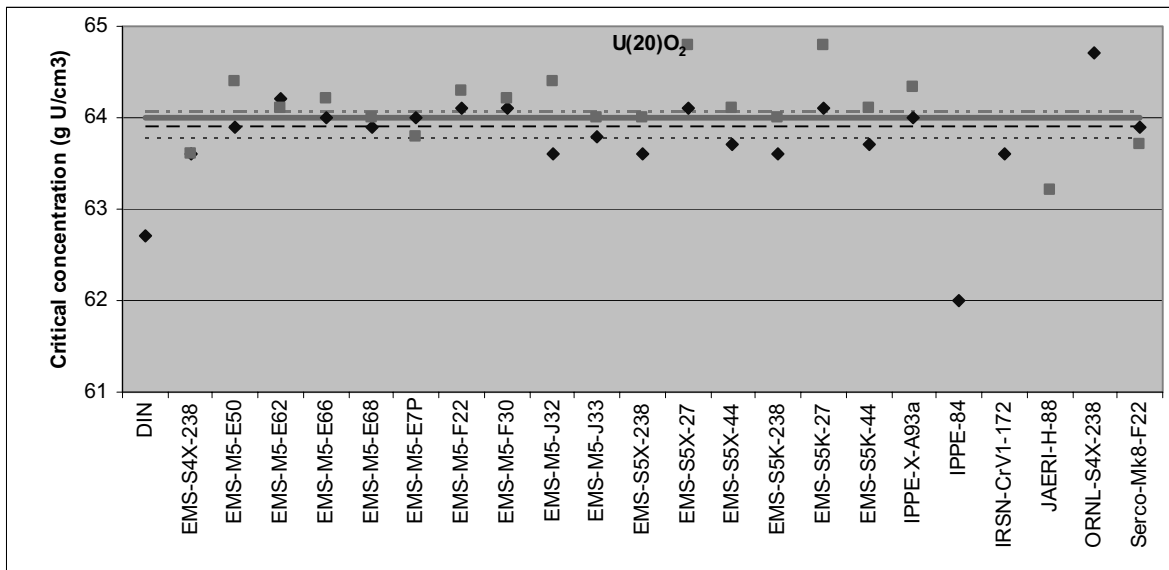


Figure G12. $U(20)O_2$ – Moderation H/U

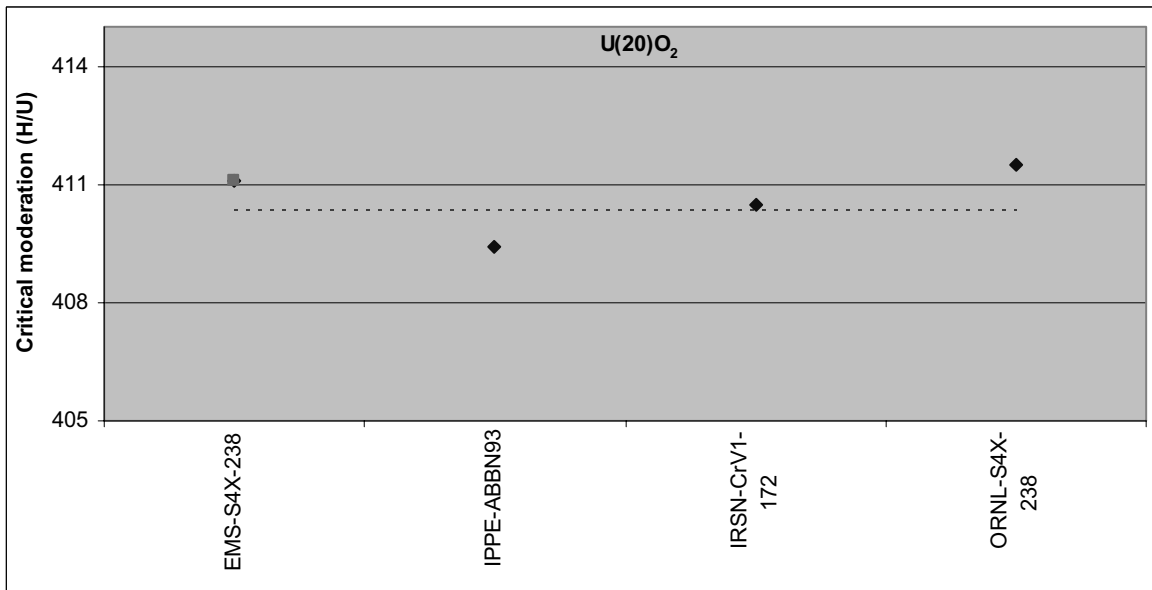


Table G11. Concentration U(20)O₂

Critical concentration for H₂O-reflected U(20)O₂ + H₂O systems			
EALF = 0.0312	U concentration (g/cm ³)		
Source	Raw data	Best-estimate	2 σ
DIN	62.7		
EMS-S4X-238	63.6	(63.6)	+2.7/-2.5
EMS-M5-E50	63.9	64.4	
EMS-M5-E62	64.2	64.1	
EMS-M5-E66	64.0	64.2	
EMS-M5-E68	63.9	64.0	
EMS-M5-E7P	64.0	63.8	
EMS-M5-F22	64.1	64.3	
EMS-M5-F30	64.1	64.2	
EMS-M5-J32	63.6	64.4	
EMS-M5-J33	63.8	64.0	
EMS-S5X-238	63.6	64.0	
EMS-S5X-27	64.1	64.8	
EMS-S5X-44	63.7	64.1	
EMS-S5K-238	63.6	64.0	
EMS-S5K-27	64.1	64.8	
EMS-S5K-44	63.7	64.1	
IPPE-ABBN93	64.0	64.3	
IPPE-84	62		
IRSN-CrV1-172	63.6		
JAERI-H-88		63.2	
ORNL-S4X-238	64.7		
Serco-Mk8-F22	63.9	63.7	0.8 %

Table G12. Moderation U(20)O₂

Critical moderation for H₂O-reflected U(20)O₂ + H₂O systems			
EALF = 0.0312	Moderation (H/U)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	411.1	411.1)	-16.7/ +17.4
IPPE-ABBN93	409.4		
IRSN-CrV1-172	410.5		
ORNL-S4X-238	411.5		

Figure G13. $U(5)O_2$ – Mass

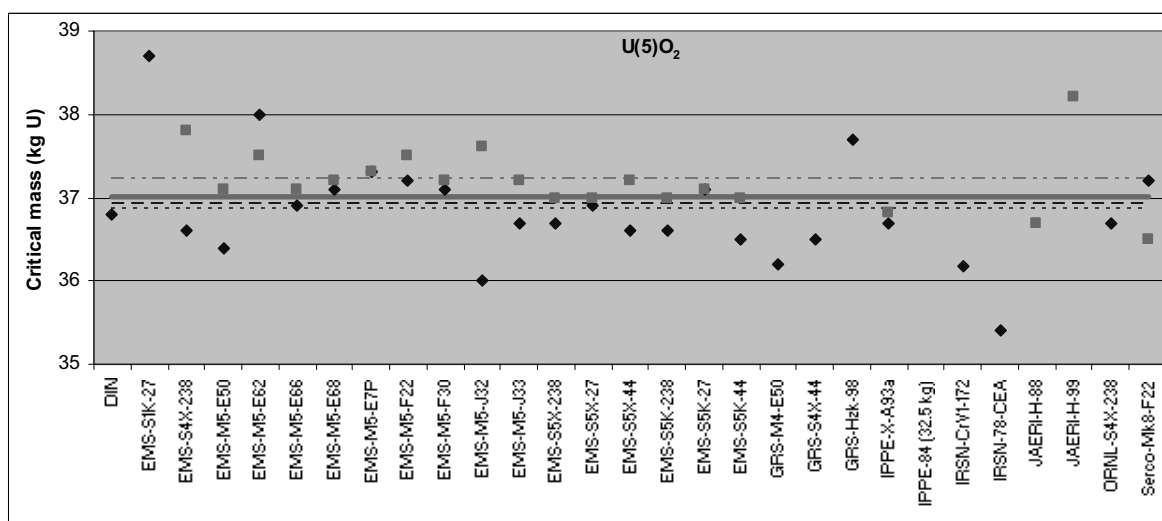


Figure G14. $U(5)O_2$ – Volume

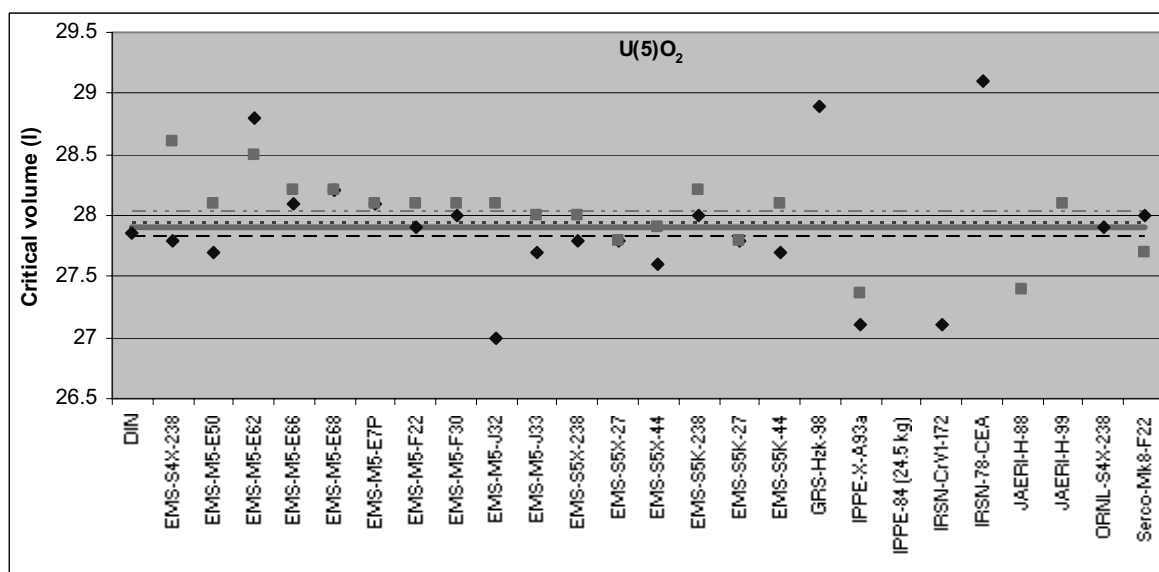


Table G13. Mass for U(5)O₂

Critical mass for H ₂ O-reflected U(5)O ₂ + H ₂ O systems			
EALF = 0.0514	Mass (kg U)		
Source	Raw data	Best-estimate	2 σ
DIN	36.8		
EMS-S1K-27	38.7		
EMS-S4X-238	36.6	37.8)	+3.9/-3.5
EMS-M5-E50	36.4	37.1	
EMS-M5-E62	38.0	37.5	
EMS-M5-E66	36.9	37.1	
EMS-M5-E68	37.1	37.2	
EMS-M5-E7P	37.3	37.3	
EMS-M5-F22	37.2	37.5	
EMS-M5-F30	37.1	37.2	
EMS-M5-J32	36.0	37.6	
EMS-M5-J33	36.7	37.2	
EMS-S5X-238	36.7	37.0	
EMS-S5X-27	36.9	37.0	
EMS-S5X-44	36.6	37.2	
EMS-S5K-238	36.6	37.0	
EMS-S5K-27	37.1	37.1	
EMS-S5K-44	36.5	37.0	
GRS-M4-E50	36.2		
GRS-S4X-44	36.5		
GRS-Hzk-98	37.7		
IPPE-ABBN93	36.7	36.8	
IPPE-84	32.5		
IRSN-CrV1-172	36.2		
IRSN-78-CEA	35.4		
JAERI-H-88		36.7	
JAERI-H-99		38.2	
ORNL-S4X-238	36.7		
Serco-Mk8-F22	37.2	36.5	5.6%

Table G14. Volume for U(5)O₂

Critical volume for H ₂ O-reflected U(5)O ₂ + H ₂ O systems			
EALF = 0.0965	Volume (l)		
Source	Raw data	Best-estimate	2 σ
DIN	27.86		
EMS-S4X-238	27.8	28.6	+2.7/-2.4
EMS-M5-E50	27.7	28.1	
EMS-M5-E62	28.8	28.5	
EMS-M5-E66	28.1	28.2	
EMS-M5-E68	28.2	28.2	
EMS-M5-E7P	28.1	28.1	
EMS-M5-F22	27.9	28.1	
EMS-M5-F30	28.0	28.1	
EMS-M5-J32	27.0	28.1	
EMS-M5-J33	27.7	28.0	
EMS-S5X-238	27.8	28.0	
EMS-S5X-27	27.8	27.8	
EMS-S5X-44	27.6	27.9	
EMS-S5K-238	28.0	28.2	
EMS-S5K-27	27.8	27.8	
EMS-S5K-44	27.7	28.1	
GRS-Hzk-98	28.9		
IPPE-ABBN93	27.1	27.4	
IPPE-84	24.5		
IRSN-CrV1-172	27.1		
IRSN-78-CEA	29.1		
JAERI-H-88		27.4	
JAERI-H-99		28.1	
ORNL-S4X-238	27.9		
Serco-Mk8-F22	28.0	27.7	2.2%

Figure G15. $U(5)O_2$ – Cylinder diameter

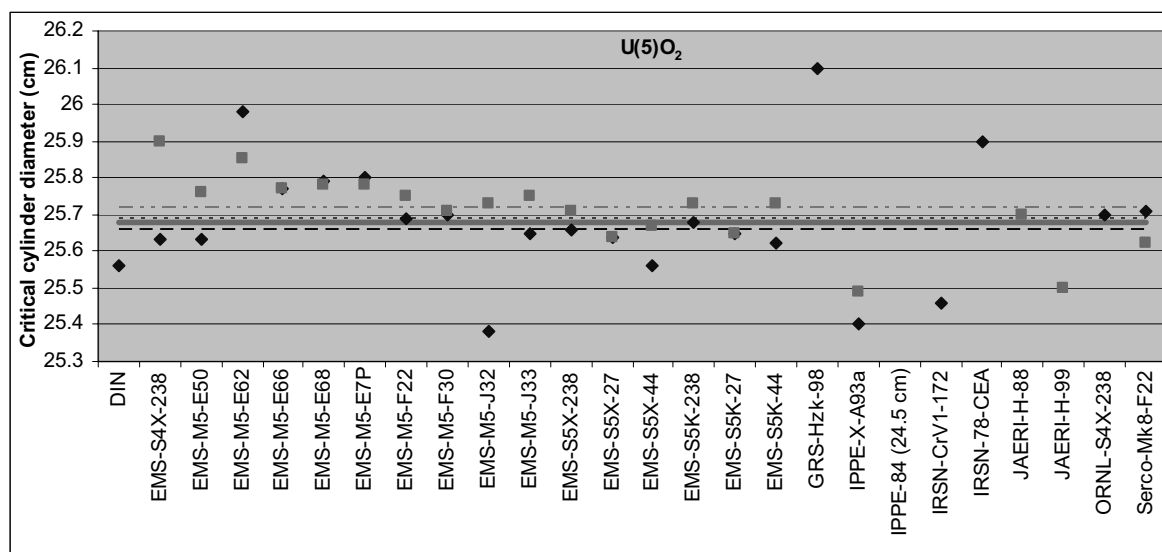


Figure G16. $U(5)O_2$ – Slab thickness

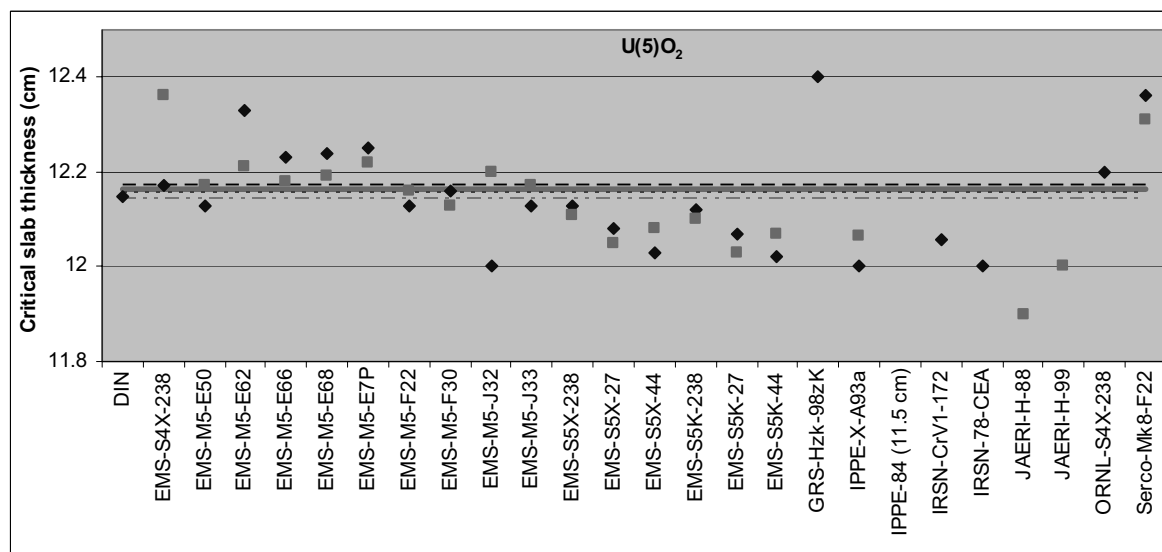


Table G15. Cylinder diameter U(5)O₂

Critical cylinder diameter for H ₂ O-reflected U(5)O ₂ + H ₂ O systems			
EALF = 0.0974	Cylinder diameter (cm)		
Source	Raw data	Best-estimate	2 σ
DIN	25.56		
EMS-S4X-238	25.63	25.90	+0.87/-0.83
EMS-M5-E50	25.63	25.76	
EMS-M5-E62	25.98	25.85	
EMS-M5-E66	25.77	25.77	
EMS-M5-E68	25.79	25.78	
EMS-M5-E7P	25.80	25.78	
EMS-M5-F22	25.69	25.75	
EMS-M5-F30	25.70	25.71	
EMS-M5-J32	25.38	25.73	
EMS-M5-J33	25.65	25.75	
EMS-S5X-238	25.66	25.71	
EMS-S5X-27	25.64	25.64	
EMS-S5X-44	25.56	25.67	
EMS-S5K-238	25.68	25.73	
EMS-S5K-27	25.65	25.65	
EMS-S5K-44	25.62	25.73	
GRS-Hzk-98	26.1		
IPPE-ABBN93	25.4	25.49	
IPPE-84	24.5		
IRSN-CrV1-172	25.46		
IRSN-78-CEA	25.9		
JAERI-H-88		25.7	
JAERI-H-99		25.5	
ORNL-S4X-238	25.7		
Serco-Mk8-F22	25.71	25.62	0.8%

Table G16. Slab thickness U(5)O₂

Critical slab thickness for H ₂ O-reflected U(5)O ₂ + H ₂ O systems			
EALF = 0.109	Slab thickness (cm)		
Source	Raw data	Best-estimate	2 σ
DIN	12.15		
EMS-S4X-238	12.17	12.36	+0.56/-0.54
EMS-M5-E50	12.13	12.17	
EMS-M5-E62	12.33	12.21	
EMS-M5-E66	12.23	12.18	
EMS-M5-E68	12.24	12.19	
EMS-M5-E7P			
EMS-M5-F22	12.13	12.16	
EMS-M5-F30	12.16	12.13	
EMS-M5-J32	12.00	12.20	
EMS-M5-J33	12.13	12.17	
EMS-S5X-238	12.13	12.11	
EMS-S5X-27	12.08	12.05	
EMS-S5X-44	12.03	12.08	
EMS-S5K-238			
EMS-S5K-27	12.07	12.03	
EMS-S5K-44	12.02	12.07	
GRS-Hzk-98	12.4		
IPPE-ABBN93	12.0	12.06	
IPPE-84	11.5		
IRSN-CrV1-172	12.06		
IRSN-78-CEA	12.0		
JAERI-H-88		11.9	
JAERI-H-99		12	
ORNL-S4X-238	12.2		
Serco-Mk8-F22	12.36	12.31	1.0%

Figure G17. $U(5)O_2$ – Concentration

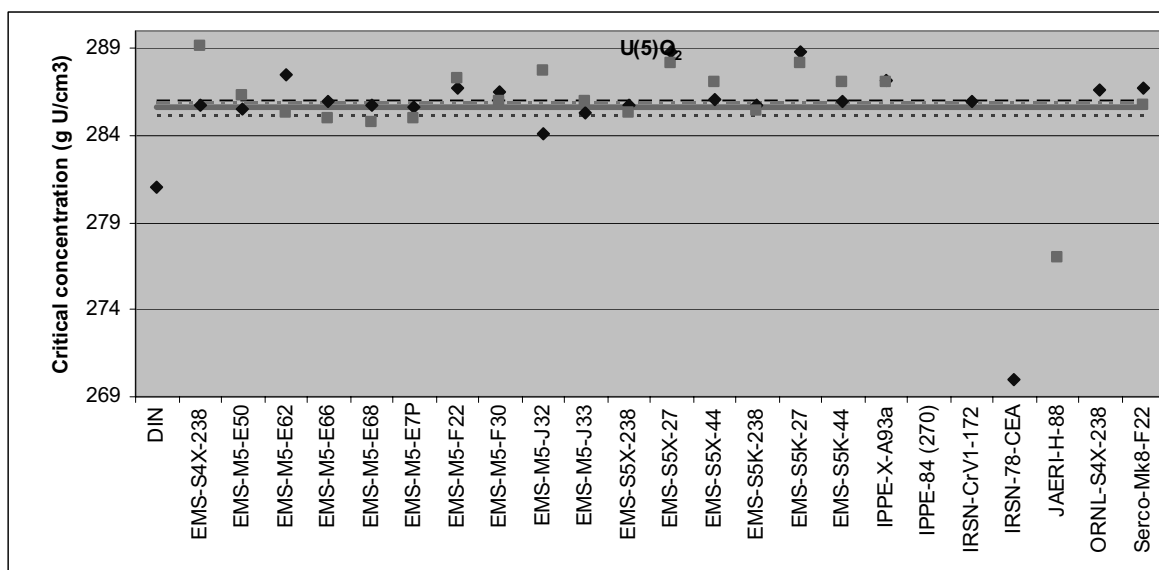


Figure G18. $U(5)O_2$ – Moderation H/U

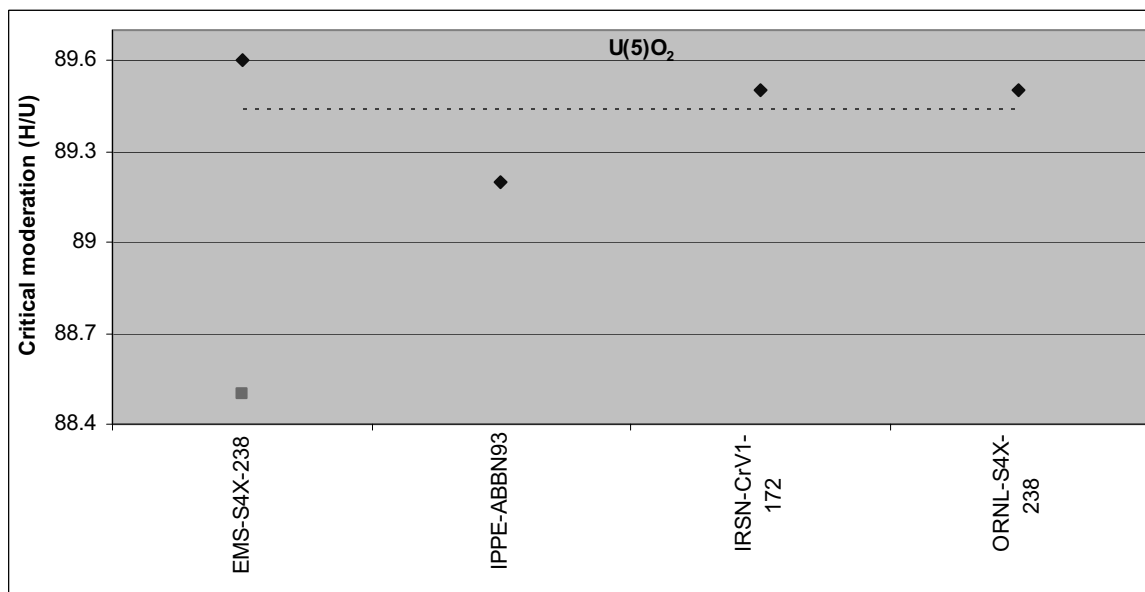


Table G17. Concentration – U(5)O₂

Critical concentration for H₂O-reflected U(5)O₂ + H₂O systems			
EALF = 0.0344	U concentration (g/cm ³)		
Source	Raw data	Best-estimate	2 σ
DIN	281		
EMS-S4X-238	285.7	289.1	+10.3/-9.9
EMS-M5-E50	285.5	286.3	
EMS-M5-E62	287.5	285.3	
EMS-M5-E66	285.9	285.0	
EMS-M5-E68	285.7	284.7	
EMS-M5-E7P			
EMS-M5-F22	286.7	287.3	
EMS-M5-F30	286.5	286.0	
EMS-M5-J32	284.1	287.7	
EMS-M5-J33	285.3	286.0	
EMS-S5X-238	285.7	285.3	
EMS-S5X-27	288.8	288.1	
EMS-S5X-44	286.1	287.1	
EMS-S5K-238			
EMS-S5K-27	288.8	288.1	
EMS-S5K-44	286.0	287.0	
IPPE-ABBN93	287.2	287.1	
IPPE-84	270		
IRSN-CrV1-172	286		
IRSN-78-CEA	270		
JAERI-H-88		277	
ORNL-S4X-238	286.6		
Serco-Mk8-F22	286.7	285.7	1.0%

Table G18. Moderation U(5)O₂

Critical moderation for H₂O-reflected U(5)O₂ + H₂O systems			
EALF = 0.0344	Moderation (H/U)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	89.6	88.5	-3.1/ +3.3
IPPE-ABBN93	89.2		
IRSN-CrV1-172	89.5		
IRSN-78-CEA	95		
ORNL-S4X-238	89.5		

Figure G19. $U(4)O_2$ – Mass

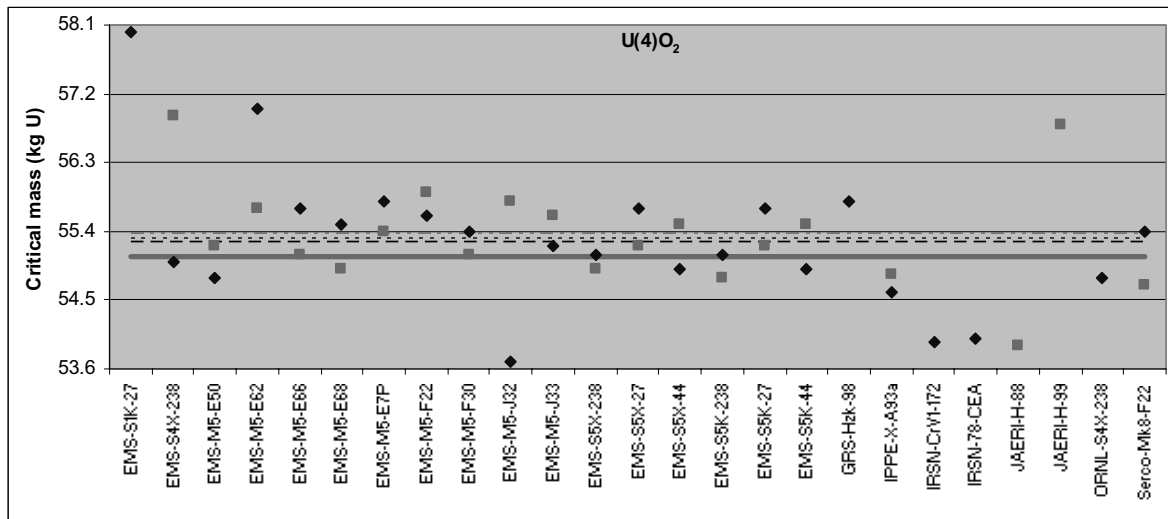


Figure G20. $U(4)O_2$ – Volume

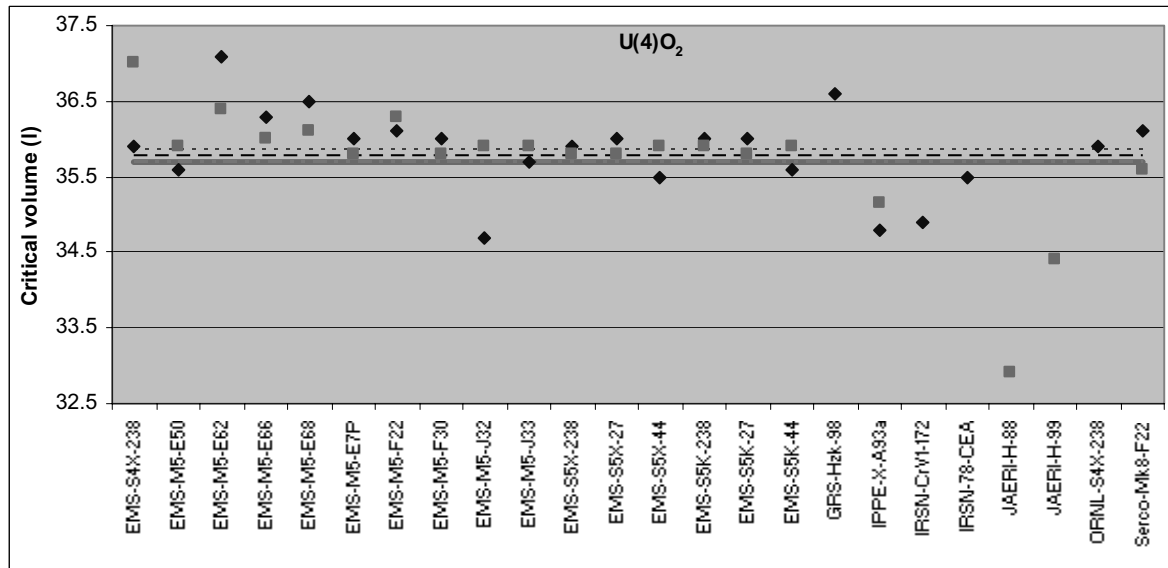


Table G19. Mass – U(4)O₂

Critical mass for H ₂ O-reflected U(4)O ₂ + H ₂ O systems			
EALF = 0.0531	Mass (kg U)		
Source	Raw data	Best-estimate	2 σ
EMS-S1K-27	58.0		
EMS-S4X-238	55.0	56.9	+6.5/-5.7
EMS-M5-E50	54.8	55.2	
EMS-M5-E62	57.0	55.7	
EMS-M5-E66	55.7	55.1	
EMS-M5-E68	55.5	54.9	
EMS-M5-E7P	55.8	55.4	
EMS-M5-F22	55.6	55.9	
EMS-M5-F30	55.4	55.1	
EMS-M5-J32	53.7	55.8	
EMS-M5-J33	55.2	55.6	
EMS-S5X-238	55.1	54.9	
EMS-S5X-27	55.7	55.2	
EMS-S5X-44	54.9	55.5	
EMS-S5K-238	55.1	54.8	
EMS-S5K-27	55.7	55.2	
EMS-S5K-44	54.9	55.5	
GRS-Hzk-98	55.8		
IPPE-ABBN93	54.6	54.8	
IRSN-CrV1-172	53.9		
IRSN-78-CEA	54.0		
JAERI-H-88		53.9	
JAERI-H-99		56.8	
ORNL-S4X-238	54.8		
Serco-Mk8-F22	55.4	54.7	3.8%

Table G20. Volume for U(4)O₂

Critical volume for H ₂ O-reflected U(4)O ₂ + H ₂ O systems			
EALF = 0.0981	Volume (l)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	35.9	37	+3.7/-3.3
EMS-M5-E50	35.6	35.9	
EMS-M5-E62	37.1	36.4	
EMS-M5-E66	36.3	36.0	
EMS-M5-E68	36.5	36.1	
EMS-M5-E7P	36.0	35.8	
EMS-M5-F22	36.1	36.3	
EMS-M5-F30	36.0	35.8	
EMS-M5-J32	34.7	35.9	
EMS-M5-J33	35.7	35.9	
EMS-S5X-238	35.9	35.8	
EMS-S5X-27	36.0	35.8	
EMS-S5X-44	35.5	35.9	
EMS-S5K-238	36.0	35.9	
EMS-S5K-27	36.0	35.8	
EMS-S5K-44	35.6	35.9	
GRS-Hzk-98	36.6		
IPPE-ABBN93	34.8	35.2	
IRSN-CrV1-172	34.9		
IRSN-78-CEA	35.5		
JAERI-H-88		32.9	
JAERI-H-99		34.4	
ORNL-S4X-238	35.9		
Serco-Mk8-F22	36.1	35.6	3.6%

Figure G21. $U(4)O_2$ – Cylinder diameter

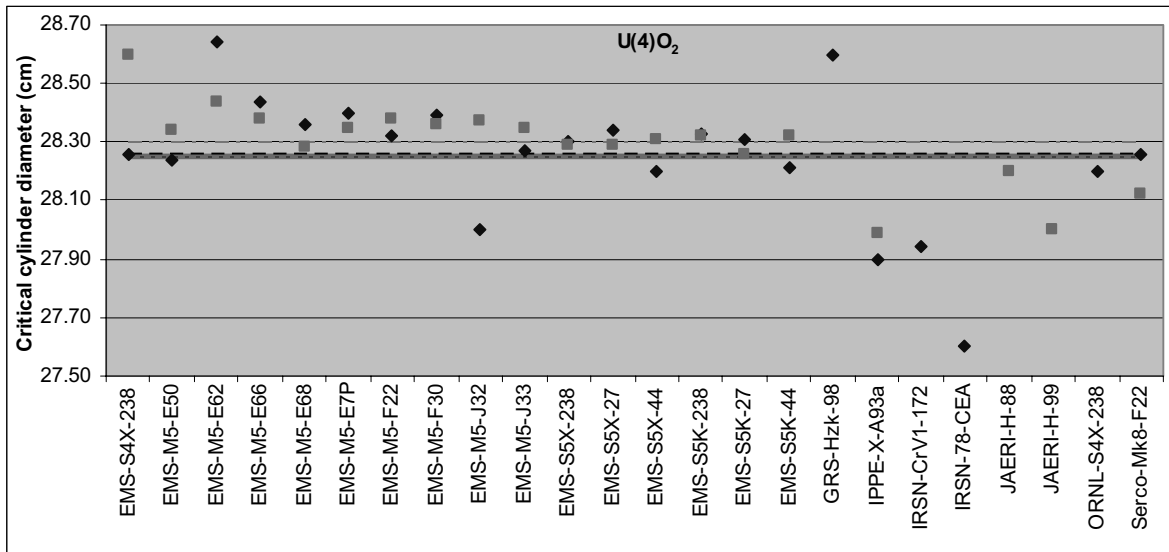


Figure G22. $U(4)O_2$ – Slab thickness

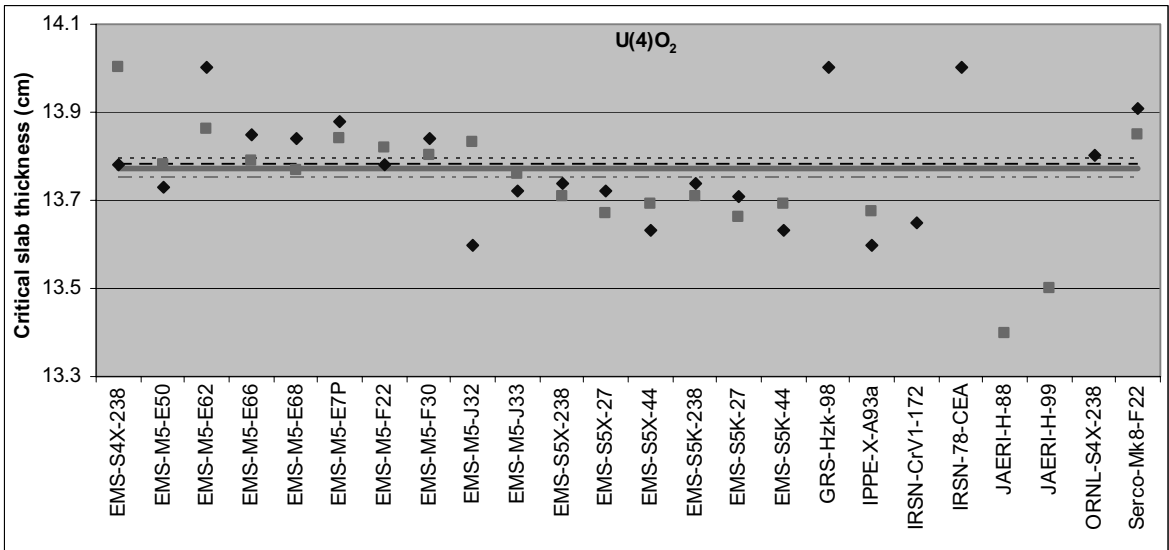


Table G21. Cylinder diameter $U(4)O_2$

Critical cylinder diameter for H_2O -reflected $U(4)O_2 + H_2O$ systems			
EALF = 0.0858	Cylinder diameter (cm)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	28.26	28.60	+1.02/-0.97
EMS-M5-E50	28.24	28.34	
EMS-M5-E62	28.64	28.44	
EMS-M5-E66	28.44	28.38	
EMS-M5-E68	28.36	28.28	
EMS-M5-E7P	28.40	28.35	
EMS-M5-F22	28.32	28.38	
EMS-M5-F30	28.39	28.36	
EMS-M5-J32	28.00	28.37	
EMS-M5-J33	28.27	28.35	
EMS-S5X-238	28.30	28.29	
EMS-S5X-27	28.34	28.29	
EMS-S5X-44	28.20	28.31	
EMS-S5K-238	28.33	28.32	
EMS-S5K-27	28.31	28.26	
EMS-S5K-44	28.21	28.32	
GRS-Hzk-98	28.6		
IPPE-ABBN93	27.9	27.99	
IRSN-CrV1-172	27.94		
IRSN-78-CEA	27.6		
JAERI-H-88		28.2	
JAERI-H-99		28	
ORNL-S4X-238	28.2		
Serco-Mk8-F22	28.26	28.12	1.2%

Table G22. Slab thickness $U(4)O_2$

Critical slab thickness for H_2O -reflected $U(4)O_2 + H_2O$ systems			
EALF = 0.105	Slab thickness (cm)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	13.78	14.0	+0.66/-0.63
EMS-M5-E50	13.73	13.78	
EMS-M5-E62	14.00	13.86	
EMS-M5-E66	13.85	13.79	
EMS-M5-E68	13.84	13.77	
EMS-M5-E7P	13.88	13.84	
EMS-M5-F22	13.78	13.82	
EMS-M5-F30	13.84	13.80	
EMS-M5-J32	13.60	13.83	
EMS-M5-J33	13.72	13.76	
EMS-S5X-238	13.74	13.71	
EMS-S5X-27	13.72	13.67	
EMS-S5X-44	13.63	13.69	
EMS-S5K-238	13.74	13.71	
EMS-S5K-27	13.71	13.66	
EMS-S5K-44	13.63	13.69	
GRS-Hzk-98	14.0		
IPPE-ABBN93	13.6	13.67	
IRSN-CrV1-172	13.65		
IRSN-78-CEA	14		
JAERI-H-88		13.4	
JAERI-H-99		13.5	
ORNL-S4X-238	13.8		
Serco-Mk8-F22	13.91	13.85	1.2%

Figure G23. $U(4)O_2$ – Concentration

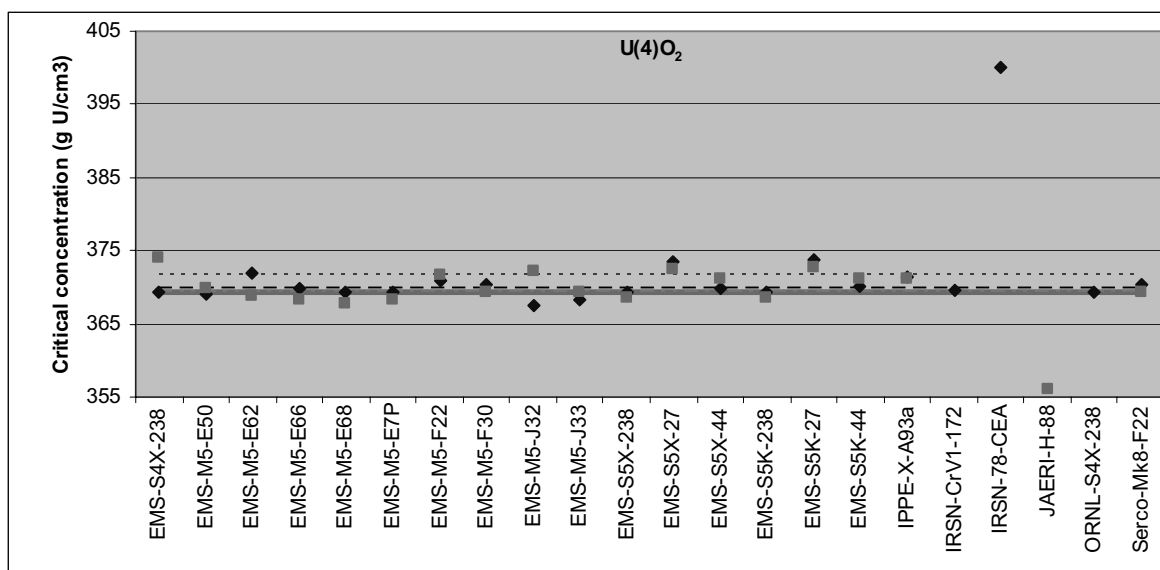


Figure G24. $U(4)O_2$ –Moderation H/U

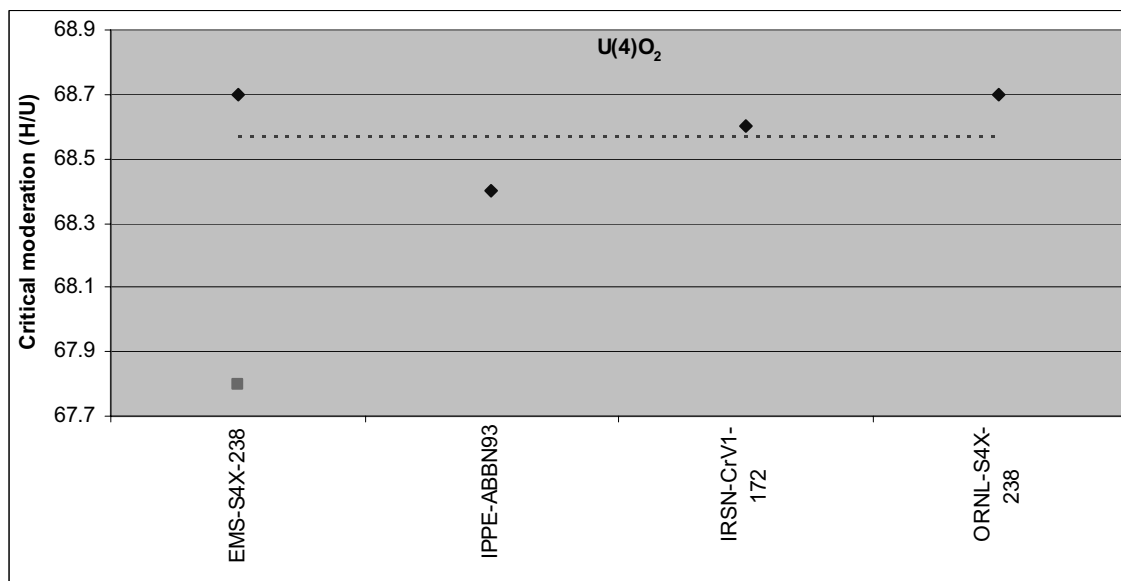


Table G23. Concentration – U(4)O₂

Critical concentration for H₂O-reflected U(4)O₂ + H₂O systems			
EALF = 0.0357	U concentration (g/cm ³)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	369.4	373.9	+13.8/-13.6
EMS-M5-E50	369.0	369.8	
EMS-M5-E62	371.9	368.8	
EMS-M5-E66	369.9	368.4	
EMS-M5-E68	369.4	367.7	
EMS-M5-E7P	369.4	368.4	
EMS-M5-F22	371.0	371.7	
EMS-M5-F30	370.3	369.4	
EMS-M5-J32	367.6	372.3	
EMS-M5-J33	368.4	369.2	
EMS-S5X-238	369.3	368.6	
EMS-S5X-27	373.6	372.5	
EMS-S5X-44	369.9	371.2	
EMS-S5K-238	369.2	368.5	
EMS-S5K-27	373.7	372.6	
EMS-S5K-44	370.0	371.2	
IPPE-ABBN93	371.3	371.2	
IRSN-CrV1-172	369.5		
IRSN-78-CEA	400		
JAERI-H-88		356.0	
ORNL-S4X-238	369.4		
Serco-Mk8-F22	370.4	369.2	1.0%

Table G24. Moderation U(4)O₂

Critical moderation for H₂O-reflected U(4)O₂ + H₂O systems			
EALF = 0.0357	Moderation (H/U)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	68.7	67.8	-2.5/ +2.6
IPPE-ABBN93	68.4		
IRSN-CrV1-172	68.6		
IRSN-78-CEA	65		
ORNL-S4X-238	68.7		

Figure G25. $U(3)O_2$ – Mass

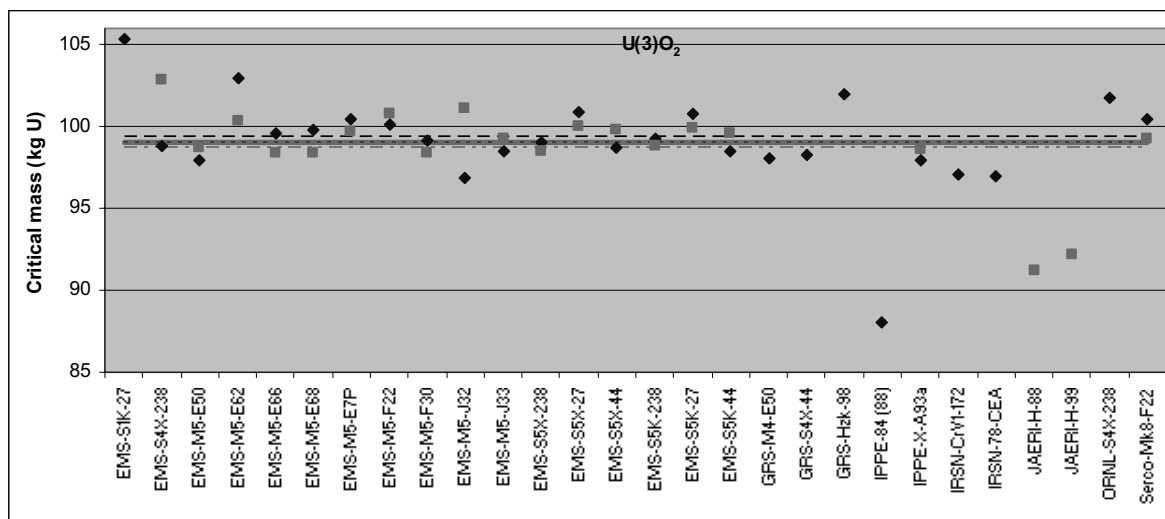


Figure G26. $U(3)O_2$ – Volume

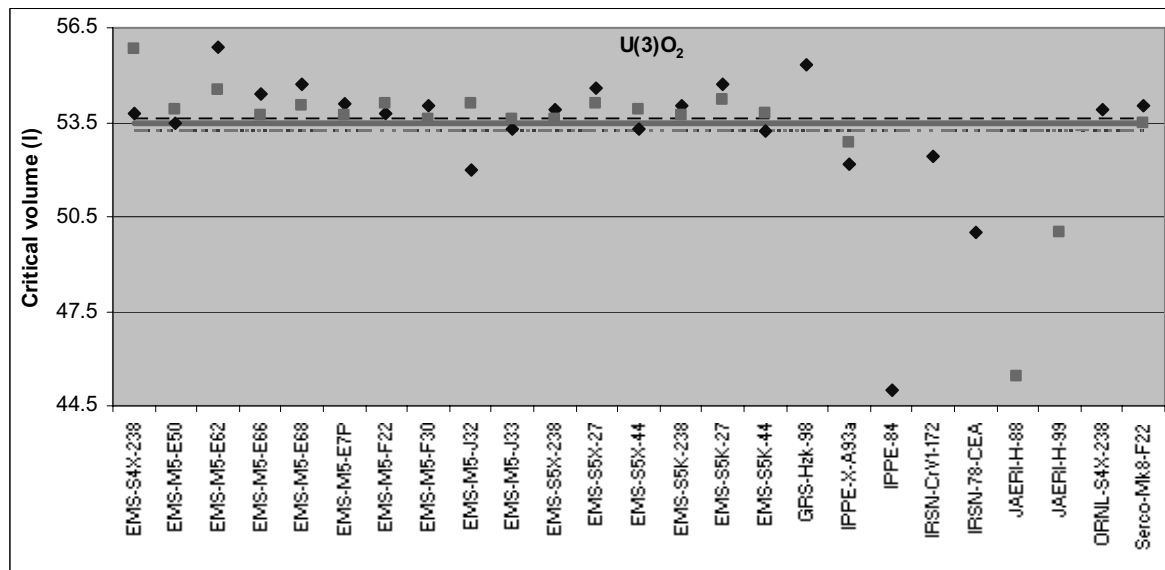


Table G25. Mass – U(3)O₂

Critical mass for H ₂ O-reflected U(3)O ₂ + H ₂ O systems			
EALF = 0.0617	Mass (kg U)		
Source	Raw data	Best-estimate	2 σ
EMS-S1K-27	105.3		
EMS-S4X-238	98.8	102.8	+13.2/-11.2
EMS-M5-E50	97.9	98.7	
EMS-M5-E62	103.0	100.3	
EMS-M5-E66	99.6	98.4	
EMS-M5-E68	99.8	98.4	
EMS-M5-E7P	100.5	99.7	
EMS-M5-F22	100.1	100.8	
EMS-M5-F30	99.1	98.4	
EMS-M5-J32	96.9	101.1	
EMS-M5-J33	98.5	99.2	
EMS-S5X-238	99.0	98.5	
EMS-S5X-27	100.9	100.0	
EMS-S5X-44	98.7	99.8	
EMS-S5K-238	99.3	98.8	
EMS-S5K-27	100.8	99.9	
EMS-S5K-44	98.5	99.6	
GRS-M4-E50	98.1		
GRS-S4K-44	98.3		
GRS-Hzk-98	102		
IPPE-84	88		
IPPE-ABBN93	98.0	98.7	
IRSN-CrV1-172	97.1		
IRSN-78-CEA	97*		
JAERI-H-88		91.2	
JAERI-H-99		92.2	
ORNL-S4X-238	101.8**		
Serco-Mk8-F22	100.5	99.3	3.4%

Table G26. Volume for U(3)O₂

Critical volume for H ₂ O-reflected U(3)O ₂ + H ₂ O systems			
EALF = 0.1011	Volume (l)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	53.8	55.8	+6.5/-5.7
EMS-M5-E50	53.5	53.9	
EMS-M5-E62	55.9	54.5	
EMS-M5-E66	54.4	53.7	
EMS-M5-E68	54.7	54.0	
EMS-M5-E7P	54.1	53.7	
EMS-M5-F22	53.8	54.1	
EMS-M5-F30	54.0	53.6	
EMS-M5-J32	52.0	54.1	
EMS-M5-J33	53.3	53.6	
EMS-S5X-238	53.9	53.6	
EMS-S5X-27	54.6	54.1	
EMS-S5X-44	53.3	53.9	
EMS-S5K-238	54.0	53.7	
EMS-S5K-27	54.7	54.2	
EMS-S5K-44	53.2	53.8	
GRS-Hzk-98	55.3		
IPPE-ABBN93	52.2	52.9	
IPPE-84	45		
IRSN-CrV1-172	52.4		
IRSN-78-CEA	50		
JAERI-H-88		45.4	
JAERI-H-99		50.0	
ORNL-S4X-238	53.9		
Serco-Mk8-F22	54.0	53.5	2.4%

* From Figure U.1

** Curved interpolation gives about 98.8 kg U.

Figure G27. $U(3)O_2$ – Cylinder diameter

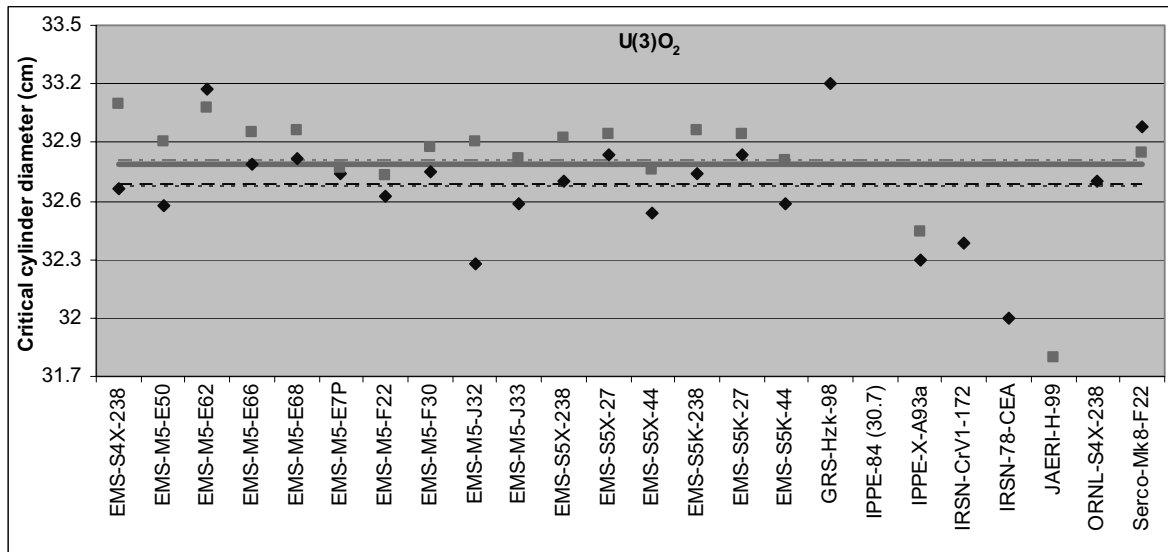


Figure G28. $U(3)O_2$ – Slab thickness

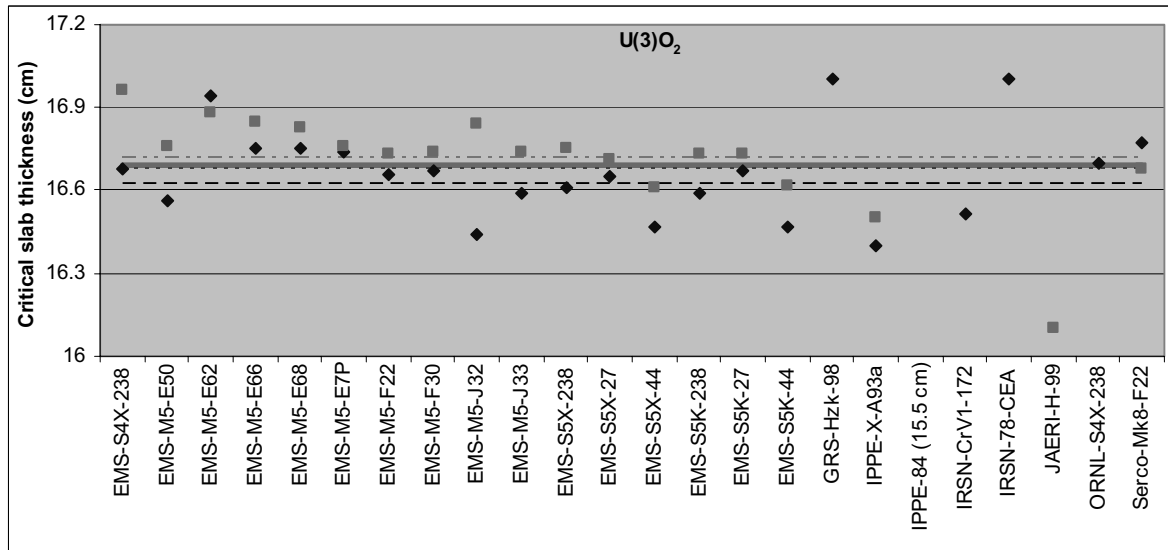


Table G27. Cylinder diameter U(3)O₂

Critical cylinder diameter for H ₂ O-reflected U(3)O ₂ + H ₂ O systems			
EALF = 0.1031	Cylinder diameter (cm)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	32.66	33.10	+1.35/-1.28
EMS-M5-E50	32.58	32.90	
EMS-M5-E62	33.17	33.08	
EMS-M5-E66	32.79	32.95	
EMS-M5-E68	32.82	32.96	
EMS-M5-E7P	32.74	32.77	
EMS-M5-F22	32.62	32.73	
EMS-M5-F30	32.75	32.87	
EMS-M5-J32	32.28	32.90	
EMS-M5-J33	32.59	32.82	
EMS-S5X-238	32.70	32.92	
EMS-S5X-27	32.84	32.94	
EMS-S5X-44	32.54	32.76	
EMS-S5K-238	32.74	32.96	
EMS-S5K-27	32.84	32.94	
EMS-S5K-44	32.59	32.81	
GRS-Hzk-98	33.2		
IPPE-84	30.7		
IPPE-ABBN93	32.3	32.44	
IRSN-CrV1-172	32.38		
IRSN-78-CEA	32.0		
JAERI-H-99		31.8	
ORNL-S4X-238	32.7		
Serco-Mk8-F22	32.98	32.85	1.0%

Table G28. Slab thickness U(3)O₂

Critical slab thickness for H ₂ O-reflected U(3)O ₂ + H ₂ O systems			
EALF = 0.1092	Slab thickness (cm)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	16.68	16.96	+0.88/-0.82
EMS-M5-E50	16.56	16.76	
EMS-M5-E62	16.94	16.88	
EMS-M5-E66	16.75	16.85	
EMS-M5-E68	16.75	16.83	
EMS-M5-E7P	16.74	16.76	
EMS-M5-F22	16.66	16.73	
EMS-M5-F30	16.67	16.74	
EMS-M5-J32	16.44	16.84	
EMS-M5-J33	16.59	16.74	
EMS-S5X-238	16.61	16.75	
EMS-S5X-27	16.65	16.71	
EMS-S5X-44	16.47	16.61	
EMS-S5K-238	16.59	16.73	
EMS-S5K-27	16.67	16.73	
EMS-S5K-44	16.47	16.62	
GRS-Hzk-98	17.0		
IPPE-ABBN93	16.4	16.50	
IPPE-84	15.5		
IRSN-CrV1-172	16.51		
IRSN-78-CEA*	17.0		
JAERI-H-99		16.1	
ORNL-S4X-238	16.7		
Serco-Mk8-F22	16.77	16.68	1.4%

* From Figure U-4

Figure G29. $U(3)O_2$ – Concentration

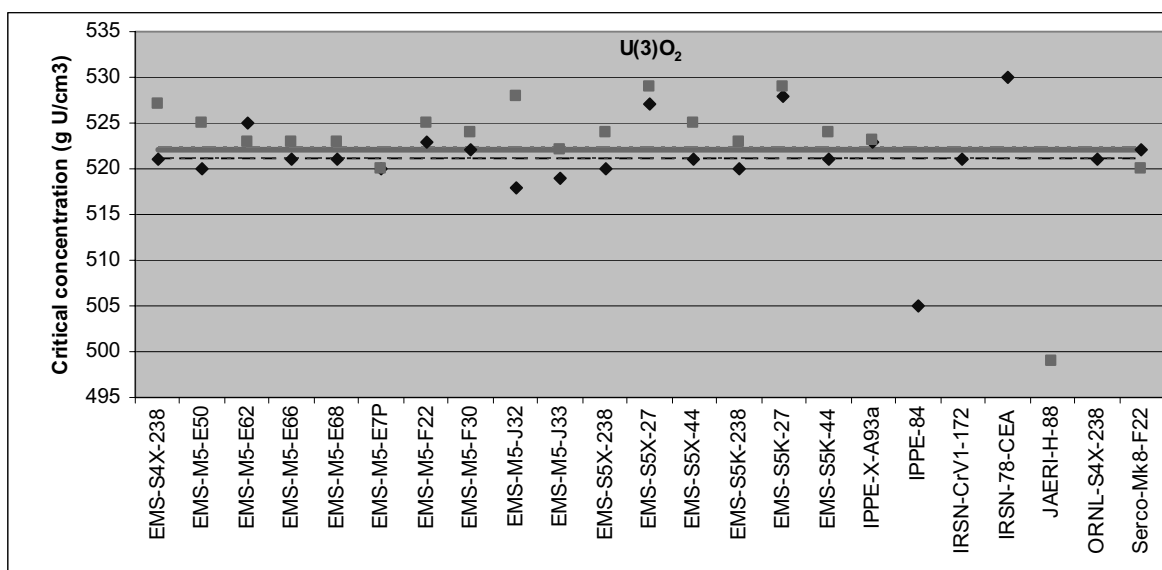


Figure G30. $U(3)O_2$ – Moderation H/U

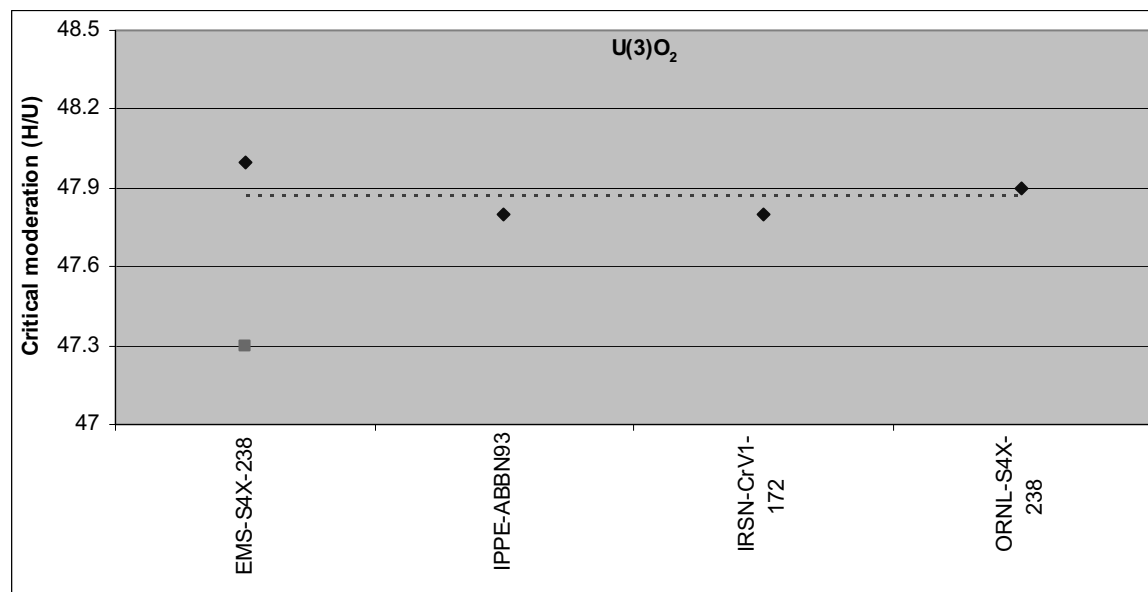


Table G29. Concentration –U(3)O₂

Critical concentration for H₂O-reflected U(3)O₂ + H₂O systems			
EALF = 0.0380	U concentration (g/cm ³)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	521	527	+21/-20
EMS-M5-E50	520	525	
EMS-M5-E62	525	523	
EMS-M5-E66	521	523	
EMS-M5-E68	521	523	
EMS-M5-E7P	520	520	
EMS-M5-F22	523	525	
EMS-M5-F30	522	524	
EMS-M5-J32	518	528	
EMS-M5-J33	519	522	
EMS-S5X-238	520	524	
EMS-S5X-27	527	529	
EMS-S5X-44	521	525	
EMS-S5K-238	520	523	
EMS-S5K-27	528	529	
EMS-S5K-44	521	524	
IPPE-ABBN93	523	523	
IPPE-84	505		
IRSN-CrV1-172	521		
IRSN-78-CEA	530		
JAERI-H-88		499	
ORNL-S4X-238	521		
Serco-Mk8-F22	522	520	1.0%

Table G30. Moderation U(3)O₂

Critical moderation for H₂O-reflected U(3)O₂ + H₂O systems			
EALF = 0.0380	Moderation (H/U)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	48.0	47.3	-1.9/ +2.0
IPPE-ABBN93	47.8		
IRSN-CrV1-172	47.8		
IRSN-78-CEA	46		
ORNL-S4X-238	47.9		

UNH reference values

Figure G31. U(100)NH – Mass

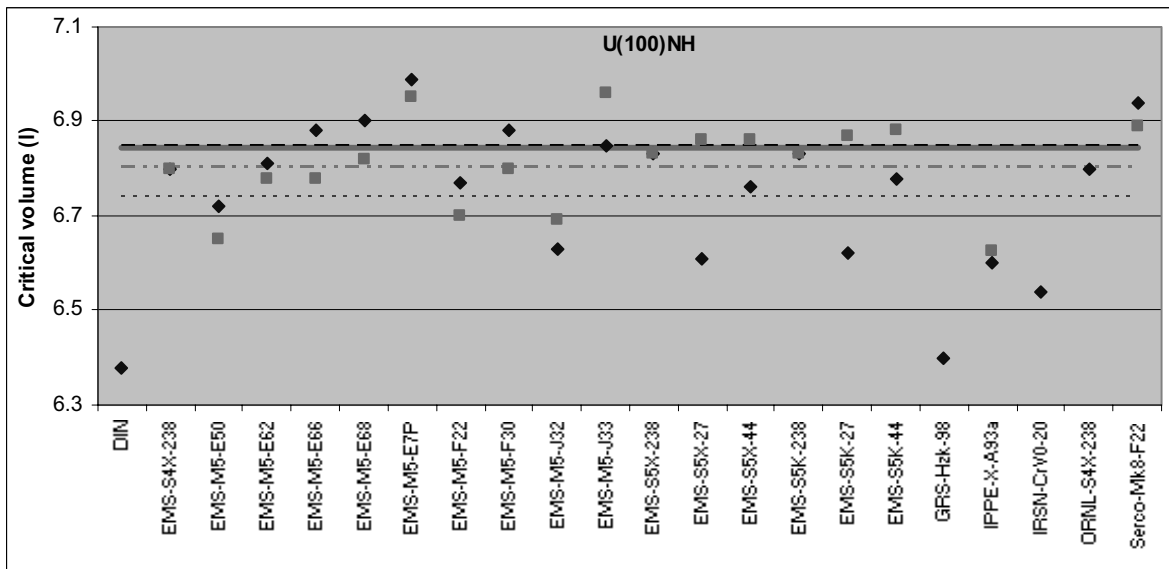
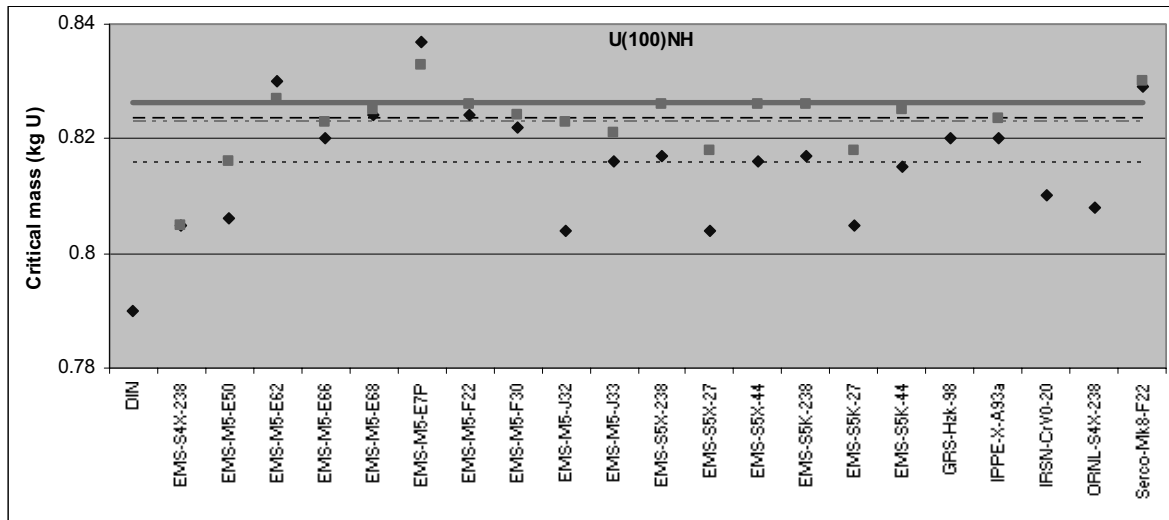


Table G31. Mass - U(100)NH

Critical mass for H ₂ O-reflected U(100)NH + H ₂ O systems			
EALF = 0.0416	Mass (kg U)		
Source	Raw data	Best- estimate	2 σ
DIN	0.79		
EMS-S4X-238	0.805	0.805	+0.077/-0.069
EMS-M5-E50	0.806	0.816	
EMS-M5-E62	0.830	0.827	
EMS-M5-E66	0.820	0.823	
EMS-M5-E68	0.824	0.825	
EMS-M5-E7P	0.837	0.833	
EMS-M5-F22	0.824	0.826	
EMS-M5-F30	0.822	0.824	
EMS-M5-J32	0.804	0.823	
EMS-M5-J33	0.816	0.821	
EMS-S5X-238	0.817	0.826	
EMS-S5X-27	0.804	0.818	
EMS-S5X-44	0.816	0.826	
EMS-S5K-238	0.817	0.826	
EMS-S5K-27	0.805	0.818	
EMS-S5K-44	0.815	0.825	
GRS-Hzk-98	0.82		
IPPE-ABBN93	0.82	0.824	
IRSN-CrV0-20	0.81		
ORNL-S4X-238	0.808		
Serco-Mk8-F22	0.829	0.830	0.8%

Table G32. Volume for U(100)NH

Critical volume for H ₂ O-reflected U(100)NH + H ₂ O systems			
EALF = 0.171	Volume (l)		
Source	Raw data	Best- estimate	2 σ
DIN	6.38		
EMS-S4X-238	6.8	6.8	+0.58/-0.54
EMS-M5-E50	6.72	6.65	
EMS-M5-E62	6.81	6.78	
EMS-M5-E66	6.88	6.78	
EMS-M5-E68	6.90	6.82	
EMS-M5-E7P	6.99	6.95	
EMS-M5-F22	6.77	6.70	
EMS-M5-F30	6.88	6.80	
EMS-M5-J32	6.63	6.69	
EMS-M5-J33	6.85	6.96	
EMS-S5X-238	6.83	6.83	
EMS-S5X-27	6.61	6.86	
EMS-S5X-44	6.76	6.86	
EMS-S5K-238	6.83	6.83	
EMS-S5K-27	6.62	6.87	
EMS-S5K-44	6.78	6.88	
GRS-Hzk-98	6.4		
IPPE-ABBN93	6.6	6.63	
IRSN-CrV0-20	6.54		
ORNL-S4X-238	6.8		
Serco-Mk8-F22	6.94	6.89	1.8%

Figure G33. U(100)NH – Cylinder diameter

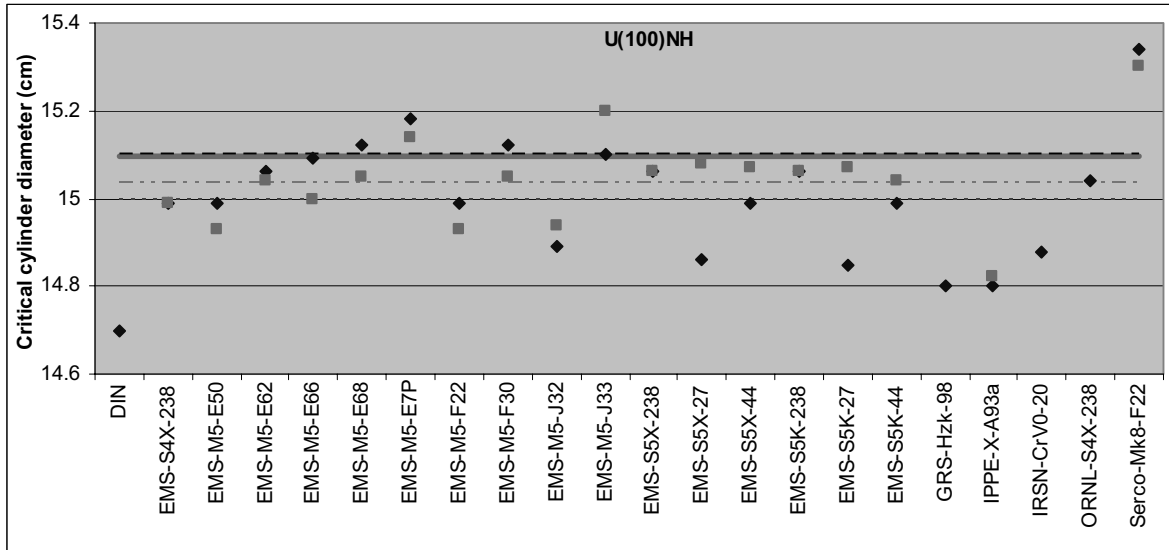


Figure G34. U(100)NH – Slab thickness

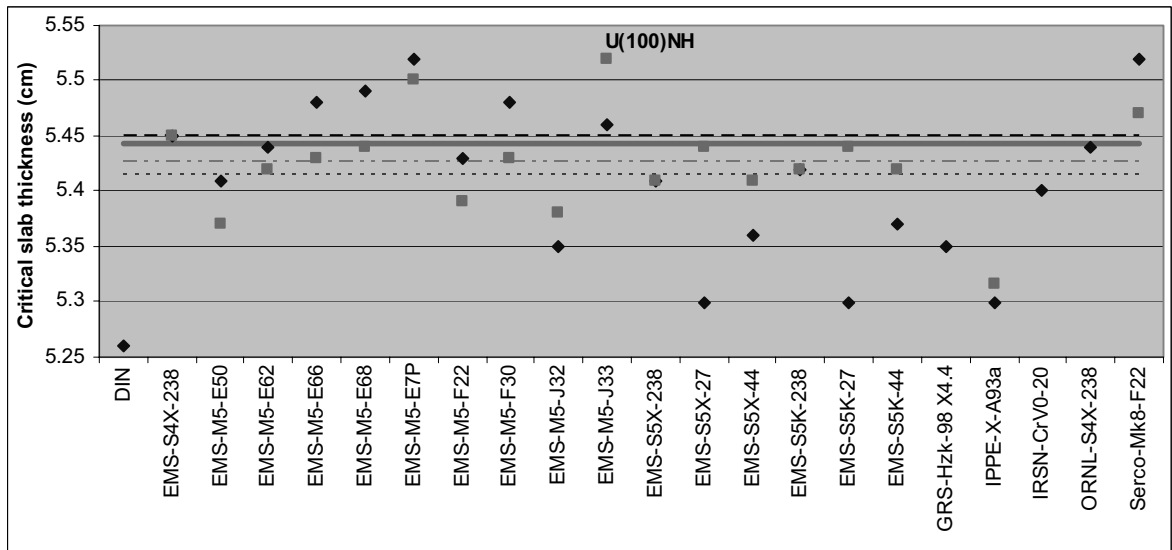


Table G33. Cylinder diameter U(100)NH

Critical cylinder diameter for H ₂ O-reflected U(100)NH + H ₂ O systems			
EALF = 0.163	Cylinder diameter (cm)		
Source	Raw data	Best-estimate	2 σ
DIN	14.7		
EMS-S4X-238	14.99	14.99	+0.50/-0.48
EMS-M5-E50	14.99	14.93	
EMS-M5-E62	15.06	15.04	
EMS-M5-E66	15.09	15.00	
EMS-M5-E68	15.12	15.05	
EMS-M5-E7P	15.18	15.14	
EMS-M5-F22	14.99	14.93	
EMS-M5-F30	15.12	15.05	
EMS-M5-J32	14.89	14.94	
EMS-M5-J33	15.10	15.20	
EMS-S5X-238	15.06	15.06	
EMS-S5X-27	14.86	15.08	
EMS-S5X-44	14.99	15.07	
EMS-S5K-238	15.06	15.06	
EMS-S5K-27	14.85	15.07	
EMS-S5K-44	14.99	15.04	
GRS-Hzk-98	14.8		
IPPE-ABBN93	14.8	14.88	
IRSN-CrV0-20	14.88		
ORNL-S4X-238	15.04		
Serco-Mk8-F22	15.34	15.30	0.6%

Table G34. Slab thickness U(100)NH

Critical slab thickness for H ₂ O-reflected U(100)NH + H ₂ O systems			
EALF = 0.195	Slab thickness (cm)		
Source	Raw data	Best-estimate	2 σ
DIN	5.26		
EMS-S4X-238	5.45	5.45	+0.32/-0.31
EMS-M5-E50	5.41	5.37	
EMS-M5-E62	5.44	5.42	
EMS-M5-E66	5.48	5.43	
EMS-M5-E68	5.49	5.44	
EMS-M5-E7P	5.52	5.50	
EMS-M5-F22	5.43	5.39	
EMS-M5-F30	5.48	5.43	
EMS-M5-J32	5.35	5.38	
EMS-M5-J33	5.46	5.52	
EMS-S5X-238	5.41	5.41	
EMS-S5X-27	5.30	5.44	
EMS-S5X-44	5.36	5.41	
EMS-S5K-238	5.42	5.42	
EMS-S5K-27	5.30	5.44	
EMS-S5K-44	5.37	5.42	
GRS-HzK-98	4.4		
IPPE-ABBN93	5.3	5.32	
IRSN-CrV0-20	5.40		
ORNL-S4X-238	5.44		
Serco-Mk8-F22	5.52	5.47	2.4%

Figure G35. U(100)NH – Concentration

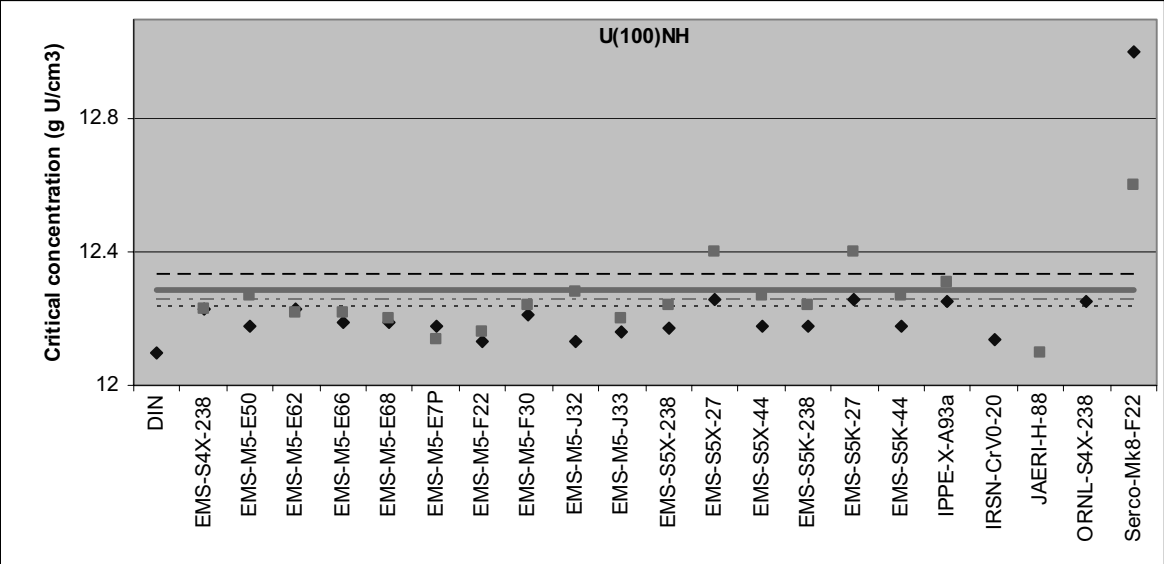


Figure G36. U(100)NH – Moderation

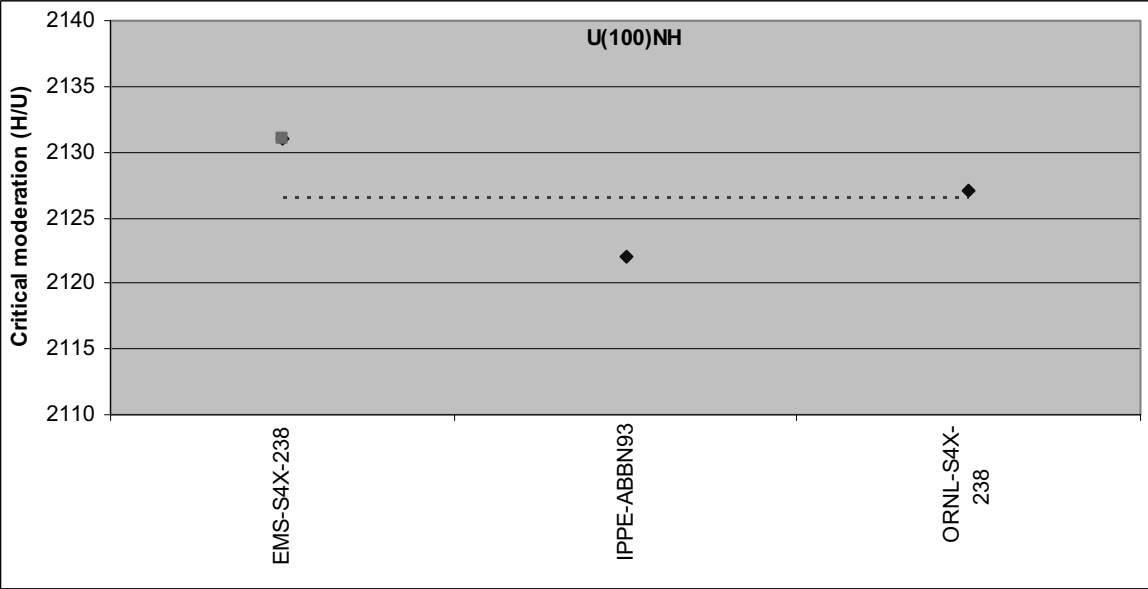


Table G35. Concentration U(100)NH

Critical concentration for H ₂ O-reflected U(100)NH + H ₂ O systems			
EALF = 0.0306	U concentration (g/cm ³)		
Source	Raw data	Best-estimate	2 σ
DIN	12.1		
EMS-S4X-238	12.23	12.23	+0.48/-0.47
EMS-M5-E50	12.18	12.27	
EMS-M5-E62	12.23	12.22	
EMS-M5-E66	12.19	12.22	
EMS-M5-E68	12.19	12.20	
EMS-M5-E7P	12.18	12.14	
EMS-M5-F22	12.13	12.16	
EMS-M5-F30	12.21	12.24	
EMS-M5-J32	12.13	12.28	
EMS-M5-J33	12.16	12.20	
EMS-S5X-238	12.17	12.24	
EMS-S5X-27	12.26	12.40	
EMS-S5X-44	12.18	12.27	
EMS-S5K-238	12.18	12.24	
EMS-S5K-27	12.26	12.40	
EMS-S5K-44	12.18	12.27	
IPPE-ABBN93	12.25	12.31	
IRSN-CrV0-20	12.14		
JAERI-H-88		12.1	
ORNL-S4X-238	12.25		
Serco-Mk8-F22	13	12.6	1.0%

Table G36. Moderation U(100)NH

Critical moderation for H ₂ O-reflected U(100)NH + H ₂ O systems			
EALF = 0.0306	Moderation (H/U)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	2131	2131	-82/ +85
IPPE-ABBN93	2122		
ORNL-S4X-238	2127		

Figure G37. U(20)NH – Mass

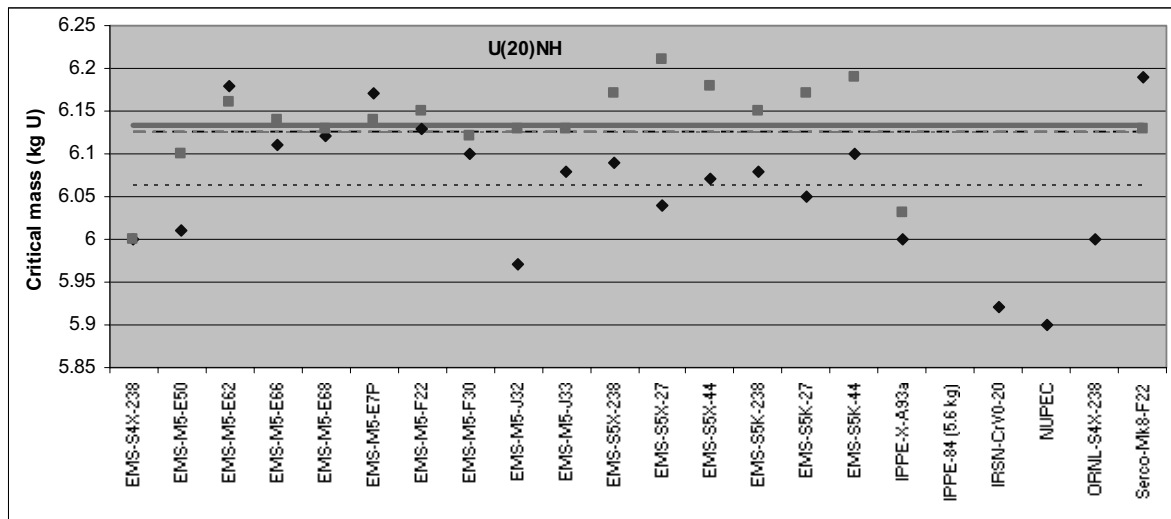


Figure G38. U(20)NH – Volume

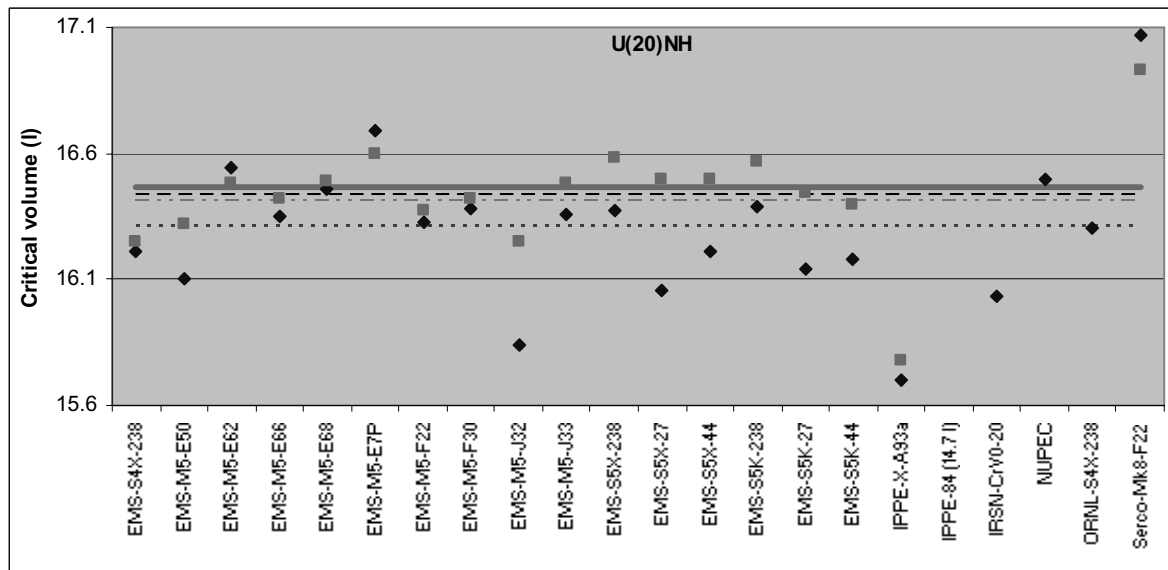


Table G37. Mass – U(20)NH

Critical mass for H ₂ O-reflected U(20)NH + H ₂ O systems			
EALF = 0.0436	Mass (kg U)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	6.0	6.0	+0.68/-0.60
EMS-M5-E50	6.01	6.10	
EMS-M5-E62	6.18	6.16	
EMS-M5-E66	6.11	6.14	
EMS-M5-E68	6.12	6.13	
EMS-M5-E7P	6.17	6.14	
EMS-M5-F22	6.13	6.15	
EMS-M5-F30	6.10	6.12	
EMS-M5-J32	5.97	6.13	
EMS-M5-J33	6.08	6.13	
EMS-S5X-238	6.09	6.17	
EMS-S5X-27	6.04	6.21	
EMS-S5X-44	6.07	6.18	
EMS-S5K-238	6.08	6.15	
EMS-S5K-27	6.05	6.17	
EMS-S5K-44	6.10	6.19	
IPPE-ABBN93	6.0	6.03	
IPPE-84	5.6		
IRSN-CrV0-20	5.92		
NUPEC	5.9		
ORNL-S4X-238	6.0		
Serco-Mk8-F22	6.19	6.13	2.6%

Table G38. Volume for U(20)NH

Critical volume for H ₂ O-reflected U(20)NH + H ₂ O systems			
EALF = 0.0770	Volume (l)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	16.21	16.25	+1.66/-1.48
EMS-M5-E50	16.10	16.32	
EMS-M5-E62	16.54	16.48	
EMS-M5-E66	16.35	16.42	
EMS-M5-E68	16.46	16.49	
EMS-M5-E7P			
EMS-M5-F22	16.33	16.37	
EMS-M5-F30			
EMS-M5-J32	15.84	16.25	
EMS-M5-J33	16.36	16.48	
EMS-S5X-238	16.37	16.58	
EMS-S5X-27	16.06	16.50	
EMS-S5X-44	16.21	16.50	
EMS-S5K-238			
EMS-S5K-27	16.14	16.44	
EMS-S5K-44	16.18	16.40	
IPPE-ABBN93	15.7	15.78	
IPPE-84	14.7		
IRSN-CrV0-20	16.03		
NUPEC	16.5		
ORNL-S4X-238	16.3		
Serco-Mk8-F22	17.07	16.93	2.2%

Figure G39. U(20)NH – Cylinder diameter

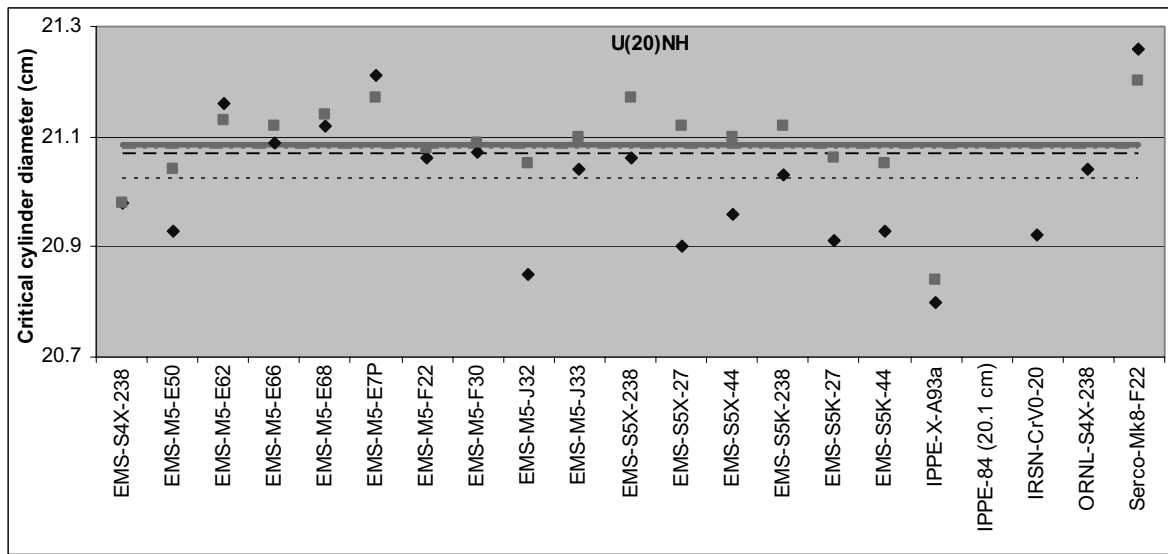


Figure G40. U(20)NH – Slab thickness

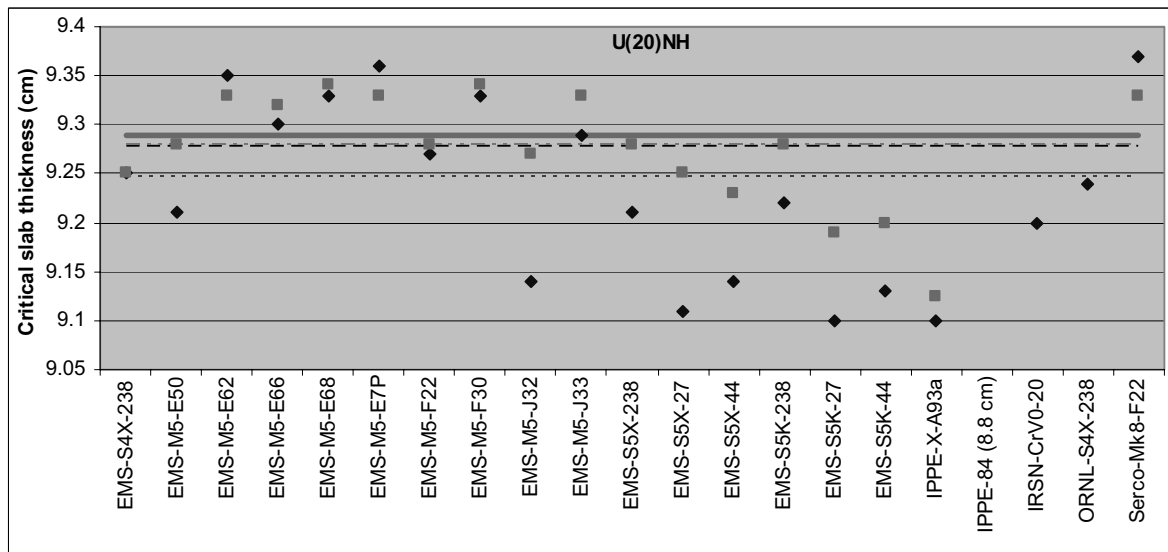


Table G39. Cylinder diameter U(20)NH

Critical cylinder diameter for H ₂ O-reflected U(20)NH + H ₂ O systems			
EALF = 0.0807	Cylinder diameter (cm)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	20.98	20.98	+0.78/-0.74
EMS-M5-E50	20.93	21.04	
EMS-M5-E62	21.16	21.13	
EMS-M5-E66	21.09	21.12	
EMS-M5-E68	21.12	21.14	
EMS-M5-E7P	21.21	21.17	
EMS-M5-F22	21.06	21.08	
EMS-M5-F30	21.07	21.09	
EMS-M5-J32	20.85	21.05	
EMS-M5-J33	21.04	21.10	
EMS-S5X-238	21.06	21.17	
EMS-S5X-27	20.90	21.12	
EMS-S5X-44	20.96	21.10	
EMS-S5K-238	21.03	21.12	
EMS-S5K-27	20.91	21.06	
EMS-S5K-44	20.93	21.05	
IPPE-ABBN93	20.8	20.84	
IPPE-84	20.1		
IRSN-CrV0-20	20.92		
ORNL-S4X-238	21.04		
Serco-Mk8-F22	21.26	21.20	0.8%

Table G40. Slab thickness U(20)NH

Critical slab thickness for H ₂ O-reflected U(20)NH + H ₂ O systems			
EALF = 0.0859	Slab thickness (cm)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	9.25	9.25	+0.50/-0.47
EMS-M5-E50	9.21	9.28	
EMS-M5-E62	9.35	9.33	
EMS-M5-E66	9.30	9.32	
EMS-M5-E68	9.33	9.34	
EMS-M5-E7P			
EMS-M5-F22	9.27	9.28	
EMS-M5-F30			
EMS-M5-J32	9.14	9.27	
EMS-M5-J33	9.29	9.33	
EMS-S5X-238	9.21	9.28	
EMS-S5X-27	9.11	9.25	
EMS-S5X-44	9.14	9.23	
EMS-S5K-238			
EMS-S5K-27	9.10	9.19	
EMS-S5K-44	9.13	9.20	
IPPE-ABBN93	9.1	9.13	
IPPE-84	8.8		
IRSN-CrV0-20	9.2		
ORNL-S4X-238	9.24		
Serco-Mk8-F22	9.37	9.33	

Figure G41. U(20)NH – Concentration

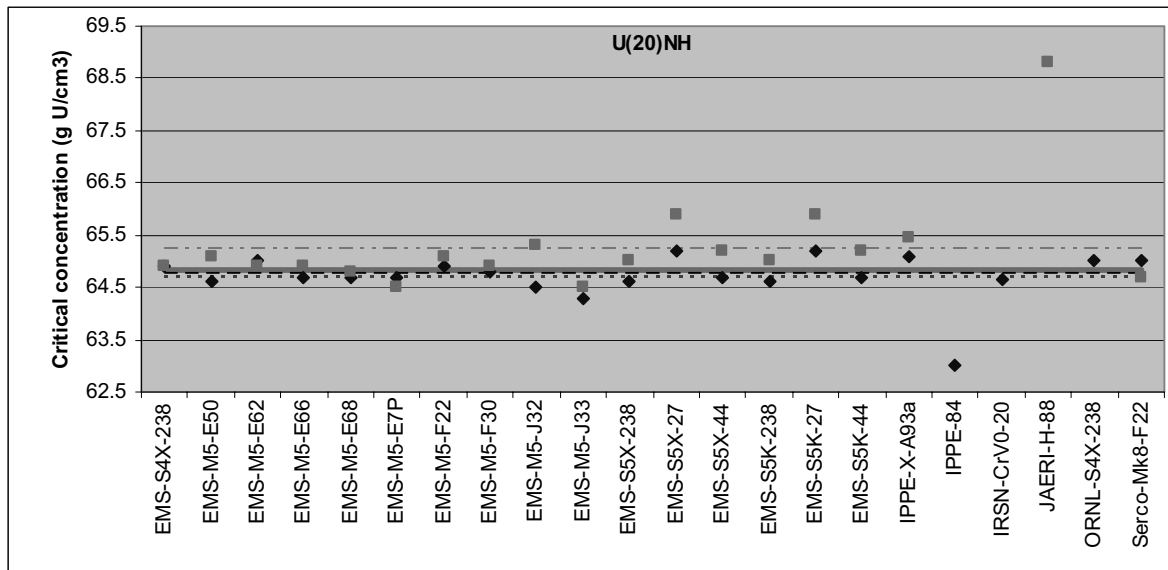


Figure G42. U(20)NH – Moderation H/U

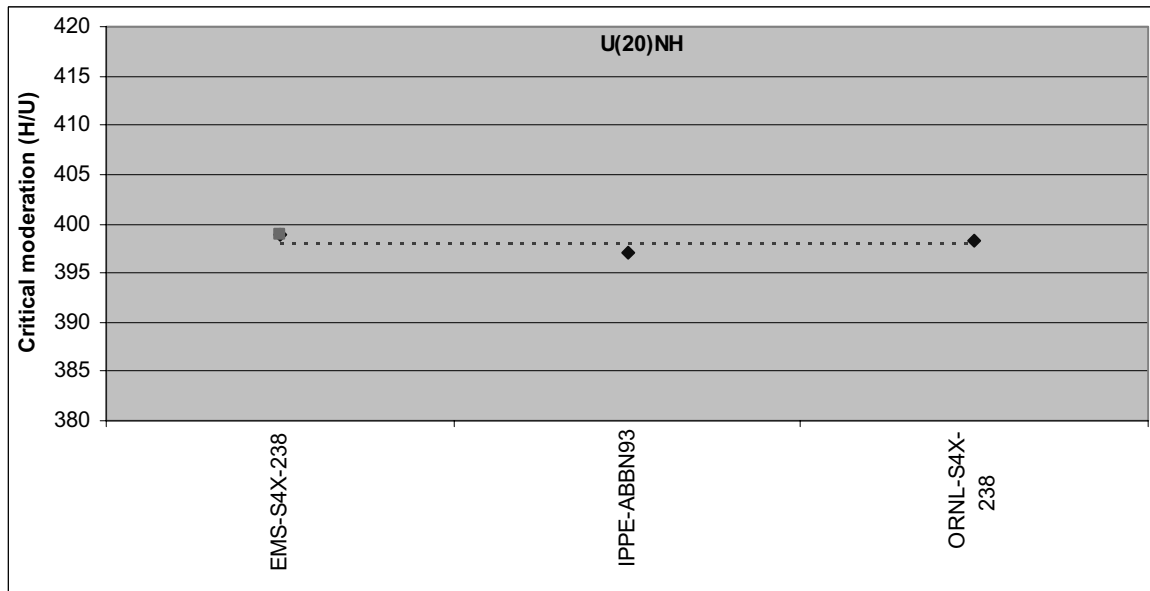


Table G41. Concentration – U(20)NH

Critical concentration for H ₂ O-reflected U(20)NH + H ₂ O systems			
EALF = 0.0316	U concentration (g/cm ³)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	64.9	64.9	+2.7/-2.7
EMS-M5-E50	64.6	65.1	
EMS-M5-E62	65.0	64.9	
EMS-M5-E66	64.7	64.9	
EMS-M5-E68	64.7	64.8	
EMS-M5-E7P	64.7	64.5	
EMS-M5-F22	64.9	65.1	
EMS-M5-F30	64.8	64.9	
EMS-M5-J32	64.5	65.3	
EMS-M5-J33	64.3	64.5	
EMS-S5X-238	64.6	65.0	
EMS-S5X-27	65.2	65.9	
EMS-S5X-44	64.7	65.2	
EMS-S5K-238	64.6	65.0	
EMS-S5K-27	65.2	65.9	
EMS-S5K-44	64.7	65.2	
IPPE-ABBN93	65.1	65.4	
IPPE-84	63		
IRSN-CrV0-20	64.64		
JAERI-H-88		68.8	
ORNL-S4X-238	65.0		
Serco-Mk8-F22	65	64.7	0.8%

Table G42. Moderation U(20)NH

Critical moderation for H ₂ O-reflected U(20)NH + H ₂ O systems			
EALF = 0.0316	Moderation (H/U)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	398.9	398.9	-16.6/ +17.4
IPPE-ABBN93	397.0		
ORNL-S4X-238	398.2		

Figure G43. U(5)NH – Mass

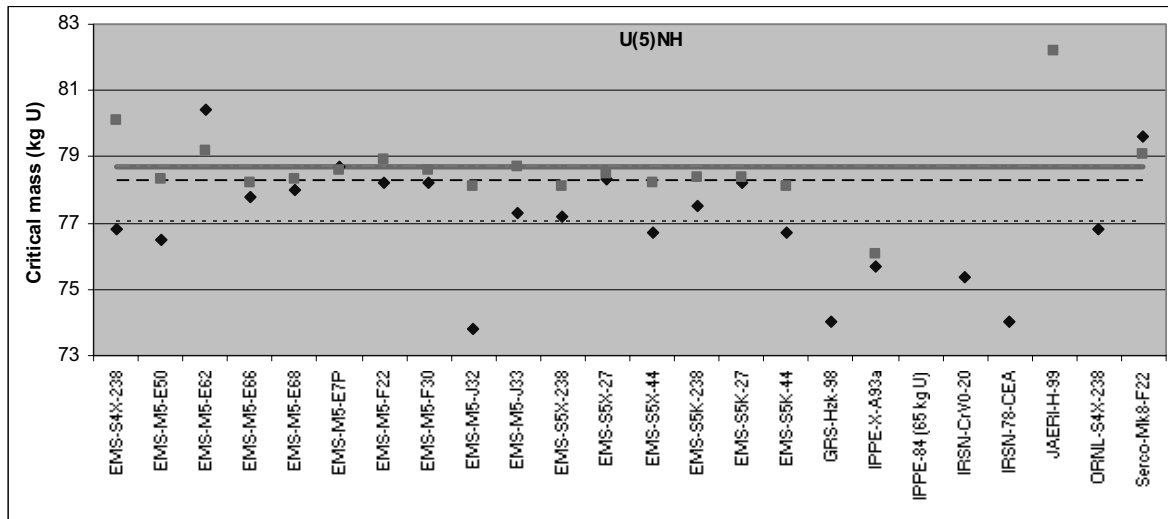


Figure G44. U(5)NH – Volume

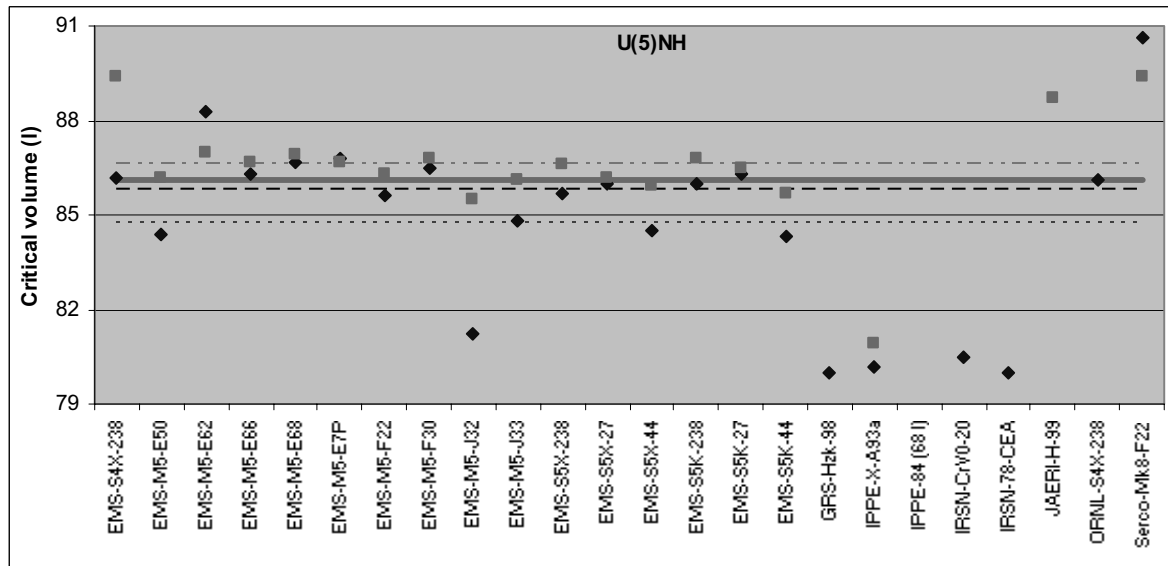


Table G43. Mass – U(5)NH

Critical mass for H ₂ O-reflected U(5)NH + H ₂ O systems			
EALF = 0.0534	Mass (kg U)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	76.8	80.1	+10.9/-9.4
EMS-M5-E50	76.5	78.3	
EMS-M5-E62	80.4	79.2	
EMS-M5-E66	77.8	78.2	
EMS-M5-E68	78.0	78.3	
EMS-M5-E7P	78.7	78.6	
EMS-M5-F22	78.2	78.9	
EMS-M5-F30	78.2	78.6	
EMS-M5-J32	73.8	78.1	
EMS-M5-J33	77.3	78.7	
EMS-S5X-238	77.2	78.1	
EMS-S5X-27	78.3	78.5	
EMS-S5X-44	76.7	78.2	
EMS-S5K-238	77.5	78.4	
EMS-S5K-27	78.2	78.4	
EMS-S5K-44	76.7	78.1	
GRS-HzK-98	74 ²¹		
GRS-S4X-8-Iso	77.0		
IPPE-ABBN93	75.7	76.1	
IPPE-84	65		
IRSN-CrV0-20	75.4		
IRSN-78-CEA	74*		
JAERI-H-99		82.2	
ORNL-S4X-238	76.8		
Serco-Mk8-F22	79.6	79.1	1.8%

Table G44. Volume for U(5)NH

Critical volume for H ₂ O-reflected U(5)NH + H ₂ O systems			
EALF = 0.0709	Volume (l)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	86.2	89.4	+11.1/-9.5
EMS-M5-E50	84.4	86.2	
EMS-M5-E62	88.3	87.0	
EMS-M5-E66	86.3	86.7	
EMS-M5-E68	86.7	86.9	
EMS-M5-E7P	86.8	86.7	
EMS-M5-F22	85.6	86.3	
EMS-M5-F30	86.5	86.8	
EMS-M5-J32	81.2	85.5	
EMS-M5-J33	84.8	86.1	
EMS-S5X-238	85.7	86.6	
EMS-S5X-27	86.0	86.2	
EMS-S5X-44	84.5	85.9	
EMS-S5K-238	86.0	86.8	
EMS-S5K-27	86.3	86.5	
EMS-S5K-44	84.3	85.7	
GRS-HzK-98	80 ¹		
GRS-S4X-8-Iso	81.6		
IPPE-ABBN93	80.2	80.9	
IPPE-84	68		
IRSN-CrV0-20	80.5		
IRSN-78-CEA	80 ¹		
JAERI-H-99		88.7	
ORNL-S4X-238	86.1		
Serco-Mk8-F22	90.6	89.4	3.4 %

* Many GRS-HzK and IRSN-78 values are identical
GRS values do not agree with curves

Figure G45. U(5)NH – Cylinder diameter

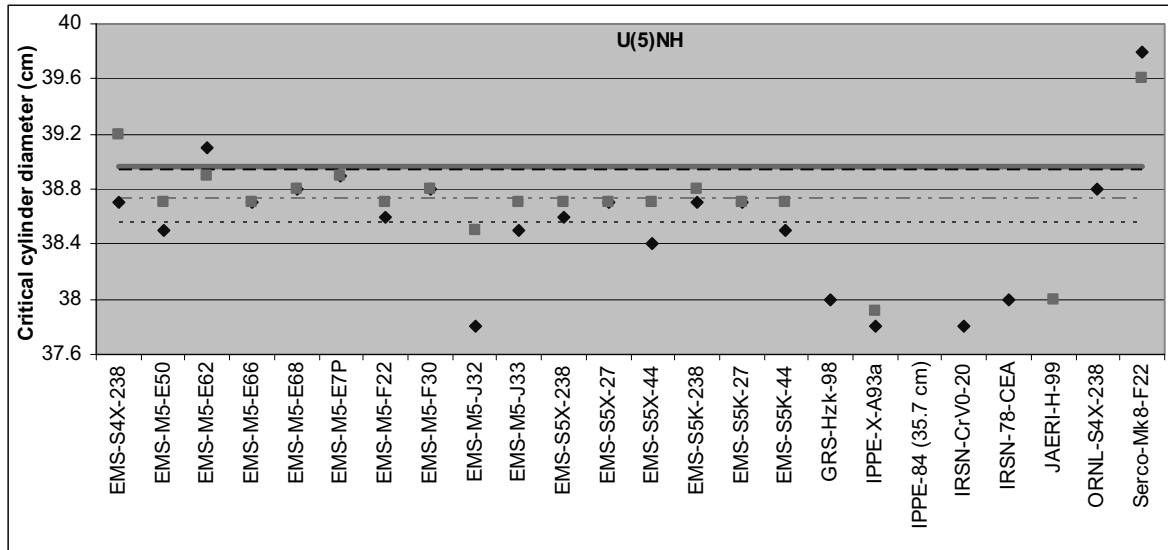


Figure G46. U(5)NH – Slab thickness

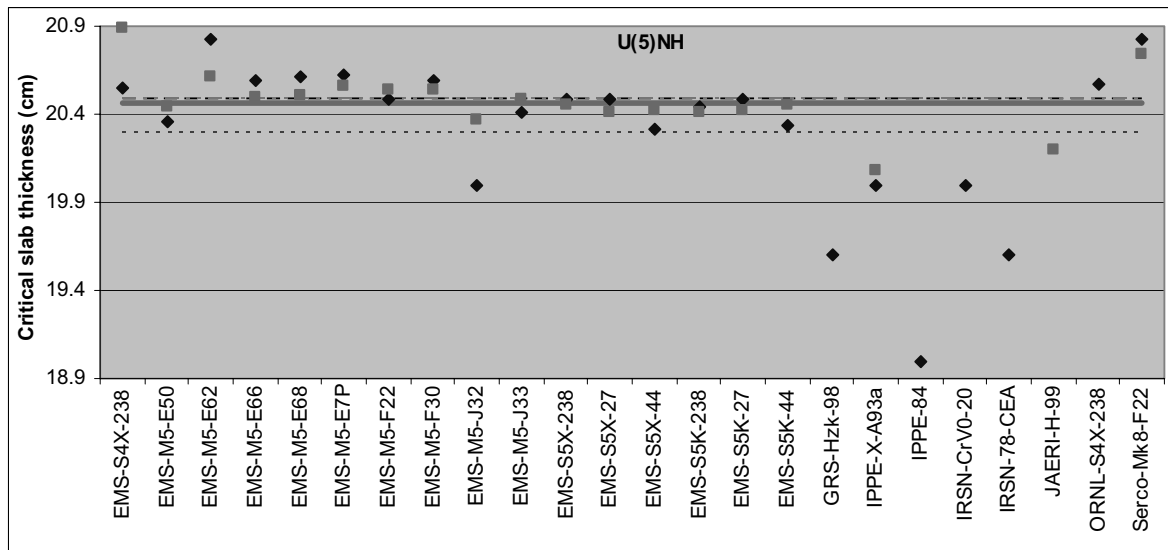


Table G45. Cylinder diameter U(5)NH

Critical cylinder diameter for H ₂ O-reflected U(5)NH + H ₂ O systems			
EALF = 0.0713	Cylinder diameter (cm)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	38.7	39.2	+1.7/-1.5
EMS-M5-E50	38.5	38.7	
EMS-M5-E62	39.1	38.9	
EMS-M5-E66	38.7	38.7	
EMS-M5-E68	38.8	38.8	
EMS-M5-E7P	38.9	38.9	
EMS-M5-F22	38.6	38.7	
EMS-M5-F30	38.8	38.8	
EMS-M5-J32	37.8	38.5	
EMS-M5-J33	38.5	38.7	
EMS-S5X-238	38.6	38.7	
EMS-S5X-27	38.7	38.7	
EMS-S5X-44	38.4	38.7	
EMS-S5K-238	38.7	38.8	
EMS-S5K-27	38.7	38.7	
EMS-S5K-44	38.5	38.7	
GRS-HzK-98	38 ²²		
IPPE-ABBN93	37.8	37.9	
IPPE-84	35.7		
IRSN-CrV0-20	37.8		
IRSN-78-CEA	38.0		
JAERI-H-99		38	
ORNL-S4X-238	38.8		
Serco-Mk8-F22	39.8	39.6	1.2%

Table G46. Slab thickness U(5)NH

Critical slab thickness for H ₂ O-reflected U(5)NH + H ₂ O systems			
EALF = 0.0735	Slab thickness (cm)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	20.55	20.89	+1.08/-1.10
EMS-M5-E50	20.36	20.44	
EMS-M5-E62	20.83	20.61	
EMS-M5-E66	20.59	20.50	
EMS-M5-E68	20.61	20.51	
EMS-M5-E7P	20.62	20.56	
EMS-M5-F22	20.48	20.54	
EMS-M5-F30	20.59	20.54	
EMS-M5-J32	20.00	20.37	
EMS-M5-J33	20.41	20.48	
EMS-S5X-238	20.48	20.45	
EMS-S5X-27	20.48	20.41	
EMS-S5X-44	20.32	20.42	
EMS-S5K-238	20.44	20.41	
EMS-S5K-27	20.49	20.42	
EMS-S5K-44	20.34	20.45	
GRS-HzK-98	19.6		
IPPE-ABBN93	20.0	20.08	
IPPE-84	19.0		
IRSN-CrV0-20	20		
IRSN-78-CEA	19.6		
JAERI-H-99		20.2	
ORNL-S4X-238	20.57		
Serco-Mk8-F22	20.83	20.74	1.0%

* Many GRS-HzK and IRSN-78 values are identical
GRS values do not agree with curves

Figure G47. U(5)NH – Concentration

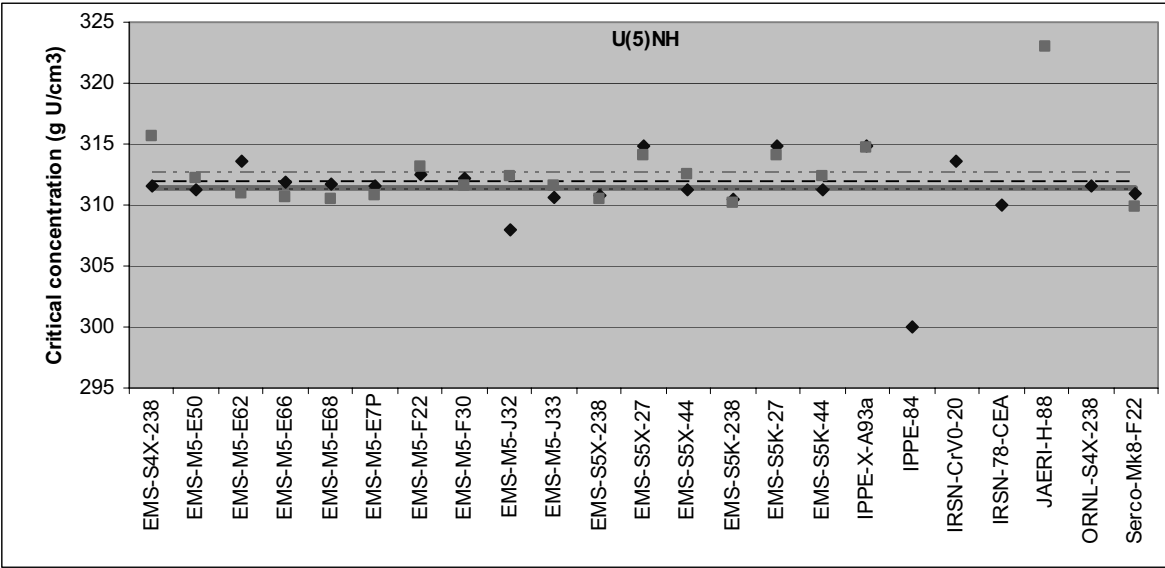


Figure G48. U(5)NH – Moderation H/U

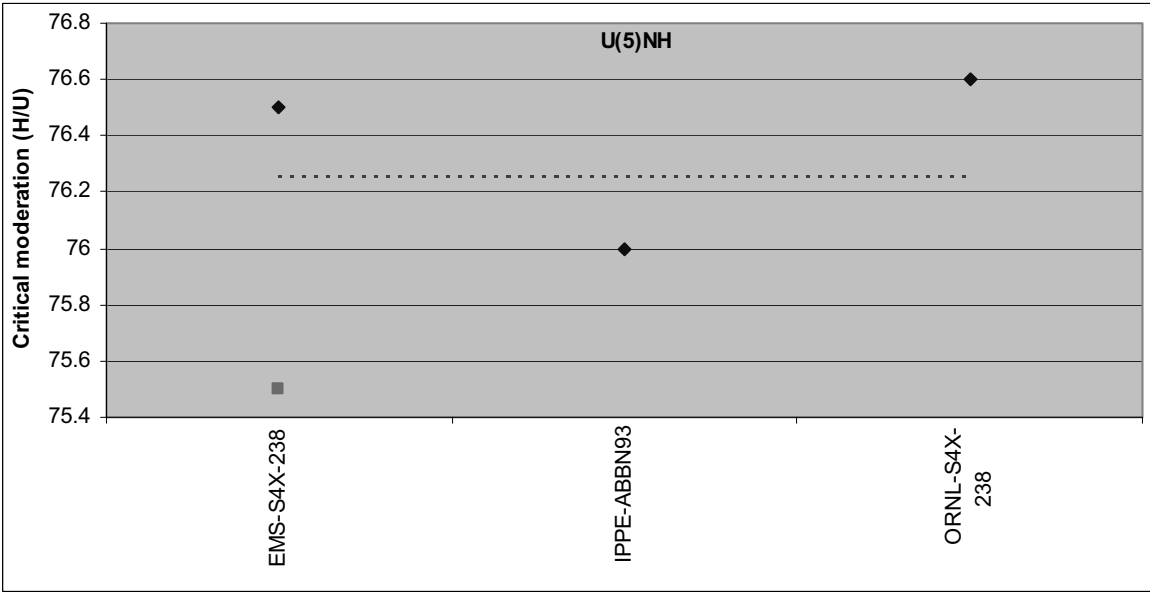


Table G47. Concentration U(5)NH

Critical concentration for H ₂ O-reflected U(5)NH + H ₂ O systems			
EALF = 0.0361	U concentration (g/cm ³)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	311.6	315.7	+12.6/-12.0
EMS-M5-E50	311.2	312.2	
EMS-M5-E62	313.6	311.0	
EMS-M5-E66	311.8	310.7	
EMS-M5-E68	311.7	310.4	
EMS-M5-E7P	311.6	310.8	
EMS-M5-F22	312.5	313.2	
EMS-M5-F30	312.2	311.6	
EMS-M5-J32	308.0	312.4	
EMS-M5-J33	310.7	311.5	
EMS-S5X-238	310.8	310.4	
EMS-S5X-27	314.8	314.0	
EMS-S5X-44	311.3	312.5	
EMS-S5K-238	310.5	310.1	
EMS-S5K-27	314.8	314.0	
EMS-S5K-44	311.2	312.4	
IPPE-ABBN93	314.8	314.7	
IPPE-84	300		
IRSN-CrV0-20	313.6		
IRSN-78-CEA	310		
JAERI-H-88		323	
ORNL-S4X-238	311.5		
Serco-Mk8-F22	311.0	309.9	1.0%

Table G48. Moderation U(5)NH

Critical moderation for H ₂ O-reflected U(5)NH + H ₂ O systems			
EALF = 0.0361	Moderation (H/U)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	76.5	75.5	-3.3/ +3.3
IPPE-ABBN93	76.0		
IRSN-78-CEA	72		
ORNL-S4X-238	76.6		

Figure G49. U(4)NH – Mass

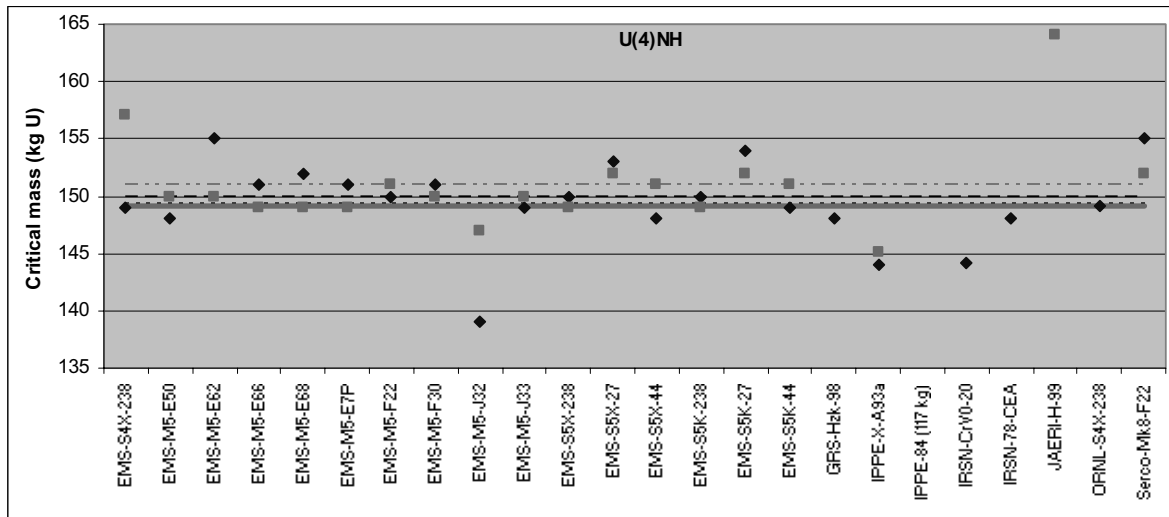


Figure G50. U(4)NH – Volume

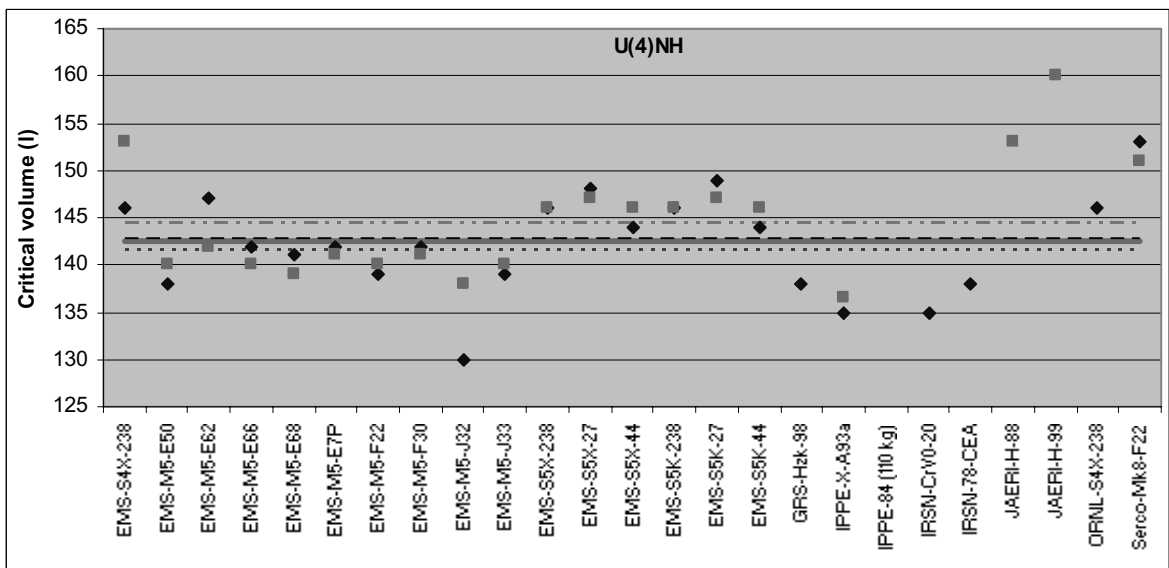


Table G49. Mass – U(4)NH

Critical mass for H ₂ O-reflected U(4)NH + H ₂ O systems			
EALF = 0.0572	Mass (kg U)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	149	157	+27/-22
EMS-M5-E50	148	150	
EMS-M5-E62	155	150	
EMS-M5-E66	151	149	
EMS-M5-E68	152	149	
EMS-M5-E7P	151	149	
EMS-M5-F22	150	151	
EMS-M5-F30	151	150	
EMS-M5-J32	139	147	
EMS-M5-J33	149	150	
EMS-S5X-238	150	149	
EMS-S5X-27	153	152	
EMS-S5X-44	148	151	
EMS-S5K-238	150	149	
EMS-S5K-27	154	152	
EMS-S5K-44	149	151	
GRS-HzK-98	148 ²³		
GRS-S4X-8-Iso	142.8		
IPPE-ABBN93	144	145	
IPPE-84	117		
IRSN-CrV0-20	144.2		
IRSN-78-CEA	148		
JAERI-H-99		164	
ORNL-S4X-238	149.1		
Serco-Mk8-F22	155	152	6.0%

Table G50. Volume for U(4)NH

Critical volume for H ₂ O-reflected U(4)NH + H ₂ O systems			
EALF = 0.0730	Volume (l)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	146	153	+24/-19
EMS-M5-E50	138	140	
EMS-M5-E62	147	142	
EMS-M5-E66	142	140	
EMS-M5-E68	141	139	
EMS-M5-E7P	142	141	
EMS-M5-F22	139	140	
EMS-M5-F30	142	141	
EMS-M5-J32	130	138	
EMS-M5-J33	139	140	
EMS-S5X-238	146	146	
EMS-S5X-27	148	147	
EMS-S5X-44	144	146	
EMS-S5K-238	146	146	
EMS-S5K-27	149	147	
EMS-S5K-44	144	146	
GRS-HzK-98	138		
GRS-S4X-8-Iso	137		
IPPE-ABBN93	135	137	
IPPE-84	110		
IRSN-CrV0-20	135		
IRSN-78-CEA	138		
JAERI-H-88		153	
JAERI-H-99		160	
ORNL-S4X-238	146		
Serco-Mk8-F22	153	151	2.8%

* Many GRS-HzK and IRSN-78 values are identical
GRS values do not agree with curves

Figure G51. U(4)NH – Cylinder diameter

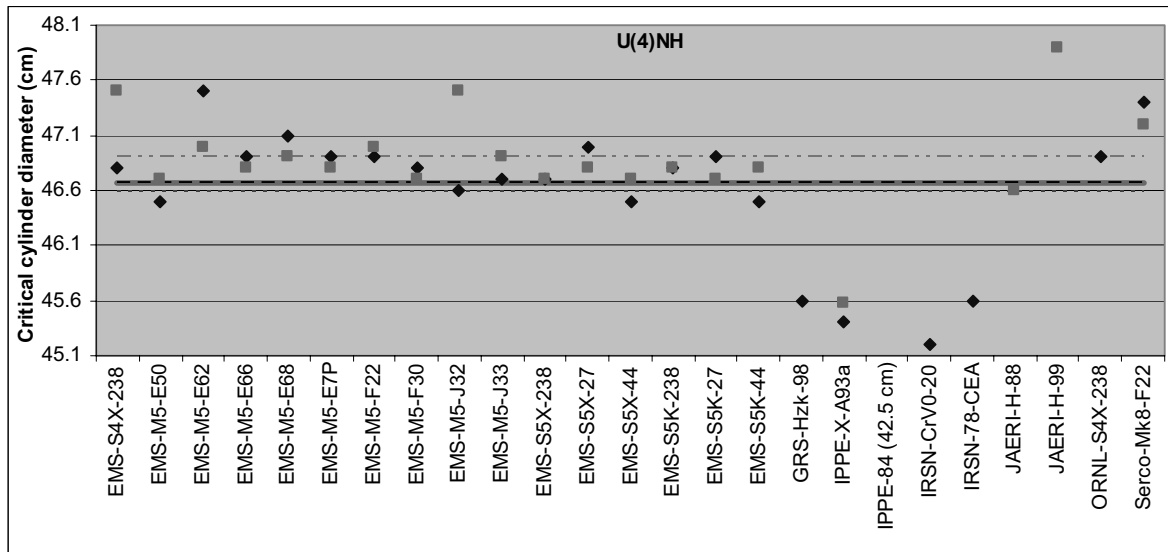


Figure G52. U(4)NH – Slab thickness

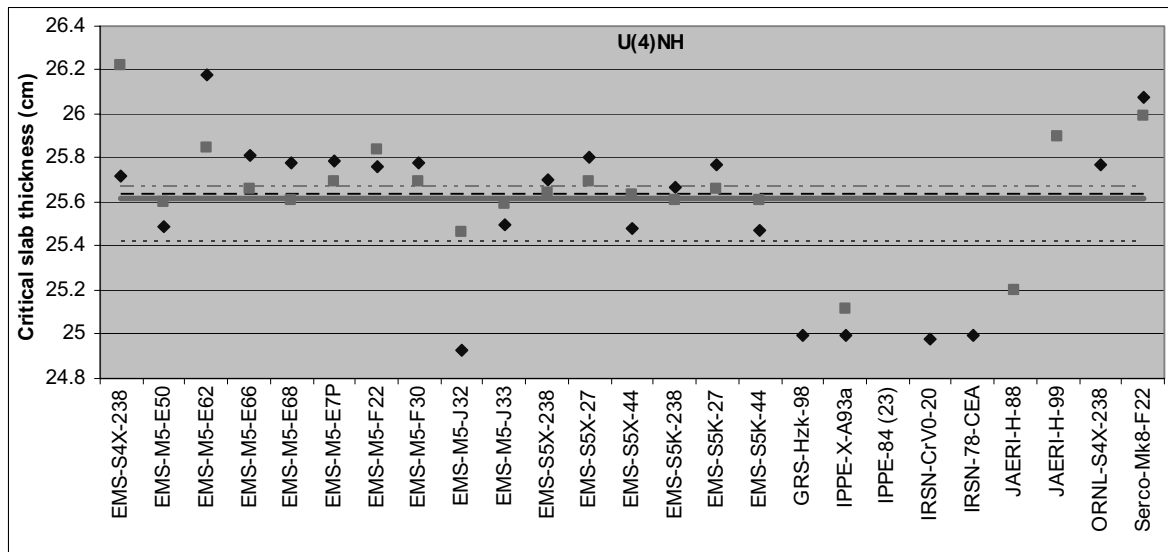


Table G51. Cylinder diameter U(4)NH

Critical cylinder diameter for H ₂ O-reflected U(4)NH + H ₂ O systems			
EALF = 0.0727	Cylinder diameter (cm)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	46.8	47.5	+2.5/-2.2
EMS-M5-E50	46.5	46.7	
EMS-M5-E62	47.5	47.0	
EMS-M5-E66	46.9	46.8	
EMS-M5-E68	47.1	46.9	
EMS-M5-E7P	46.9	46.8	
EMS-M5-F22	46.9	47.0	
EMS-M5-F30	46.8	46.7	
EMS-M5-J32	46.6	47.5	
EMS-M5-J33	46.7	46.9	
EMS-S5X-238	46.7	46.7	
EMS-S5X-27	47.0	46.8	
EMS-S5X-44	46.5	46.7	
EMS-S5K-238	46.8	46.8	
EMS-S5K-27	46.9	46.7	
EMS-S5K-44	46.5	46.8	
GRS-HzK-98	45.6*		
IPPE-ABBN93	45.4	45.6	
IPPE-84	42.5		
IRSN-CrV0-20	45.2		
IRSN-78-CEA	45.6		
JAERI-H-88		46.6	
JAERI-H-99		47.9	
ORNL-S4X-238	46.9		
Serco-Mk8-F22	47.4	47.2	1.4%

Table G52. Slab thickness U(4)NH

Critical slab thickness for H ₂ O-reflected U(4)NH + H ₂ O systems			
EALF = 0.0753	Slab thickness (cm)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	25.72	26.22	+1.59/-1.45
EMS-M5-E50	25.49	25.60	
EMS-M5-E62	26.18	25.85	
EMS-M5-E66	25.81	25.66	
EMS-M5-E68	25.78	25.61	
EMS-M5-E7P	25.79	25.69	
EMS-M5-F22	25.76	25.84	
EMS-M5-F30	25.78	25.69	
EMS-M5-J32	24.93	25.46	
EMS-M5-J33	25.50	25.59	
EMS-S5X-238	25.70	25.64	
EMS-S5X-27	25.80	25.69	
EMS-S5X-44	25.48	25.63	
EMS-S5K-238	25.67	25.61	
EMS-S5K-27	25.77	25.66	
EMS-S5K-44	25.47	25.61	
GRS-HzK-98	25		
IPPE-ABBN93	25.0	25.11	
IPPE-84	23.0		
IRSN-CrV0-20	24.98		
IRSN-78-CEA	25		
JAERI-H-88		25.2	
JAERI-H-99		25.9	
ORNL-S4X-238	25.77		
Serco-Mk8-F22	26.08	25.99	0.8%

* Many GRS-HzK and IRSN-78 values are identical.
GRS values do not agree with curves.

Figure G53. U(4)NH – Concentration

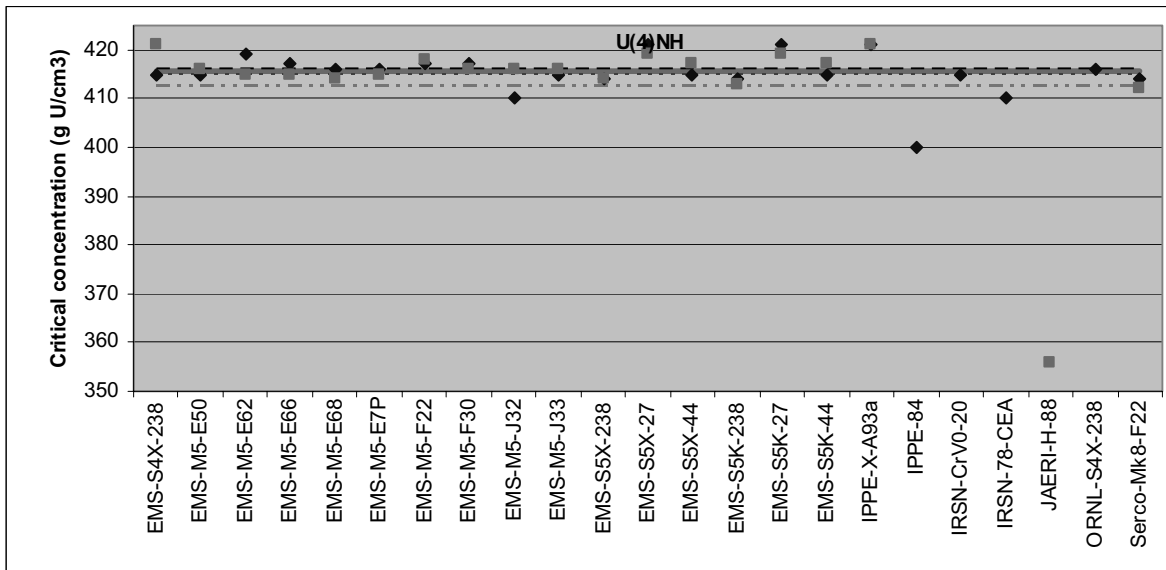


Figure G54. U(4)NH – Moderation H/U

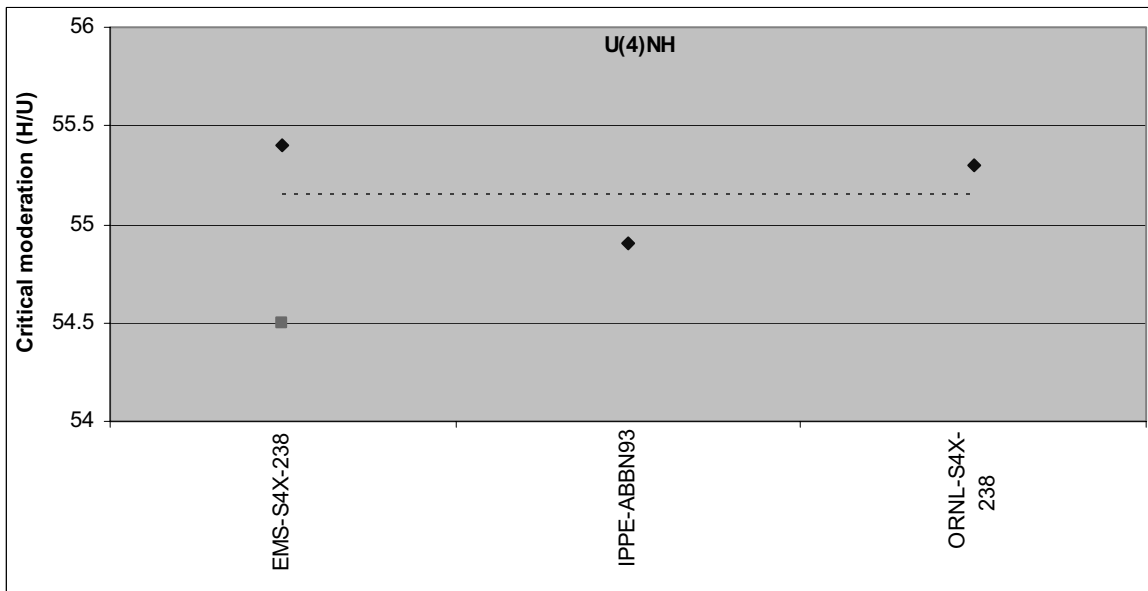


Table G53. Concentration – U(4)NH

Critical concentration for H₂O-reflected U(4)NH + H₂O systems			
EALF = 0.0384	U concentration (g/cm ³)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	415	421	+18/-17
EMS-M5-E50	415	416	
EMS-M5-E62	419	415	
EMS-M5-E66	417	415	
EMS-M5-E68	416	414	
EMS-M5-E7P	416	415	
EMS-M5-F22	417	418	
EMS-M5-F30	417	416	
EMS-M5-J32	410	416	
EMS-M5-J33	415	416	
EMS-S5X-238	414	414	
EMS-S5X-27	421	419	
EMS-S5X-44	415	417	
EMS-S5K-238	414	413	
EMS-S5K-27	421	419	
EMS-S5K-44	415	417	
IPPE-ABBN93	421	421	
IPPE-84	400		
IRSN-CrV0-20	415		
IRSN-78-CEA	410		
JAERI-H-88		356	
ORNL-S4X-238	416		
Serco-Mk8-F22	414	412	1.2%

Table G54. Moderation U(4)NH

Critical moderation for H₂O-reflected U(4)NH + H₂O systems			
EALF = 0.0384	Moderation (H/U)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	55.4	54.5	-2.7/ +2.7
IPPE-ABBN93	54.9		
IRSN-78-CEA	56		
ORNL-S4X-238	55.3		

Figure G55. U(3)NH – Mass

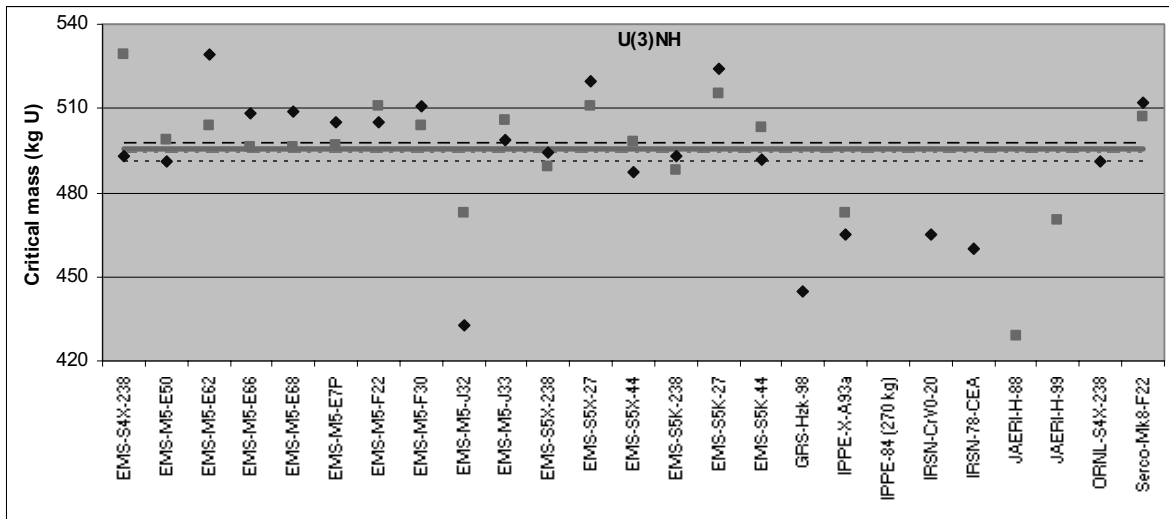


Figure G56. U(3)NH – Volume

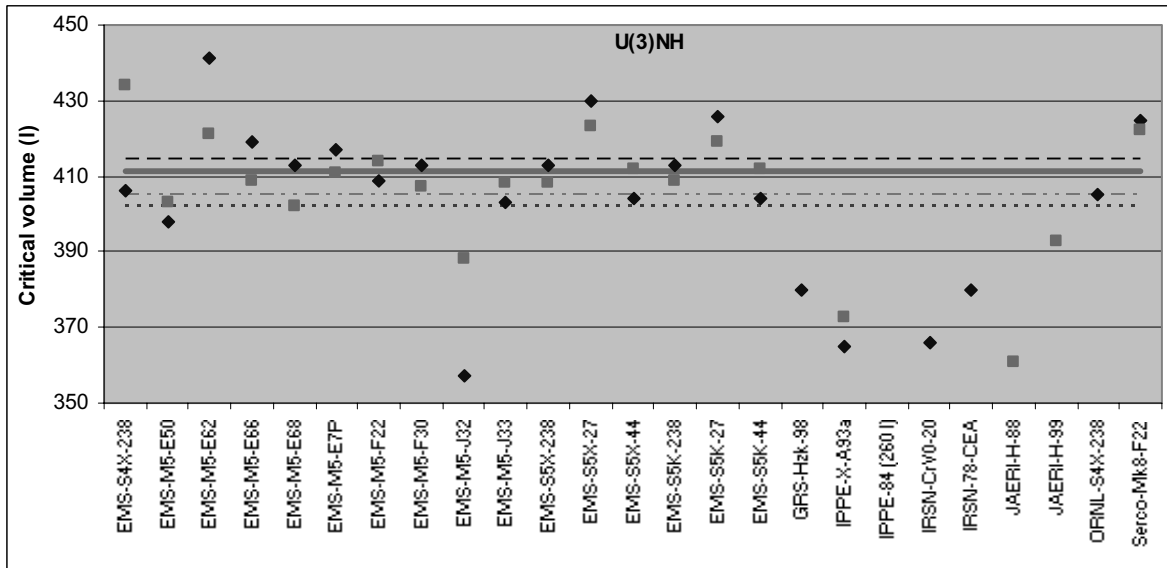


Table G55. Mass – U(3)NH

Critical mass for H ₂ O-reflected U(3)NH + H ₂ O systems			
EALF = 0.0689	Mass (kg U)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	493	529	+144/-103
EMS-M5-E50	491	499	
EMS-M5-E62	529	504	
EMS-M5-E66	508	496	
EMS-M5-E68	509	496	
EMS-M5-E7P	505	497	
EMS-M5-F22	505	511	
EMS-M5-F30	511	504	
EMS-M5-J32	433	473	
EMS-M5-J33	499	506	
EMS-S5X-238	494	489	
EMS-S5X-27	520	511	
EMS-S5X-44	487	498	
EMS-S5K-238	493	488	
EMS-S5K-27	524	515	
EMS-S5K-44	492	503	
GRS-HzK-98	445*		
GRS-S4X-8-Iso	426		
IPPE-ABBN93	465	473	
IPPE-84	270		
IRSN-CrV0-20	465		
IRSN-78-CEA	460		
JAERI-H-88		429	
JAERI-H-99		470	
ORNL-S4X-238	491		
Serco-Mk8-F22	512	507	2.8%

* Corrected from 485 (in 1985 rev. of Handbook)
The only low-enriched UNH system with different
GRS and IRSN-78 values

Table G56. Volume for U(3)NH

Critical volume for H ₂ O-reflected U(3)NH + H ₂ O systems			
EALF = 0.0809	Volume (l)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	406	434	+110/-81
EMS-M5-E50	398	403	
EMS-M5-E62	441	421	
EMS-M5-E66	419	409	
EMS-M5-E68	413	402	
EMS-M5-E7P	417	411	
EMS-M5-F22	409	414	
EMS-M5-F30	413	407	
EMS-M5-J32	357	388	
EMS-M5-J33	403	408	
EMS-S5X-238	413	408	
EMS-S5X-27	430	423	
EMS-S5X-44	404	412	
EMS-S5K-238	413	409	
EMS-S5K-27	426	419	
EMS-S5K-44	404	412	
GRS-HzK-98	380*		
GRS-S4X-8-Iso	370		
IPPE-ABBN93	365	373	
IPPE-84	260		
IRSN-CrV0-20	366		
IRSN-78-CEA	380		
JAERI-H-88		361	
JAERI-H-99		393	
ORNL-S4X-238	405		
Serco-Mk8-F22	425	422	1.8%

* Many GRS-HzK and IRSN-78 values are identical
GRS values don't agree with curves

Figure G57. U(3)NH – Cylinder diameter

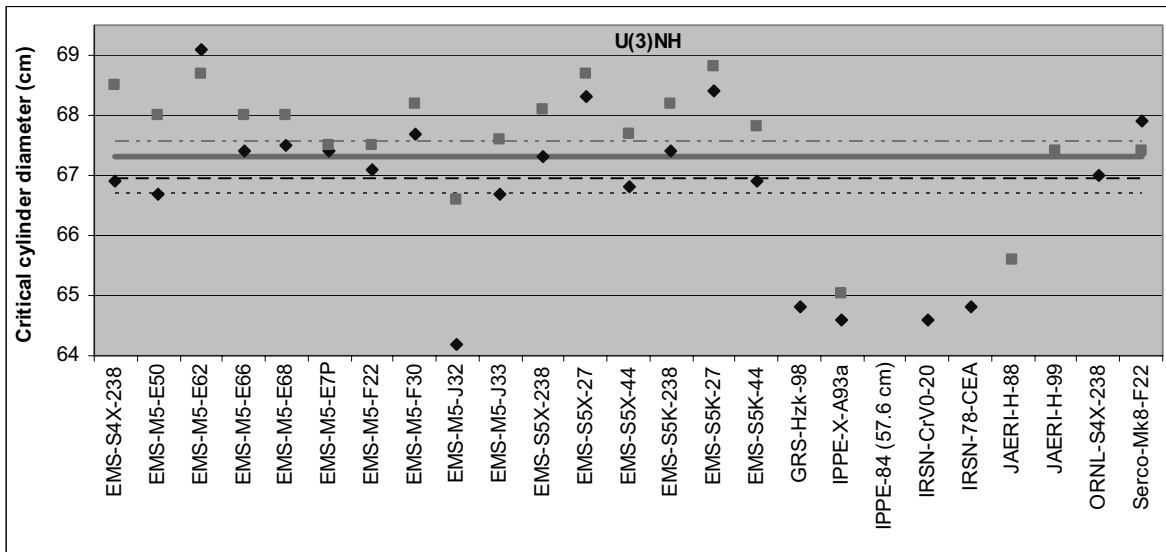


Figure G58. U(3)NH – Slab thickness

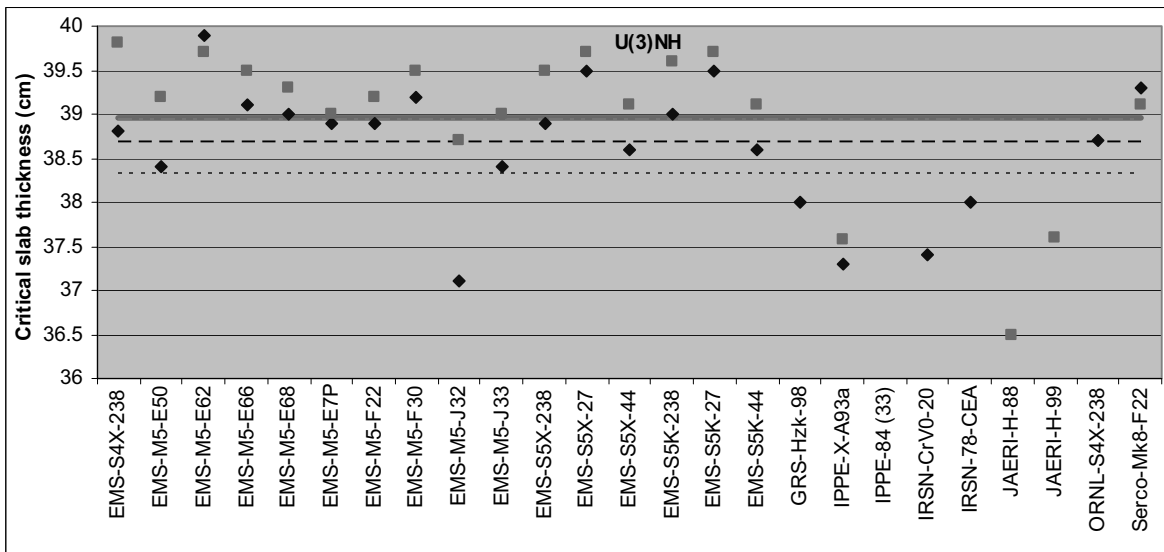


Table G57. Cylinder diameter U(3)NH

Critical cylinder diameter for H ₂ O-reflected U(3)NH + H ₂ O systems			
EALF = 0.0808	Cylinder diameter (cm)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	66.9	68.5	+5.6/-4.8
EMS-M5-E50	66.7	68.0	
EMS-M5-E62	69.1	68.7	
EMS-M5-E66	67.4	68.0	
EMS-M5-E68	67.5	68.0	
EMS-M5-E7P	67.4	67.5	
EMS-M5-F22	67.1	67.5	
EMS-M5-F30	67.7	68.2	
EMS-M5-J32	64.2	66.6	
EMS-M5-J33	66.7	67.6	
EMS-S5X-238	67.3	68.1	
EMS-S5X-27	68.3	68.7	
EMS-S5X-44	66.8	67.7	
EMS-S5K-238	67.4	68.2	
EMS-S5K-27	68.4	68.8	
EMS-S5K-44	66.9	67.8	
GRS-HzK-98	64.8 *		
IPPE-ABBN93	64.6	65.0	
IPPE-84	57.6		
IRSN-CrV0-20	64.6		
IRSN-78-CEA	64.8		
JAERI-H-88		65.6	
JAERI-H-99		67.4	
ORNL-S4X-238	67.0		
Serco-Mk8-F22	67.9	67.4	1.8%

Table G58. Slab thickness U(3)NH

Critical slab thickness for H ₂ O-reflected U(3)NH + H ₂ O systems			
EALF = 0.0804	Slab thickness (cm)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	38.8	39.8	+3.6/-3.1
EMS-M5-E50	38.4	39.2	
EMS-M5-E62	39.9	39.7	
EMS-M5-E66	39.1	39.5	
EMS-M5-E68	39.0	39.3	
EMS-M5-E7P	38.9	39.0	
EMS-M5-F22	38.9	39.2	
EMS-M5-F30	39.2	39.5	
EMS-M5-J32	37.1	38.7	
EMS-M5-J33	38.4	39.0	
EMS-S5X-238	38.9	39.5	
EMS-S5X-27	39.5	39.7	
EMS-S5X-44	38.6	39.1	
EMS-S5K-238	39.0	39.6	
EMS-S5K-27	39.5	39.7	
EMS-S5K-44	38.6	39.1	
GRS-HzK-98	38		
IPPE-ABBN93	37.3	37.6	
IPPE-84	33.0		
IRSN-CrV0-20	37.4		
IRSN-78-CEA	38.0		
JAERI-H-88		36.5	
JAERI-H-99		37.6	
ORNL-S4X-238	38.7		
Serco-Mk8-F22	39.3	39.1	1.8%

* Many GRS-HzK and IRSN-78 values are identical
GRS values do not agree with curves

Figure G59. U(3)NH – Concentration

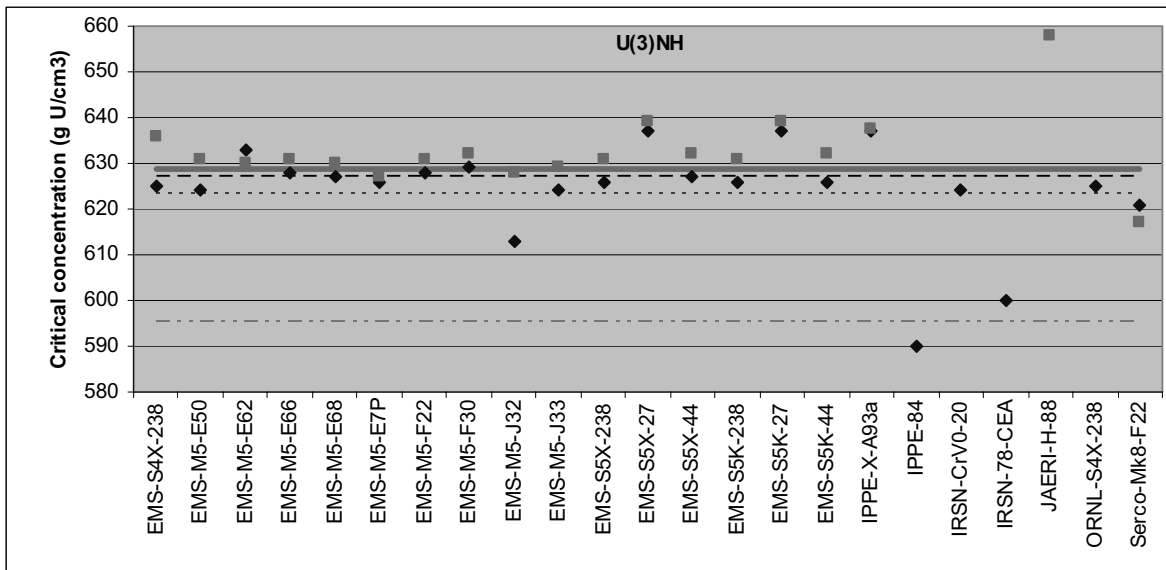


Figure G60. U(3)NH – Moderation H/U

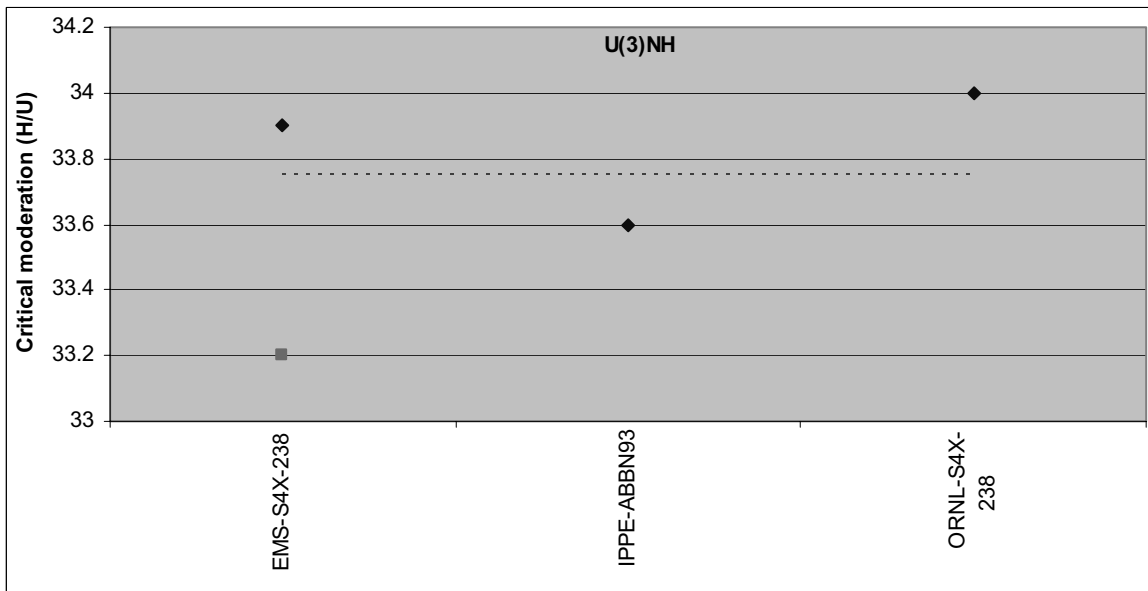


Table G59. Concentration – U(3)NH

Critical concentration for H₂O-reflected U(3)NH + H₂O systems			
EALF = 0.0438	U concentration (g/cm ³)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	625	636	+34/-31
EMS-M5-E50	624	631	
EMS-M5-E62	633	630	
EMS-M5-E66	628	631	
EMS-M5-E68	627	630	
EMS-M5-E7P	626	627	
EMS-M5-F22	628	631	
EMS-M5-F30	629	632	
EMS-M5-J32	613	628	
EMS-M5-J33	624	629	
EMS-S5X-238	626	631	
EMS-S5X-27	637	639	
EMS-S5X-44	627	632	
EMS-S5K-238	626	631	
EMS-S5K-27	637	639	
EMS-S5K-44	626	632	
IPPE-ABBN93	637	638	
IPPE-84	590		
IRSN-CrV0-20	624		
IRSN-78-CEA	600		
JAERI-H-88		658	
ORNL-S4X-238	625		
Serco-Mk8-F22	621	617	1.6%

Table G60. Moderation U(3)NH

Critical moderation for H₂O-reflected U(3)NH + H₂O systems			
EALF = 0.0438	Moderation (H/U)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	33.9	33.2	-2.1/ +2.2
IPPE-ABBN93	33.6		
IRSN-78-CEA	36		
ORNL-S4X-238	34.0		

PuO₂ reference values

Figure G61. Pu(100/0/0/0)O₂ – Mass

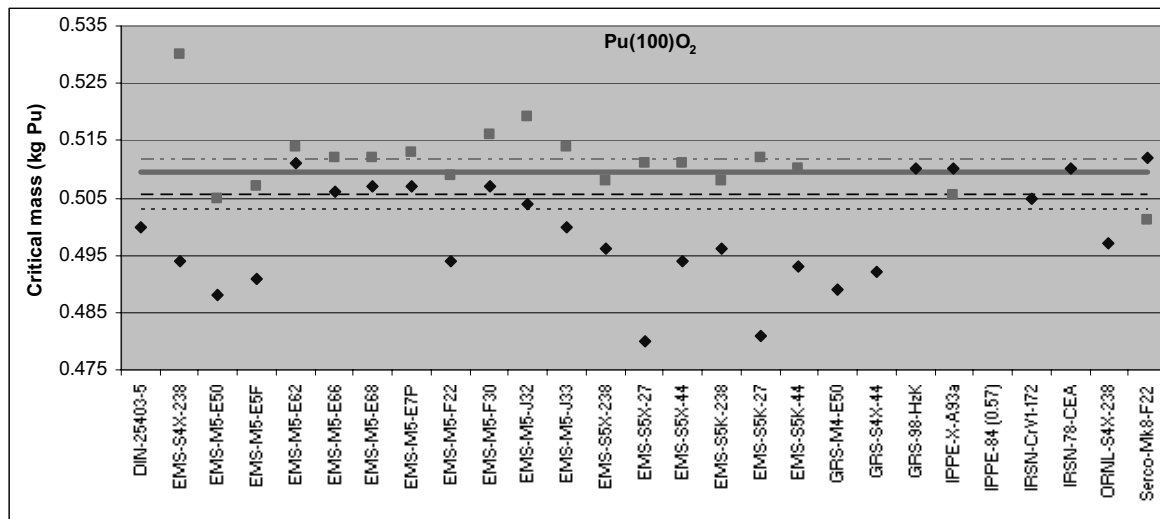


Figure G62. Pu(100/0/0/0)O₂ – Volume

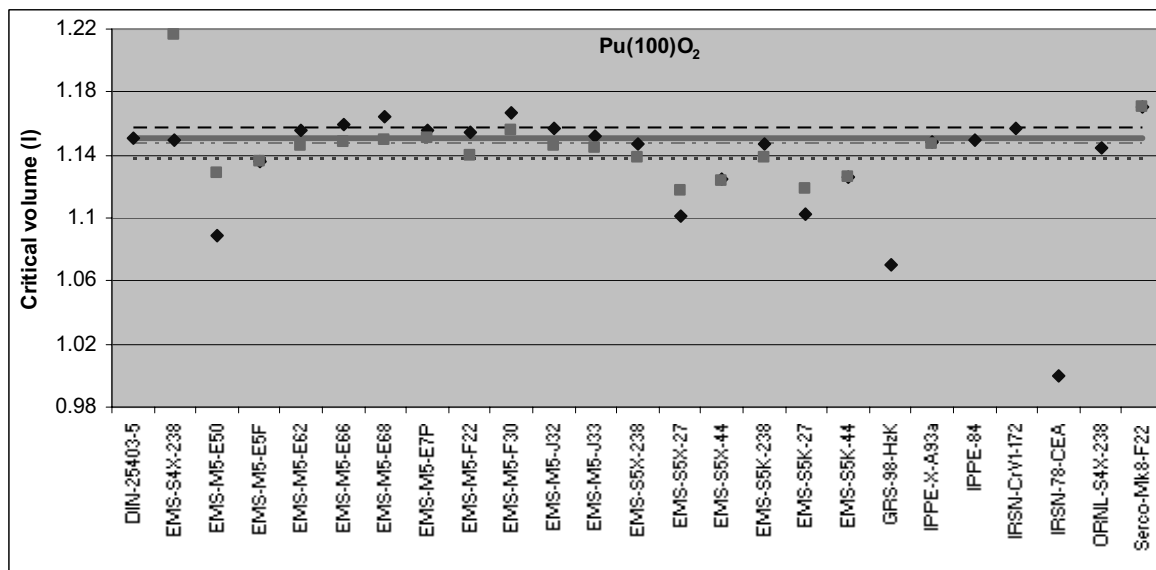


Table G61. Pu mass Pu(100/0/0/0)O₂

Critical mass for H₂O-reflected Pu(100/0/0/0)O₂ + H₂O systems			
EALF = 0.0547	Mass (kg Pu)		
Source	Raw data	Best- estimate	2 σ
DIN-25403-5	0.50		
EMS-S4X-238	0.494	0.530	+0.053/-0.047
EMS-M5-E50	0.488	0.505	
EMS-M5-E5F	0.491	0.507	
EMS-M5-E62	0.511	0.514	
EMS-M5-E66	0.506	0.512	
EMS-M5-E68	0.507	0.512	
EMS-M5-E7P	0.507	0.513	
EMS-M5-F22	0.494	0.509	
EMS-M5-F30	0.507	0.516	
EMS-M5-J32	0.504	0.519	
EMS-M5-J33	0.500	0.514	
EMS-S5X-238	0.496	0.508	
EMS-S5X-27	0.480	0.511	
EMS-S5X-44	0.494	0.511	
EMS-S5K-238	0.496	0.508	
EMS-S5K-27	0.481	0.512	
EMS-S5K-44	0.493	0.510	
GRS-M4-E50	0.489		
GRS-S4X-44	0.492		
GRS-98-HzK	0.51		
IPPE-ABBN93	0.510	0.506	
IPPE-84	0.57		
IRSN-CrV1-172	0.505		
IRSN-78-CEA	0.510		
ORNL-S4X-238	0.497		
Serco-Mk8-F22	0.512	0.501	2.0%

Table G62. Volume Pu(100/0/0/0)O₂

Critical volume for H₂O-reflected Pu(100/0/0/0)O₂ + H₂O systems			
EALF = 26164	Volume (l)		
Source	Raw data	Best- estimate	2 σ
DIN-25403-5	1.151		
EMS-S4X-238	1.150	1.216	+0.093/-0.087
EMS-M5-E50	1.089	1.129	
EMS-M5-E5F	1.136	1.136	
EMS-M5-E62	1.156	1.146	
EMS-M5-E66	1.160	1.148	
EMS-M5-E68	1.164	1.150	
EMS-M5-E7P	1.156	1.151	
EMS-M5-F22	1.154	1.139	
EMS-M5-F30	1.167	1.156	
EMS-M5-J32	1.157	1.146	
EMS-M5-J33	1.152	1.144	
EMS-S5X-238	1.147	1.138	
EMS-S5X-27	1.101	1.117	
EMS-S5X-44	1.125	1.124	
EMS-S5K-238	1.147	1.138	
EMS-S5K-27	1.103	1.119	
EMS-S5K-44	1.126	1.126	
GRS-98-HzK	1.07		
IPPE-ABBN93	1.148	1.147	
IPPE-84	1.15		
IRSN-CrV1-172	1.157		
IRSN-78-CEA	1.0		
ORNL-S4X-238	1.144		
Serco-Mk8-F22	1.17	1.17	0.4%

Figure G63. Pu(100/0/0/0)O₂ – Cylinder diameter

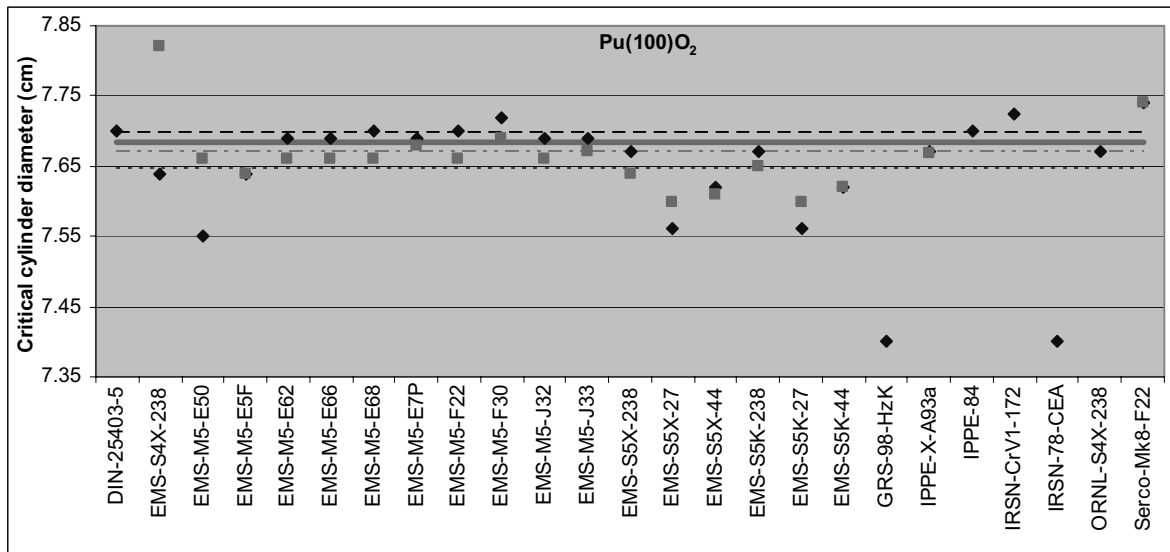


Figure G64. Pu(100/0/0/0)O₂ – Slab thickness

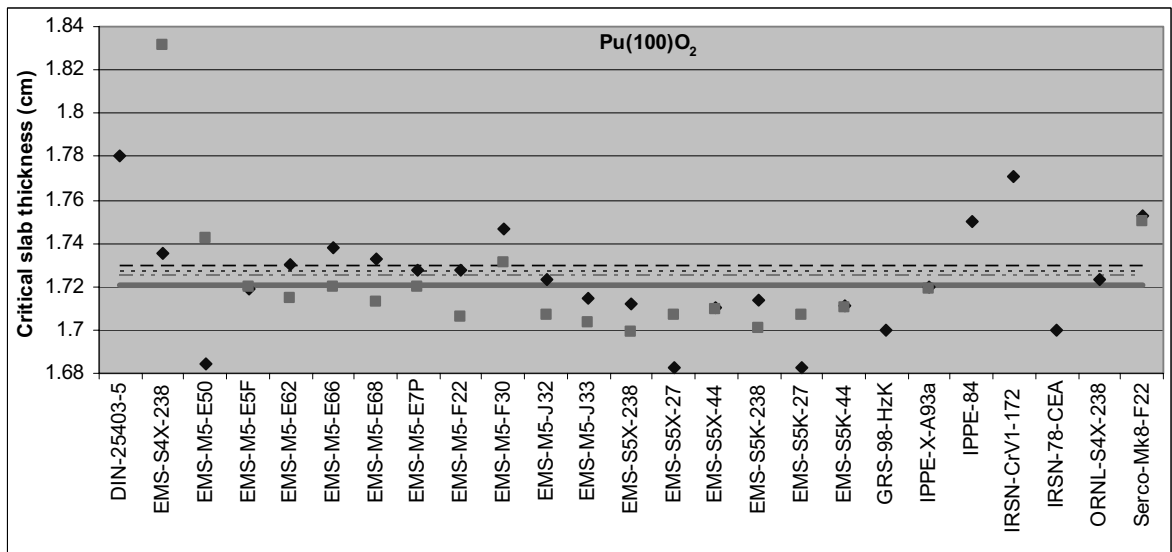


Table G63. Cylinder Pu(100/0/0/0)O₂

Critical cylinder diameter for H ₂ O-reflected Pu(100/0/0/0)O ₂ + H ₂ O systems			
EALF = 8785	Cylinder diameter (cm)		
Source	Raw data	Best-estimate	2 σ
DIN-25403-5	7.70		
EMS-S4X-238	7.64	7.82	+0.024/-0.023
EMS-M5-E50	7.55	7.66	
EMS-M5-E5F	7.64	7.64	
EMS-M5-E62	7.69	7.66	
EMS-M5-E66	7.69	7.66	
EMS-M5-E68	7.70	7.66	
EMS-M5-E7P	7.69	7.68	
EMS-M5-F22	7.70	7.66	
EMS-M5-F30	7.72	7.69	
EMS-M5-J32	7.69	7.66	
EMS-M5-J33	7.69	7.67	
EMS-S5X-238	7.67	7.64	
EMS-S5X-27	7.56	7.60	
EMS-S5X-44	7.62	7.61	
EMS-S5K-238	7.67	7.65	
EMS-S5K-27	7.56	7.60	
EMS-S5K-44	7.62	7.62	
GRS-98-HzK	7.4		
IPPE-ABBN93	7.67	7.67	
IPPE-84	7.7		
IRSN-CrV1-172	7.72		
IRSN-78-CEA	7.4		
ORNL-S4X-238	7.67		
Serco-Mk8-F22	7.74	7.74	0.2%

Table G64. Slab Pu(100/0/0/0)O₂

Critical slab thickness for H ₂ O-reflected Pu(100/0/0/0)O ₂ + H ₂ O systems			
EALF = 252	Slab thickness (cm)		
Source	Raw data	Best-estimate	2 σ
DIN-25403-5	1.78		
EMS-S4X-238	1.735	1.831	+0.131/-0.125
EMS-M5-E50	1.684	1.742	
EMS-M5-E5F	1.719	1.720	
EMS-M5-E62	1.730	1.715	
EMS-M5-E66	1.738	1.720	
EMS-M5-E68	1.733	1.713	
EMS-M5-E7P	1.728	1.720	
EMS-M5-F22	1.728	1.706	
EMS-M5-F30	1.747	1.731	
EMS-M5-J32	1.723	1.707	
EMS-M5-J33	1.715	1.703	
EMS-S5X-238	1.712	1.699	
EMS-S5X-27	1.683	1.707	
EMS-S5X-44	1.710	1.709	
EMS-S5K-238	1.714	1.701	
EMS-S5K-27	1.683	1.707	
EMS-S5K-44	1.711	1.710	
GRS-98-HzK	1.7		
IPPE-ABBN93	1.72	1.719	
IPPE-84	1.75		
IRSN-CrV1-172	1.77		
IRSN-78-CEA	1.7		
ORNL-S4X-238	1.723		
Serco-Mk8-F22	1.753	1.750	0.4%

Figure G65. Pu(100/0/0/0)O₂ – Critical Pu concentration

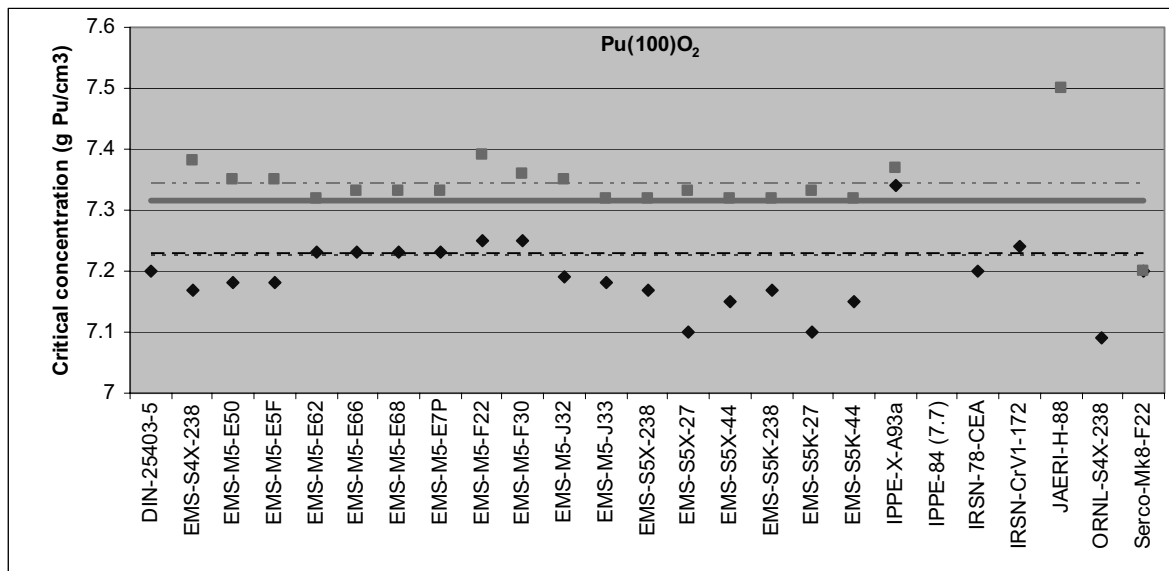


Figure G66. Pu(100/0/0/0)O₂ – Moderation H/Pu

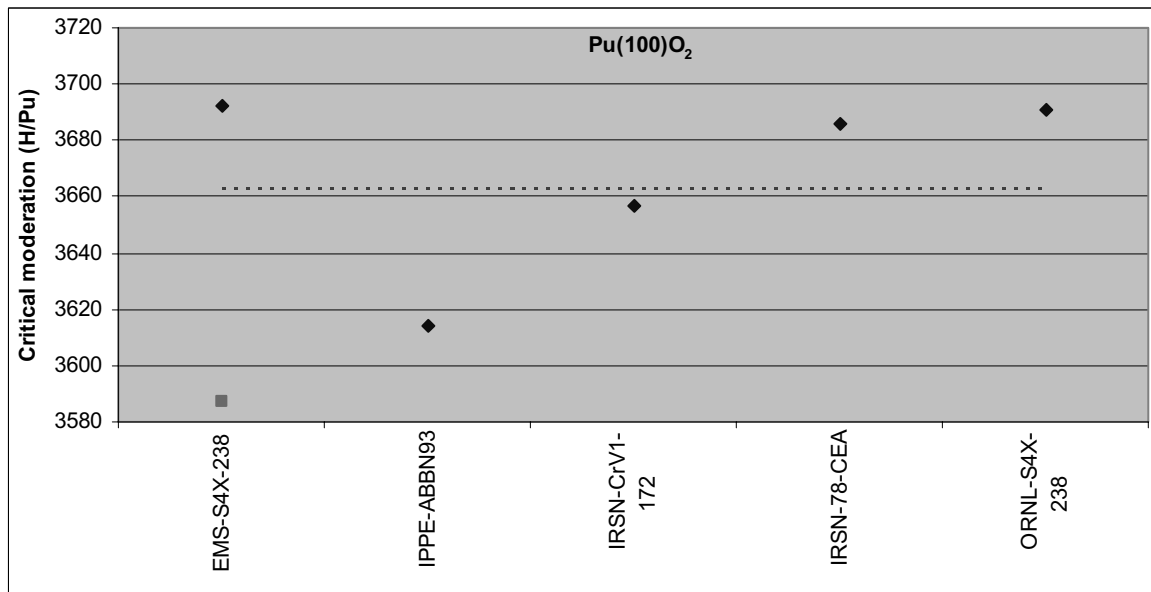


Table G65. Concentration: Pu(100/0/0/0)O₂

Critical concentration for H ₂ O-reflected Pu(100/0/0/0)O ₂ + H ₂ O systems			
EALF = 0.0193	Pu concentration (g/l)		
Source	Raw data	Best- estimate	2 σ
DIN-25403-5	7.2		
EMS-S4X-238	7.17	7.38	+0.26/-0.28
EMS-M5-E50	7.18	7.35	
EMS-M5-E5F	7.18	7.35	
EMS-M5-E62	7.23	7.32	
EMS-M5-E66	7.23	7.33	
EMS-M5-E68	7.23	7.33	
EMS-M5-E7P	7.23	7.33	
EMS-M5-F22	7.25	7.39	
EMS-M5-F30	7.25	7.36	
EMS-M5-J32	7.19	7.35	
EMS-M5-J33	7.18	7.32	
EMS-S5X-238	7.17	7.32	
EMS-S5X-27	7.10	7.33	
EMS-S5X-44	7.15	7.32	
EMS-S5K-238	7.17	7.32	
EMS-S5K-27	7.10	7.33	
EMS-S5K-44	7.15	7.32	
IPPE-ABBN93	7.34	7.37	
IPPE-84	7.7		
IRSN-78-CEA	7.2		
IRSN-CrV1-172	7.24		
JAERI-H-88		7.5	
Serco-Mk8-F22*	7.2	7.2	0.8%

Table G66. Moderation H/Pu: Pu(100)O₂

Critical moderation for H ₂ O-reflected Pu(100/0/0/0)O ₂ + H ₂ O systems			
EALF = 0.0193	Moderation (H/Pu)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	3692	3587	-137/+141
IPPE-ABBN93	3614		
IRSN-CrV1-172	3657		
IRSN-78-CEA	3686		
ORNL-S4X-238	3691		

* Corrected from 7.7 g/l (March 2005)

Figure G67. Pu(95/5/0/0)O₂ – Mass

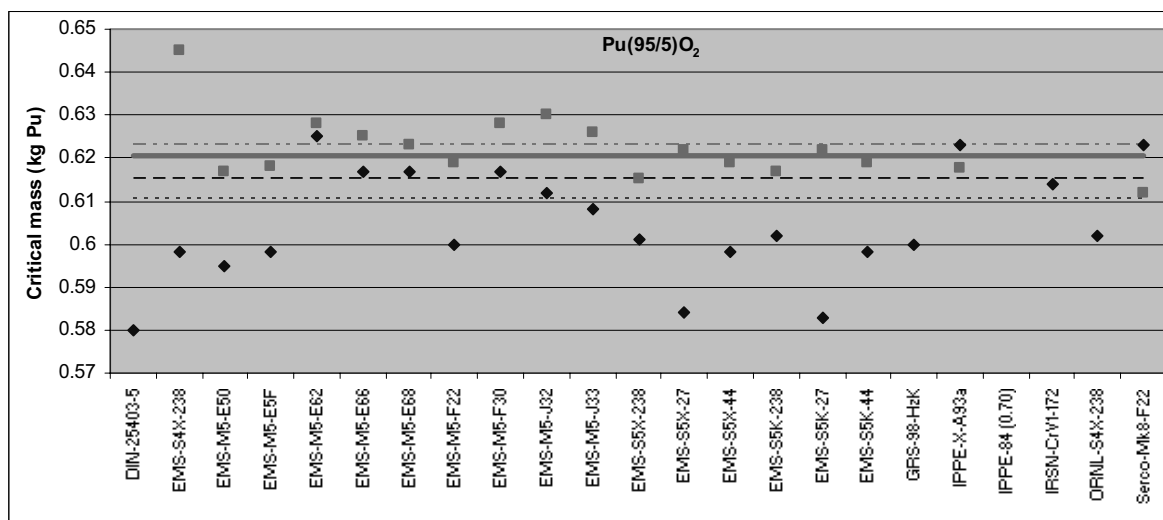


Figure G68. Pu(95/5/0/0)O₂ – Volume

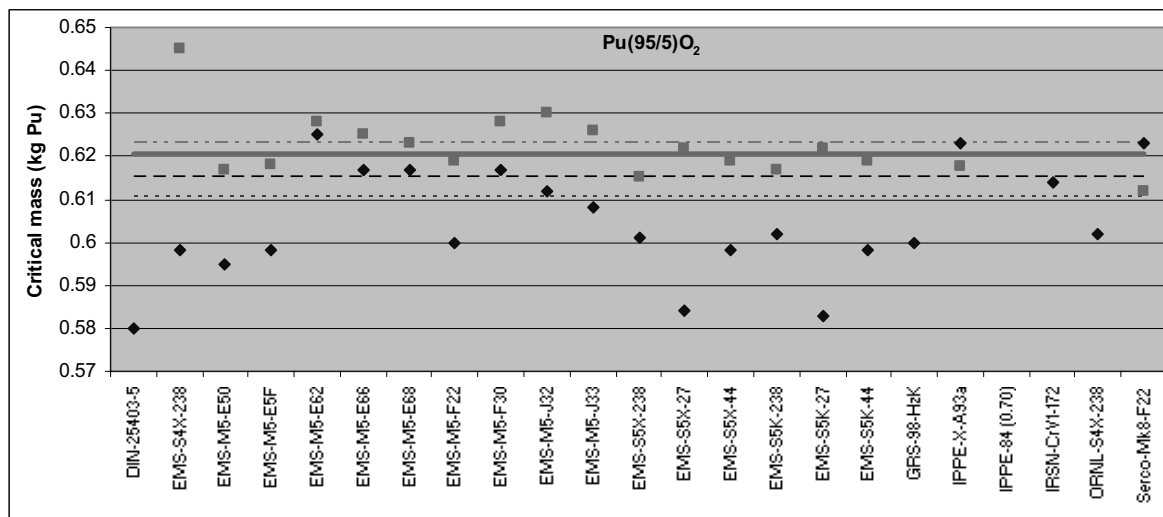


Table G67. Pu Mass Pu(95/5/0/0)O₂

Critical mass for H ₂ O-reflected Pu(95/5/0/0)O ₂ + H ₂ O systems			
EALF = 0.0550	Mass (kg Pu)		
Source	Raw data	Best- estimate	2 σ
DIN-25403-5	0.58		
EMS-S4X-238	0.598	0.645	+0.068/-0.061
EMS-M5-E50	0.595	0.617	
EMS-M5-E5F	0.598	0.618	
EMS-M5-E62	0.625	0.628	
EMS-M5-E66	0.617	0.625	
EMS-M5-E68	0.617	0.623	
EMS-M5-F22	0.600	0.619	
EMS-M5-F30	0.617	0.628	
EMS-M5-J32	0.612	0.630	
EMS-M5-J33	0.608	0.626	
EMS-S5X-238	0.601	0.615	
EMS-S5X-27	0.584	0.622	
EMS-S5X-44	0.598	0.619	
EMS-S5K-238	0.602	0.617	
EMS-S5K-27	0.583	0.622	
EMS-S5K-44	0.598	0.619	
GRS-98-HzK	0.60		
IPPE-ABBN93	0.623	0.618	
IPPE-84	0.7		
IRSN-CrV1-172	0.614		
ORNL-S4X-238	0.602		
Serco-Mk8-F22	0.623	0.612	1.6%

Table G68. Volume Pu(95/5/0/0)O₂

Critical volume for H ₂ O-reflected Pu(95/5/0/0)O ₂ + H ₂ O systems			
EALF = 29639	Volume (l)		
Source	Raw data	Best- estimate	2 σ
DIN-25403-5	1.23		
EMS-S4X-238	1.234	1.305	+0.099/-0.094
EMS-M5-E50	1.179	1.220	
EMS-M5-E5F	1.215	1.215	
EMS-M5-E62	1.240	1.229	
EMS-M5-E66	1.244	1.232	
EMS-M5-E68	1.245	1.231	
EMS-M5-F22	1.245	1.230	
EMS-M5-F30	1.246	1.235	
EMS-M5-J32	1.244	1.233	
EMS-M5-J33	1.241	1.233	
EMS-S5X-238	1.230	1.220	
EMS-S5X-27	1.178	1.195	
EMS-S5X-44	1.200	1.199	
EMS-S5K-238	1.229	1.220	
EMS-S5K-27	1.181	1.198	
EMS-S5K-44	1.203	1.202	
GRS-98-HzK	1.2		
IPPE-ABBN93	1.237	1.236	
IPPE-84	1.25		
IRSN-CrV1-172	1.247		
ORNL-S4X-238	1.227		
Serco-Mk8-F22	1.26	1.26	0.4%

Figure G69. Pu(95/5/0)O₂ – Cylinder diameter

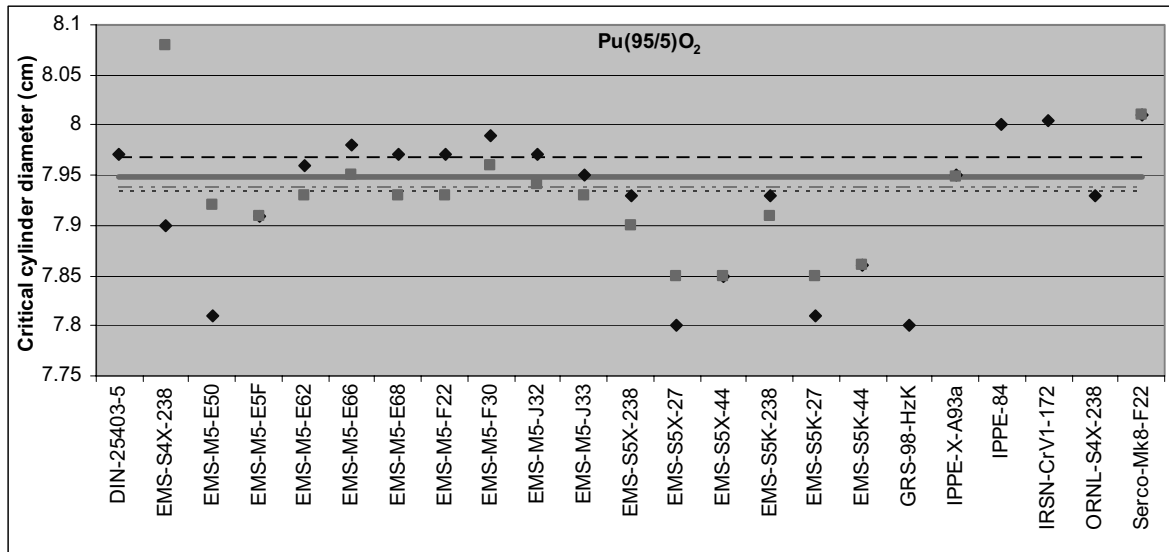


Figure G70. Pu(95/5/0)O₂ – Slab thickness

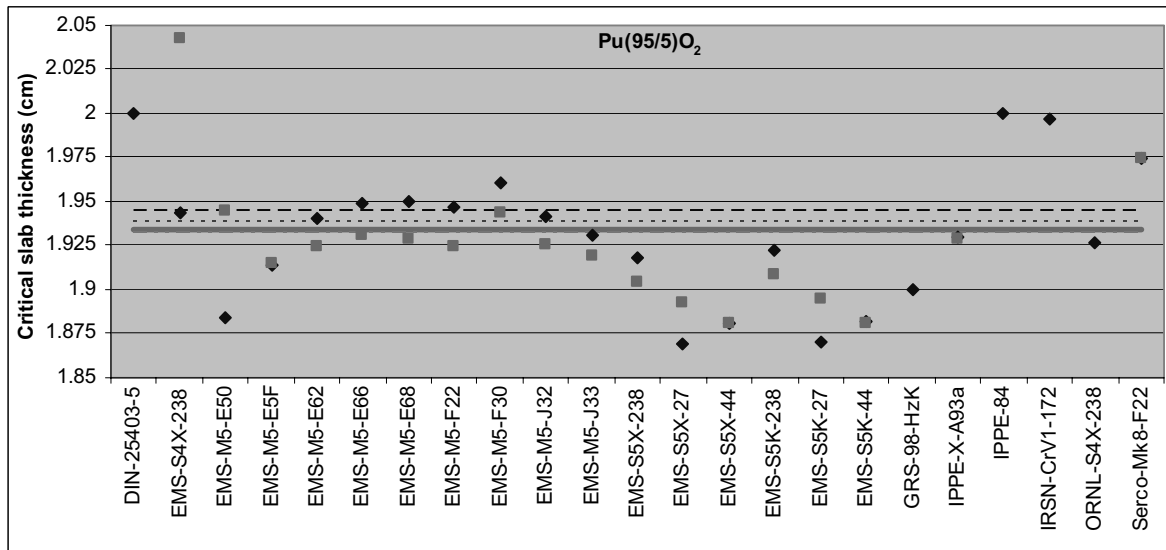


Table G69. Cylinder Pu(95/5/0/0)O₂

Critical cylinder diameter for H ₂ O-reflected Pu(95/5/0/0)O ₂ + H ₂ O systems			
EALF = 10364	Cylinder diameter (cm)		
Source	Raw data	Best-estimate	2 σ
DIN-25403-5	7.97		
EMS-S4X-238	7.90	8.08	+0.25/-0.23
EMS-M5-E50	7.81	7.92	
EMS-M5-E5F	7.91	7.91	
EMS-M5-E62	7.96	7.93	
EMS-M5-E66	7.98	7.95	
EMS-M5-E68	7.97	7.93	
EMS-M5-F22	7.97	7.93	
EMS-M5-F30	7.99	7.96	
EMS-M5-J32	7.97	7.94	
EMS-M5-J33	7.95	7.93	
EMS-S5X-238	7.93	7.90	
EMS-S5X-27	7.80	7.85	
EMS-S5X-44	7.85	7.85	
EMS-S5K-238	7.93	7.91	
EMS-S5K-27	7.81	7.85	
EMS-S5K-44	7.86	7.86	
GRS-98-HzK	7.8		
IPPE-ABBN93	7.95	7.95	
IPPE-84	8		
IRSN-CrV1-172	8.01		
ORNL-S4X-238	7.93		
Serco-Mk8-F22	8.01	8.01	0.2%

Table G70. Slab Pu(95/5/0/0)O₂

Critical slab thickness for H ₂ O-reflected Pu(95/5/0/0)O ₂ + H ₂ O systems			
EALF = 405	Slab thickness (cm)		
Source	Raw data	Best-estimate	2 σ
DIN-25403-5	2.00		
EMS-S4X-238	1.944	2.043	+0.135/-0.132
EMS-M5-E50	1.884	1.945	
EMS-M5-E5F	1.914	1.915	
EMS-M5-E62	1.940	1.924	
EMS-M5-E66	1.949	1.931	
EMS-M5-E68	1.950	1.929	
EMS-M5-F22	1.947	1.924	
EMS-M5-F30	1.961	1.944	
EMS-M5-J32	1.942	1.925	
EMS-M5-J33	1.931	1.919	
EMS-S5X-238	1.918	1.904	
EMS-S5X-27	1.869	1.893	
EMS-S5X-44	1.881	1.881	
EMS-S5K-238	1.922	1.908	
EMS-S5K-27	1.870	1.895	
EMS-S5K-44	1.882	1.881	
GRS-98-HzK	1.9		
IPPE-ABBN93	1.93	1.929	
IPPE-84	2		
IRSN-CrV1-172	1.997		
ORNL-S4X-238	1.927		
Serco-Mk8-F22	1.974	1.974	0.4%

Figure G71. Pu(95/5/0/0)O₂ – Pu concentration

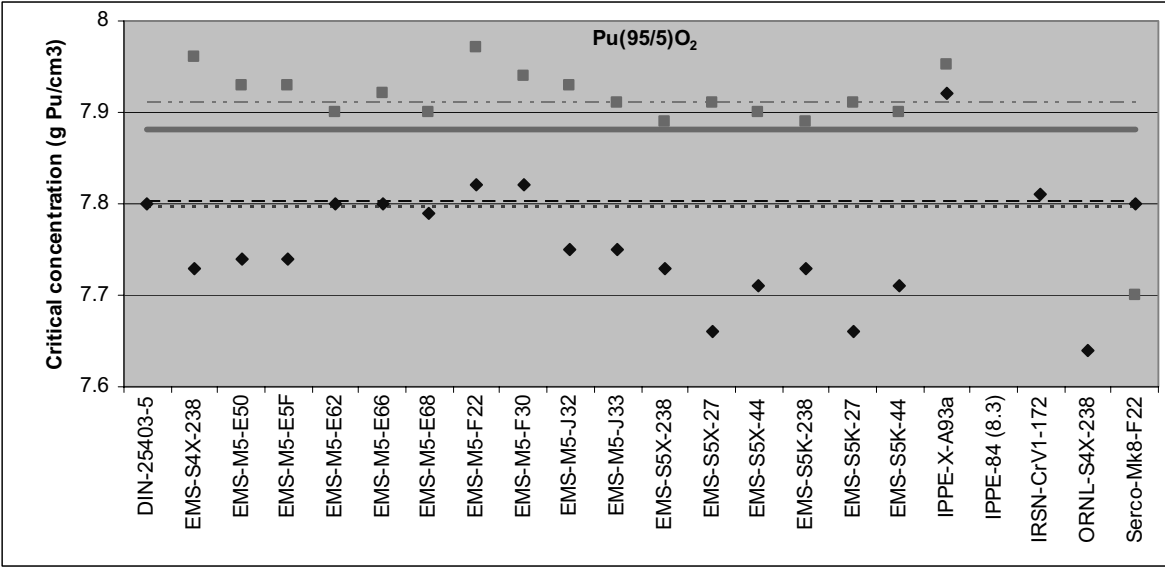


Figure G72. Pu(95/5/0/0)O₂ – Moderation H/Pu

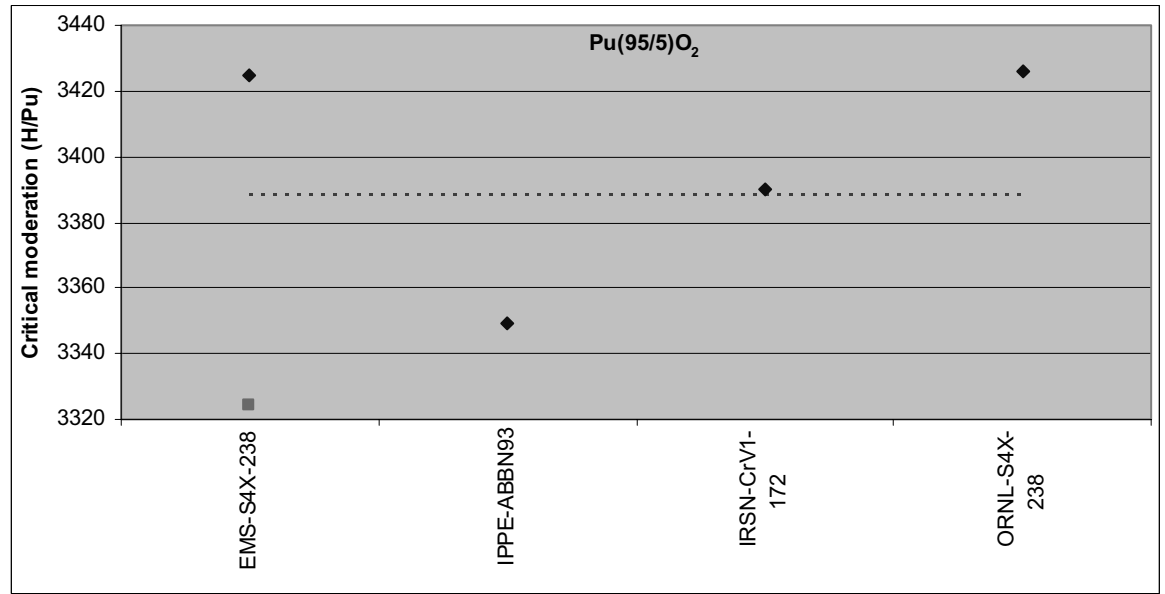


Table G71. Concentration: Pu(95/5/0/0)O₂

Critical concentration for H ₂ O-reflected Pu(95/5/0/0)O ₂ + H ₂ O systems			
EALF = 0.0194	Pu concentration (g/l)		
Source	Raw data	Best-estimate	2 σ
DIN-25403-5	7.8		
EMS-S4X-238	7.73	7.96	+0.29/-0.30
EMS-M5-E50	7.74	7.93	
EMS-M5-E5F	7.74	7.93	
EMS-M5-E62	7.80	7.90	
EMS-M5-E66	7.80	7.92	
EMS-M5-E68	7.79	7.90	
EMS-M5-F22	7.82	7.97	
EMS-M5-F30	7.82	7.94	
EMS-M5-J32	7.75	7.93	
EMS-M5-J33	7.75	7.91	
EMS-S5X-238	7.73	7.89	
EMS-S5X-27	7.66	7.91	
EMS-S5X-44	7.71	7.90	
EMS-S5K-238	7.73	7.89	
EMS-S5K-27	7.66	7.91	
EMS-S5K-44	7.71	7.90	
IPPE-ABBN93	7.92	7.95	
IPPE-84	8.3		
IRSN-CrV1-172	7.81		
ORNL-S4X-238	7.64		
Serco-Mk8-F22	7.8	7.7	0.8%

Table G72. Moderation H/Pu: Pu(95/5)O₂

Critical moderation for H ₂ O-reflected Pu(95/5/0/0)O ₂ + H ₂ O systems			
EALF = 0.0194	Moderation (H/Pu)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	3425	3324	-132/136
IPPE-ABBN93	3349		
IRSN-CrV1-172	3390		
ORNL-S4X-238	3426		

Figure G73. Pu(80/10/10/0)O₂ – Mass

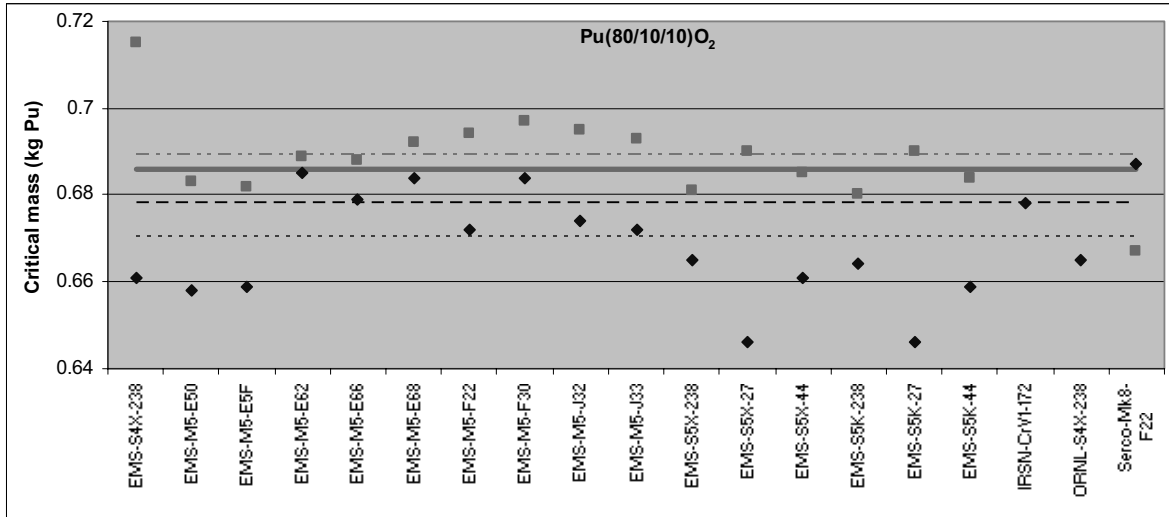


Figure G74. Pu(80/10/10/0)O₂ – Volume

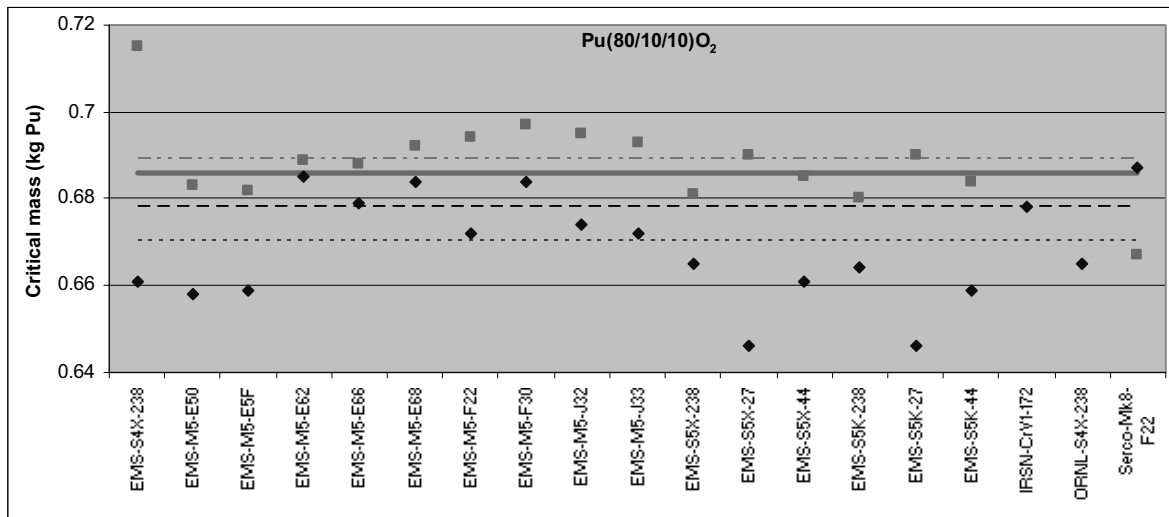


Table G73. Pu mass Pu(80/10/10/0)O₂

Critical mass for H ₂ O-reflected Pu(80/10/10/0)O ₂ + H ₂ O systems			
EALF = 0.0543	Mass (kg Pu)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	0.661	0.715	+0.079/-0.070
EMS-M5-E50	0.658	0.683	
EMS-M5-E5F	0.659	0.682	
EMS-M5-E62	0.685	0.689	
EMS-M5-E66	0.679	0.688	
EMS-M5-E68	0.684	0.692	
EMS-M5-F22	0.672	0.694	
EMS-M5-F30	0.684	0.697	
EMS-M5-J32	0.674	0.695	
EMS-M5-J33	0.672	0.693	
EMS-S5X-238	0.665	0.681	
EMS-S5X-27	0.646	0.690	
EMS-S5X-44	0.661	0.685	
EMS-S5K-238	0.664	0.680	
EMS-S5K-27	0.646	0.690	
EMS-S5K-44	0.659	0.684	
IRSN-CrV1-172	0.678		
ORNL-S4X-238	0.665		
Serco-Mk8-F22	0.687	0.667	2.6%

Table G74. Volume Pu(80/10/10/0)O₂

Critical volume for H ₂ O-reflected Pu(80/10/10/0)O ₂ + H ₂ O systems			
EALF =27949	Volume (l)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	1.289	1.363	+0.104/-0.098
EMS-M5-E50	1.232	1.277	
EMS-M5-E5F	1.269	1.269	
EMS-M5-E62	1.292	1.281	
EMS-M5-E66	1.292	1.279	
EMS-M5-E68	1.301	1.286	
EMS-M5-F22	1.296	1.279	
EMS-M5-F30	1.295	1.283	
EMS-M5-J32	1.292	1.280	
EMS-M5-J33	1.289	1.280	
EMS-S5X-238	1.282	1.272	
EMS-S5X-27	1.213	1.231	
EMS-S5X-44	1.249	1.249	
EMS-S5K-238	1.283	1.273	
EMS-S5K-27	1.213	1.231	
EMS-S5K-44	1.250	1.250	
IRSN-CrV1-172	1.297		
ORNL-S4X-238	1.279		
Serco-Mk8-F22	1.31	1.31	0.4%

Figure G75. Pu(80/10/10/0)O₂ – Cylinder diameter

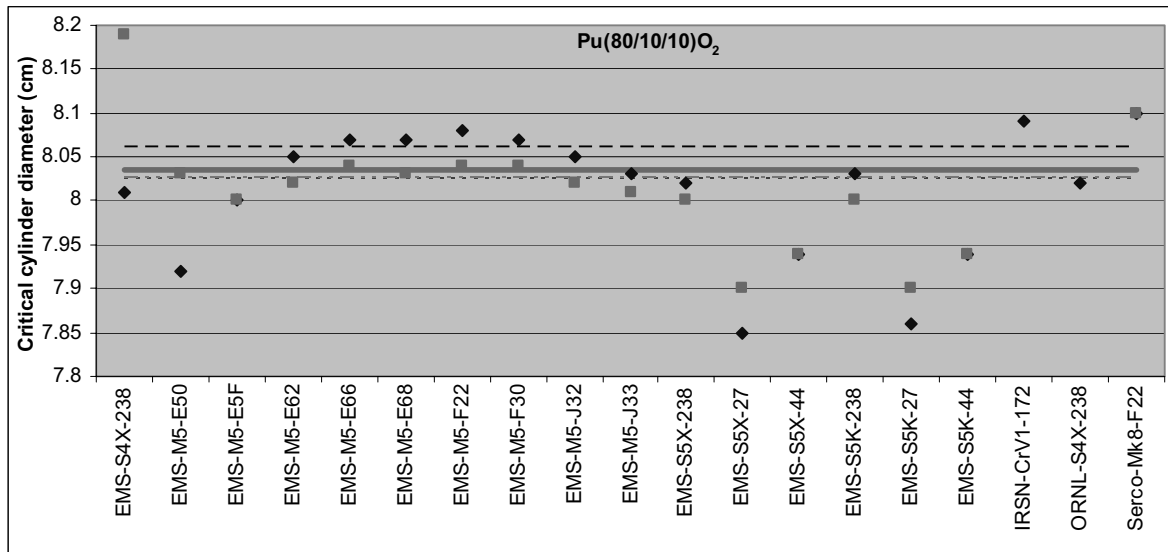


Figure G76. Pu(80/10/10/0)O₂ – Slab thickness

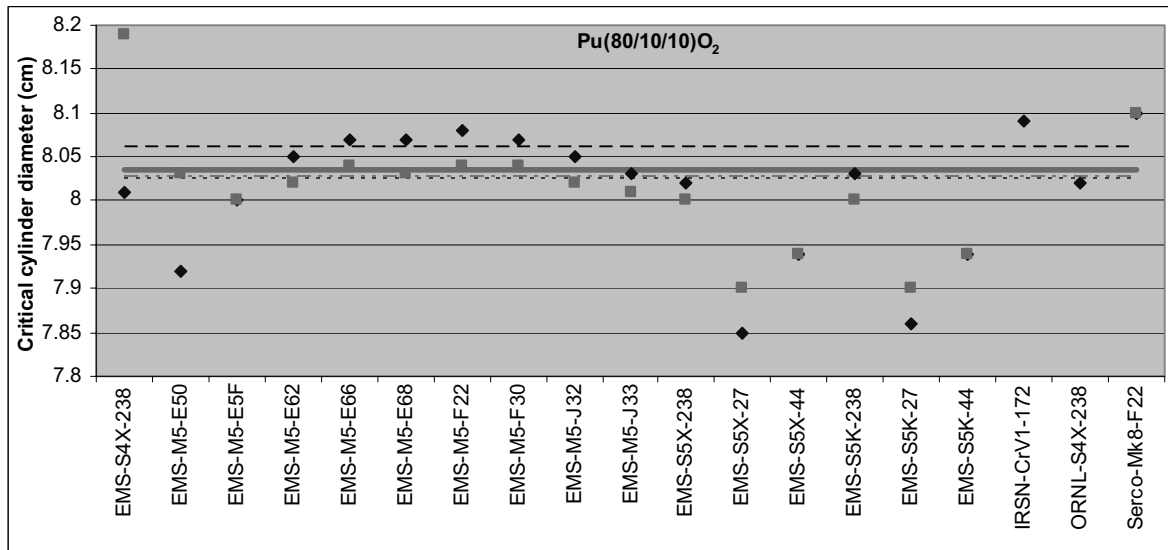


Table G75. Cylinder Pu(80/10/10/0)O₂

Critical cylinder diameter for H ₂ O-reflected Pu(80/10/10/0)O ₂ + H ₂ O systems			
EALF = 10118	Cylinder diameter (cm)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	8.01	8.19	+0.25/-0.25
EMS-M5-E50	7.92	8.03	
EMS-M5-E5F	8.00	8.00	
EMS-M5-E62	8.05	8.02	
EMS-M5-E66	8.07	8.04	
EMS-M5-E68	8.07	8.03	
EMS-M5-F22	8.08	8.04	
EMS-M5-F30	8.07	8.04	
EMS-M5-J32	8.05	8.02	
EMS-M5-J33	8.03	8.01	
EMS-S5X-238	8.02	8.00	
EMS-S5X-27	7.85	7.90	
EMS-S5X-44	7.94	7.94	
EMS-S5K-238	8.03	8.00	
EMS-S5K-27	7.86	7.90	
EMS-S5K-44	7.94	7.94	
IRSN-CrV1-172	8.09		
ORNL-S4X-238	8.02		
Serco-Mk8-F22	8.10	8.10	0.2%

Table G76. Slab Pu(80/10/10/0)O₂

Critical slab thickness for H ₂ O-reflected Pu(80/10/10/0)O ₂ + H ₂ O systems			
EALF = 396	Slab thickness (cm)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	1.929	2.028	+0.140/-0.135
EMS-M5-E50	1.873	1.937	
EMS-M5-E5F	1.902	1.903	
EMS-M5-E62	1.902	1.886	
EMS-M5-E66	1.926	1.907	
EMS-M5-E68	1.924	1.902	
EMS-M5-F22	1.923	1.899	
EMS-M5-F30	1.937	1.919	
EMS-M5-J32	1.918	1.900	
EMS-M5-J33	1.909	1.896	
EMS-S5X-238	1.898	1.884	
EMS-S5X-27	1.816	1.842	
EMS-S5X-44	1.845	1.844	
EMS-S5K-238	1.902	1.887	
EMS-S5K-27	1.815	1.841	
EMS-S5K-44	1.848	1.847	
IRSN-CrV1-172	1.965		
ORNL-S4X-238	1.908		
Serco-Mk8-F22	1.946	1.946	0.2%

Figure G77. Pu(80/10/10/0)O₂ – Critical Pu concentration

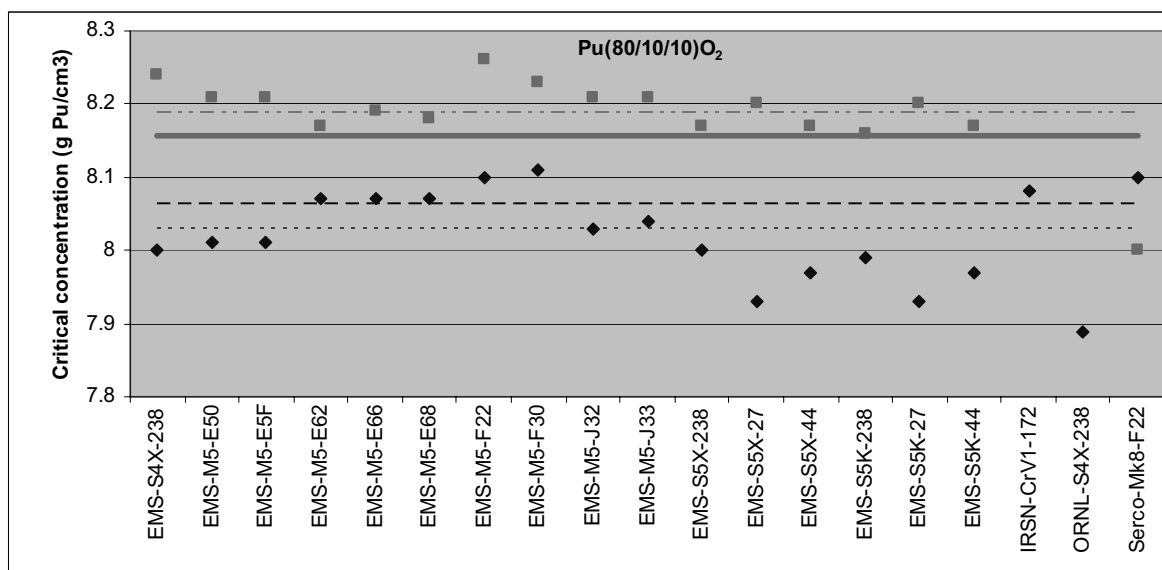


Figure G78. Pu(80/10/10/0)O₂ – Moderation H/Pu

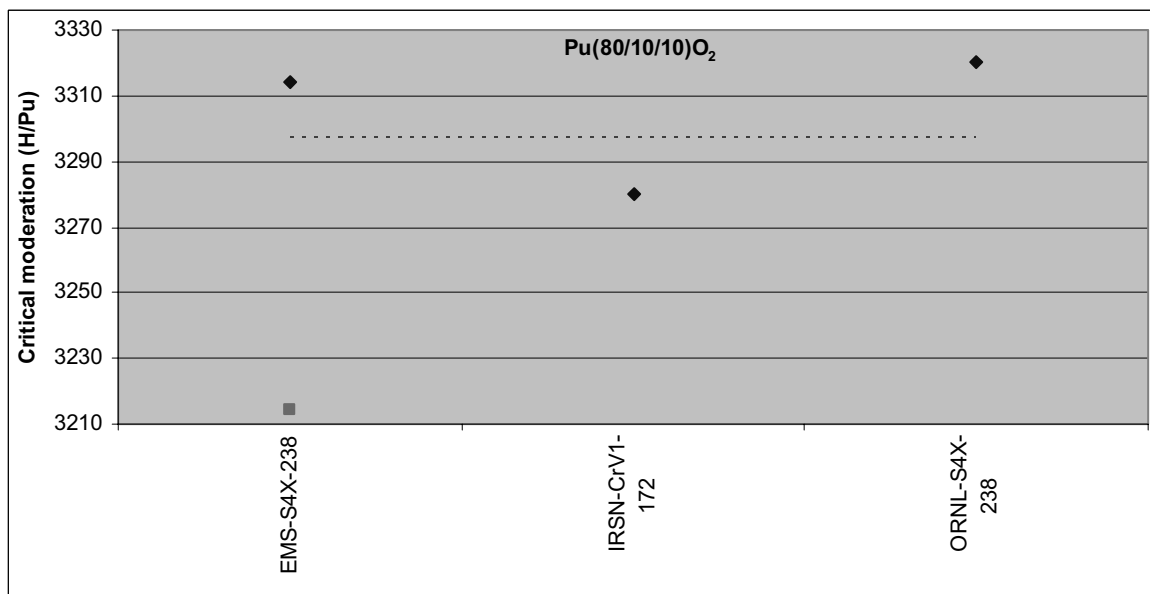


Table G77. Concentr. Pu(80/10/10/0)O₂

Critical concentration for H₂O-reflected Pu(80/10/10/0)O₂ + H₂O systems			
EALF = 0.0193	Pu concentration (g/l)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	8.00	8.24	+0.32/-0.32
EMS-M5-E50	8.01	8.21	
EMS-M5-E5F	8.01	8.21	
EMS-M5-E62	8.07	8.17	
EMS-M5-E66	8.07	8.19	
EMS-M5-E68	8.07	8.18	
EMS-M5-F22	8.10	8.26	
EMS-M5-F30	8.11	8.23	
EMS-M5-J32	8.03	8.21	
EMS-M5-J33	8.04	8.21	
EMS-S5X-238	8.00	8.17	
EMS-S5X-27	7.93	8.20	
EMS-S5X-44	7.97	8.17	
EMS-S5K-238	7.99	8.16	
EMS-S5K-27	7.93	8.20	
EMS-S5K-44	7.97	8.17	
IRSN-CrV1-172	8.08		
ORNL-S4X-238	7.889		
Serco-Mk8-F22	8.1	8.0	0.8%

Table G78. H/Pu: Pu(80/10/10/0)O₂

Critical moderation for H₂O-reflected Pu(80/10/10/0)O₂ + H₂O systems			
EALF = 0.0193	Moderation (H/Pu)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	3314	3214	-129/ +134
IRSN-CrV1-172	3280		
ORNL-S4X-238	3320		

Figure G79. Pu(90/10/0)O₂ – Mass

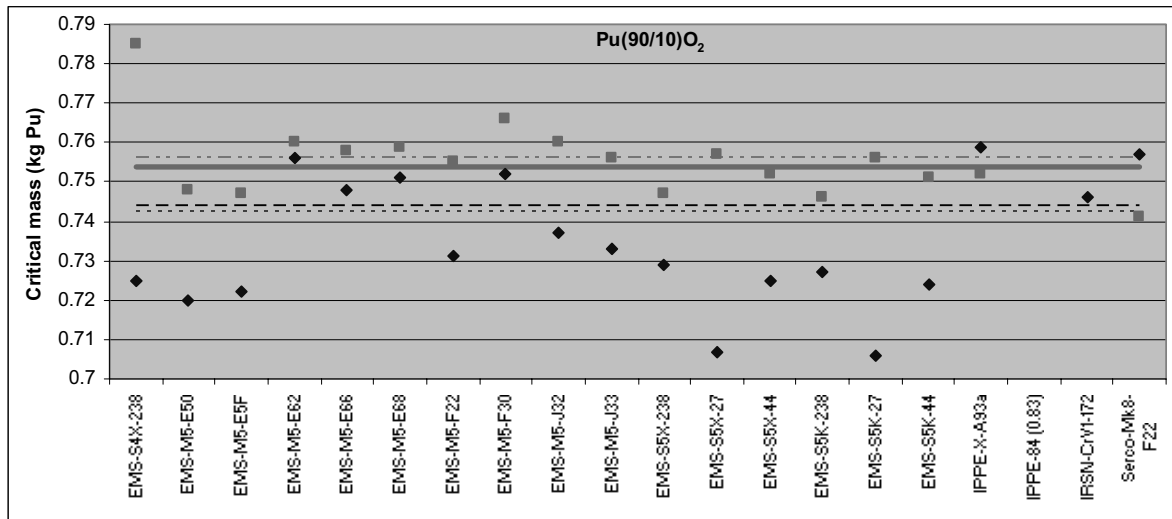


Figure G80. Pu(90/10/0)O₂ – Volume

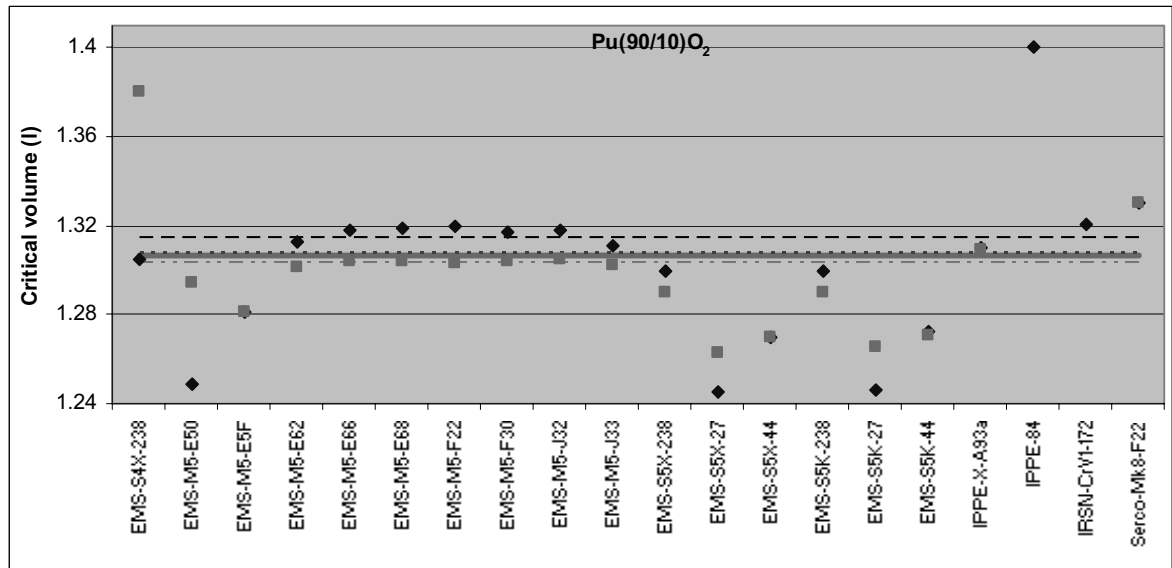


Table G79. Pu mass Pu(90/10/0/0)O₂

Critical mass for H ₂ O-reflected Pu(90/10/0/0)O ₂ + H ₂ O systems			
EALF = 0.0552	Mass (kg Pu)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	0.725	0.785	+0.089/-0.079
EMS-M5-E50	0.720	0.748	
EMS-M5-E5F	0.722	0.747	
EMS-M5-E62	0.756	0.760	
EMS-M5-E66	0.748	0.758	
EMS-M5-E68	0.751	0.759	
EMS-M5-F22	0.731	0.755	
EMS-M5-F30	0.752	0.766	
EMS-M5-J32	0.737	0.760	
EMS-M5-J33	0.733	0.756	
EMS-S5X-238	0.729	0.747	
EMS-S5X-27	0.707	0.757	
EMS-S5X-44	0.725	0.752	
EMS-S5K-238	0.727	0.746	
EMS-S5K-27	0.706	0.756	
EMS-S5K-44	0.724	0.751	
IPPE-ABBN93	0.759	0.752	
IPPE-84	0.83		
IRSN-CrV1-172	0.746		
Serco-Mk8-F22	0.757	0.741	2.0%

Table G80. Volume Pu(90/10/0/0)O₂

Critical volume for H ₂ O-reflected Pu(90/10/0/0)O ₂ + H ₂ O systems			
EALF = 31053	Volume (l)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	1.305	1.380	+0.104/-0.099
EMS-M5-E50	1.249	1.294	
EMS-M5-E5F	1.281	1.281	
EMS-M5-E62	1.313	1.301	
EMS-M5-E66	1.318	1.304	
EMS-M5-E68	1.319	1.304	
EMS-M5-F22	1.320	1.303	
EMS-M5-F30	1.317	1.304	
EMS-M5-J32	1.318	1.305	
EMS-M5-J33	1.311	1.302	
EMS-S5X-238	1.300	1.290	
EMS-S5X-27	1.245	1.263	
EMS-S5X-44	1.270	1.270	
EMS-S5K-238	1.300	1.290	
EMS-S5K-27	1.246	1.265	
EMS-S5K-44	1.272	1.271	
IPPE-ABBN93	1.310	1.309	
IPPE-84	1.4		
IRSN-CrV1-172	1.321		
Serco-Mk8-F22	1.33	1.33	0.4%

Figure G81. Pu(90/10/0/0)O₂ – Cylinder diameter

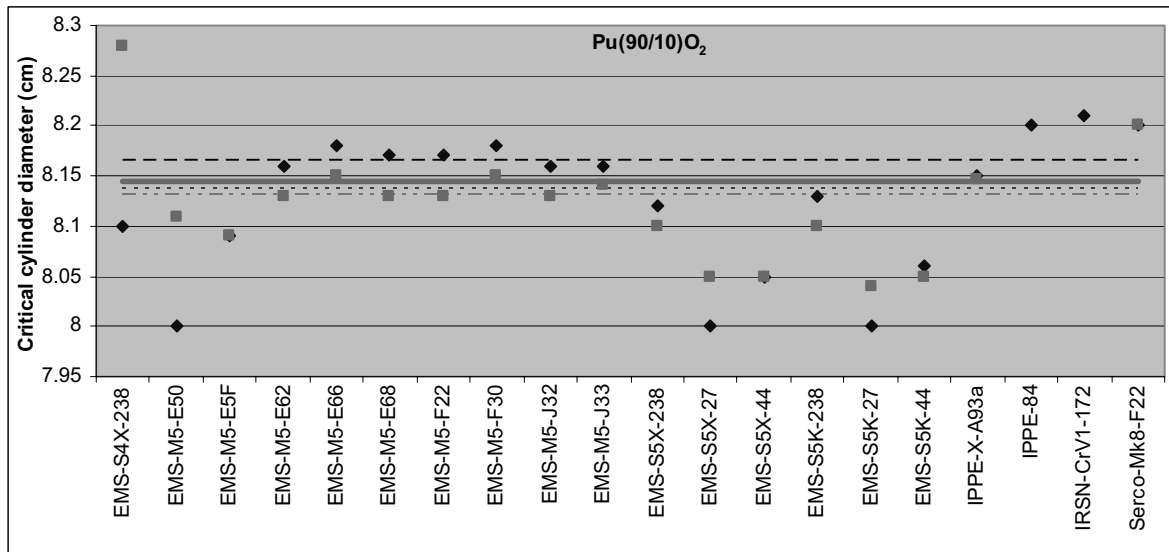


Figure G82. Pu(90/10/0/0)O₂ – Slab thickness

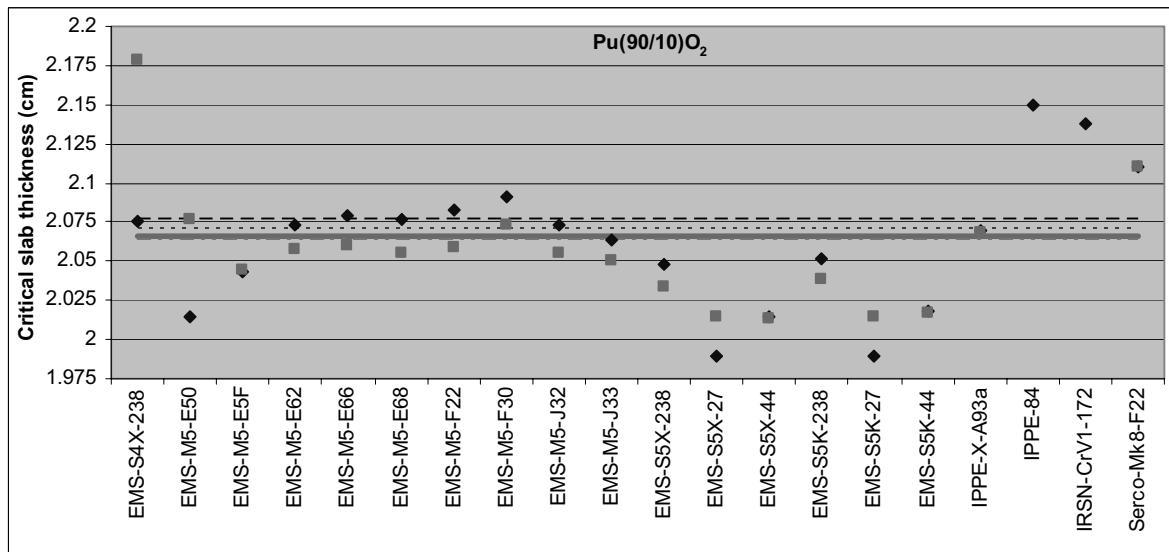


Table G81. Cylinder Pu(90/10/0/0)O₂

Critical cylinder diameter for H ₂ O-reflected Pu(90/10/0/0)O ₂ + H ₂ O systems			
EALF = 11354	Cylinder diameter (cm)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	8.10	8.28	+0.25/-0.24
EMS-M5-E50	8.00	8.11	
EMS-M5-E5F	8.09	8.09	
EMS-M5-E62	8.16	8.13	
EMS-M5-E66	8.18	8.15	
EMS-M5-E68	8.17	8.13	
EMS-M5-F22	8.17	8.13	
EMS-M5-F30	8.18	8.15	
EMS-M5-J32	8.16	8.13	
EMS-M5-J33	8.16	8.14	
EMS-S5X-238	8.12	8.10	
EMS-S5X-27	8.00	8.05	
EMS-S5X-44	8.05	8.05	
EMS-S5K-238	8.13	8.10	
EMS-S5K-27	8.00	8.04	
EMS-S5K-44	8.06	8.05	
IPPE-ABBN93	8.15	8.15	
IPPE-84	8.2		
IRSN-CrV1-172	8.21		
Serco-Mk8-F22	8.20	8.20	0.2%

Table G82. Slab Pu(90/10/0/0)O₂

Critical slab thickness for H ₂ O-reflected Pu(90/10/0/0)O ₂ + H ₂ O systems			
EALF = 510	Slab thickness (cm)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	2.075	2.178	+0.138/-0.136
EMS-M5-E50	2.014	2.077	
EMS-M5-E5F	2.043	2.044	
EMS-M5-E62	2.073	2.057	
EMS-M5-E66	2.079	2.060	
EMS-M5-E68	2.077	2.055	
EMS-M5-F22	2.083	2.059	
EMS-M5-F30	2.091	2.073	
EMS-M5-J32	2.073	2.055	
EMS-M5-J33	2.063	2.050	
EMS-S5X-238	2.048	2.034	
EMS-S5X-27	1.989	2.015	
EMS-S5X-44	2.014	2.013	
EMS-S5K-238	2.052	2.038	
EMS-S5K-27	1.989	2.015	
EMS-S5K-44	2.018	2.017	
IPPE-ABBN93	2.07	2.069	
IPPE-84	2.15		
IRSN-CrV1-172	2.138		
Serco-Mk8-F22	2.110	2.110	0.4%

Figure G83. $\text{Pu}(90/10/0/0)\text{O}_2$ – Concentration

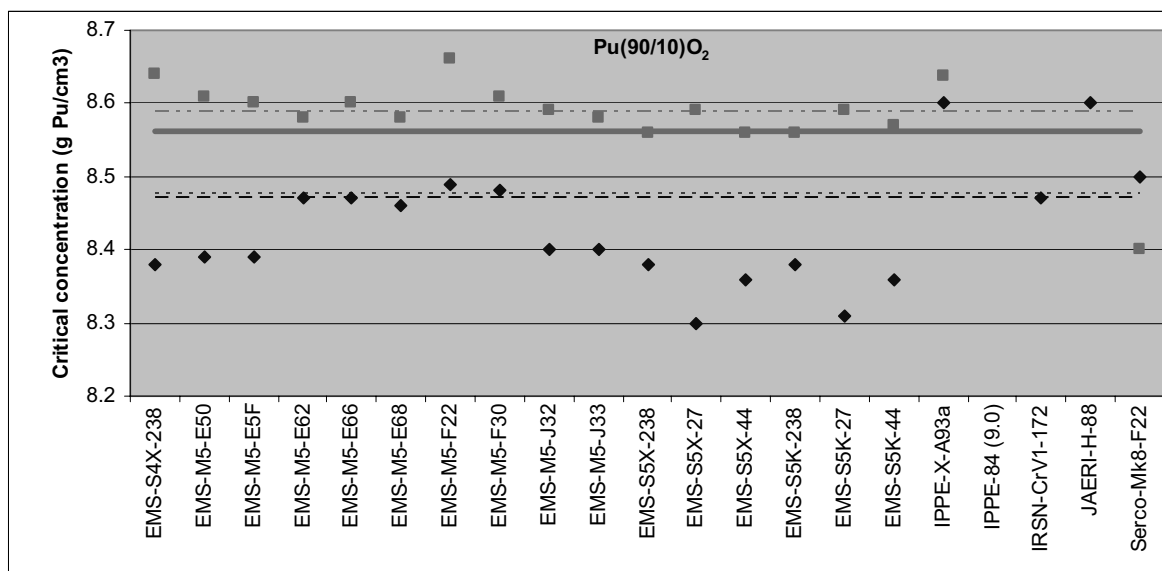


Figure G84. $\text{Pu}(90/10/0/0)\text{O}_2$ – Moderation H/Pu

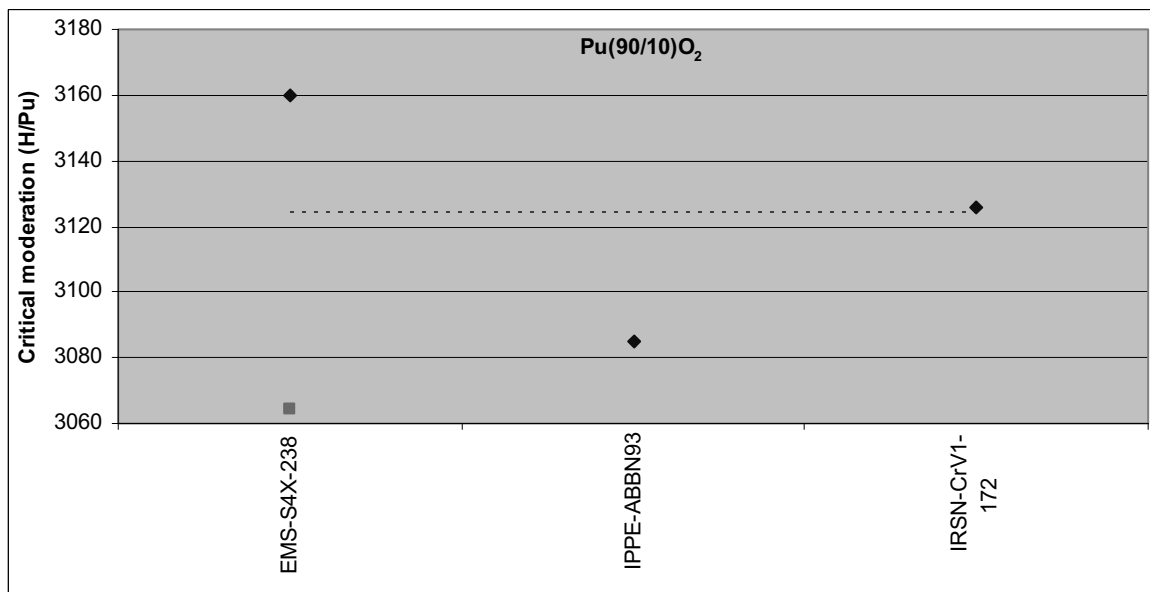


Table G83. Concentration: Pu(90/10/0/0)O₂

Critical concentration for H₂O-reflected Pu(90/10/0/0)O₂ + H₂O systems			
EALF = 0.0196	Pu concentration (g/l)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	8.38	8.64	+0.32/-0.34
EMS-M5-E50	8.39	8.61	
EMS-M5-E5F	8.39	8.60	
EMS-M5-E62	8.47	8.58	
EMS-M5-E66	8.47	8.60	
EMS-M5-E68	8.46	8.58	
EMS-M5-F22	8.49	8.66	
EMS-M5-F30	8.48	8.61	
EMS-M5-J32	8.40	8.59	
EMS-M5-J33	8.40	8.58	
EMS-S5X-238	8.38	8.56	
EMS-S5X-27	8.30	8.59	
EMS-S5X-44	8.36	8.56	
EMS-S5K-238	8.38	8.56	
EMS-S5K-27	8.31	8.59	
EMS-S5K-44	8.36	8.57	
IPPE-ABBN93	8.60	8.64	
IPPE-84	9		
IRSN-CrV1-172	8.47		
JAERI-H-88	8.6		
Serco-Mk8-F22	8.5	8.4	0.8%

Table G84. H/Pu: Pu(90/10/0/0)O₂

Critical moderation for H₂O-reflected Pu(90/10/0/0)O₂ + H₂O systems			
EALF = 0.0196	Moderation (H/Pu)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	3160	3064	-125/ +129
IPPE-ABBN93	3085		
IRSN-CrV1-172	3126		

Figure G85. Pu(80/15/5/0)O₂ – Mass

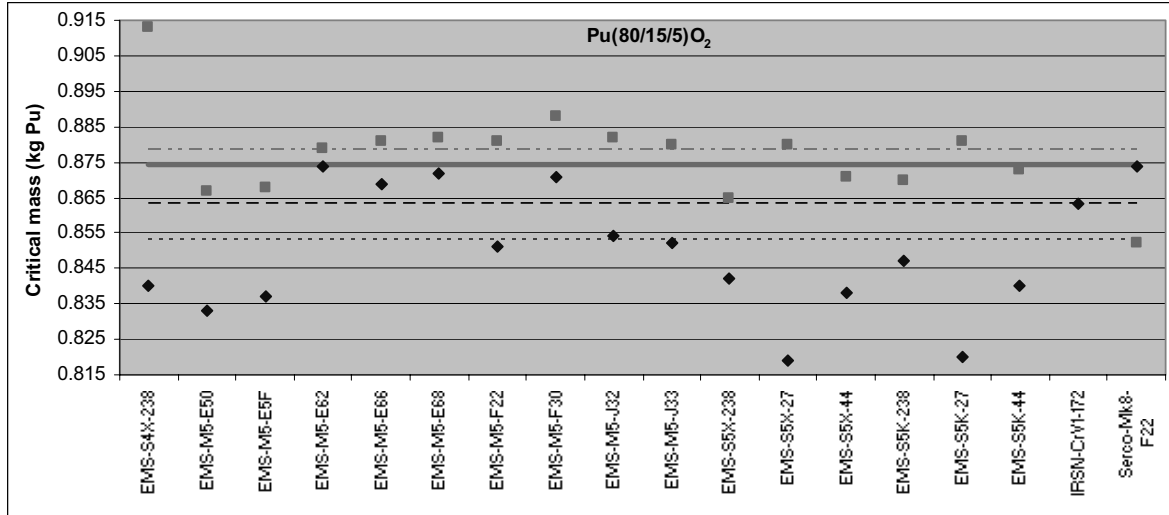


Figure G86. Pu(80/15/5/0)O₂ – Volume

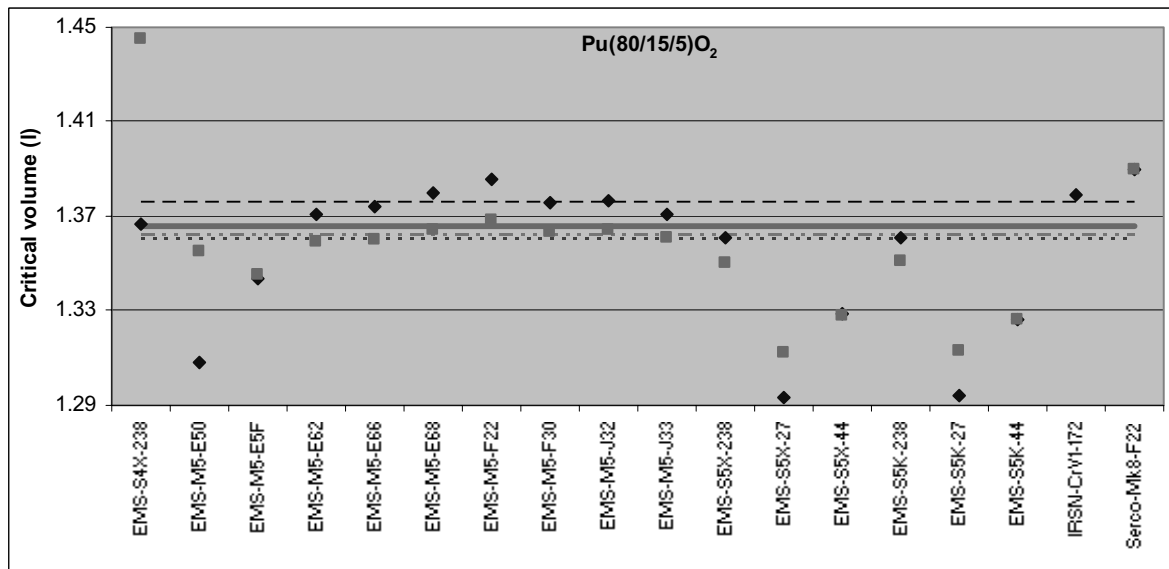


Table G85. Mass: Pu(80/15/5/0)O₂

Critical mass for H ₂ O-reflected Pu(80/15/5/0)O ₂ + H ₂ O systems			
EALF = 0.0551	Mass (kg Pu)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	0.840	0.913	+0.109/-0.096
EMS-M5-E50	0.833	0.867	
EMS-M5-E5F	0.837	0.868	
EMS-M5-E62	0.874	0.879	
EMS-M5-E66	0.869	0.881	
EMS-M5-E68	0.872	0.882	
EMS-M5-F22	0.851	0.881	
EMS-M5-F30	0.871	0.888	
EMS-M5-J32	0.854	0.882	
EMS-M5-J33	0.852	0.880	
EMS-S5X-238	0.842	0.865	
EMS-S5X-27	0.819	0.880	
EMS-S5X-44	0.838	0.871	
EMS-S5K-238	0.847	0.870	
EMS-S5K-27	0.820	0.881	
EMS-S5K-44	0.840	0.873	
IRSN-CrV1-172	0.863		
Serco-Mk8-F22	0.874	0.852	2.4%

Table G86. Volume Pu(80/15/5/0)O₂

Critical volume for H ₂ O-reflected Pu(80/15/5/0)O ₂ + H ₂ O systems			
EALF = 30557	Volume (l)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	1.367	1.445	+0.111/-0.103
EMS-M5-E50	1.308	1.355	
EMS-M5-E5F	1.344	1.345	
EMS-M5-E62	1.371	1.359	
EMS-M5-E66	1.374	1.360	
EMS-M5-E68	1.380	1.364	
EMS-M5-F22	1.386	1.368	
EMS-M5-F30	1.376	1.363	
EMS-M5-J32	1.377	1.364	
EMS-M5-J33	1.371	1.361	
EMS-S5X-238	1.361	1.350	
EMS-S5X-27	1.293	1.312	
EMS-S5X-44	1.329	1.328	
EMS-S5K-238	1.361	1.351	
EMS-S5K-27	1.294	1.313	
EMS-S5K-44	1.326	1.326	
IRSN-CrV1-172	1.379		
Serco-Mk8-F22	1.39	1.39	0.4%

Figure G87. Pu(80/15/5)O₂ – Cylinder diameter

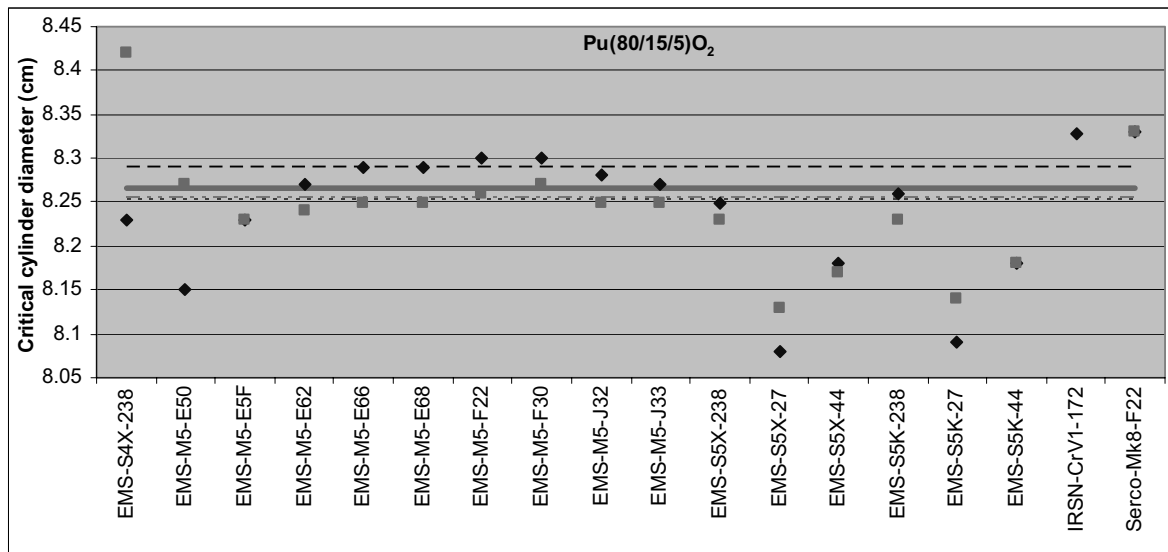


Figure G88. Pu(80/15/5)O₂ – Slab thickness

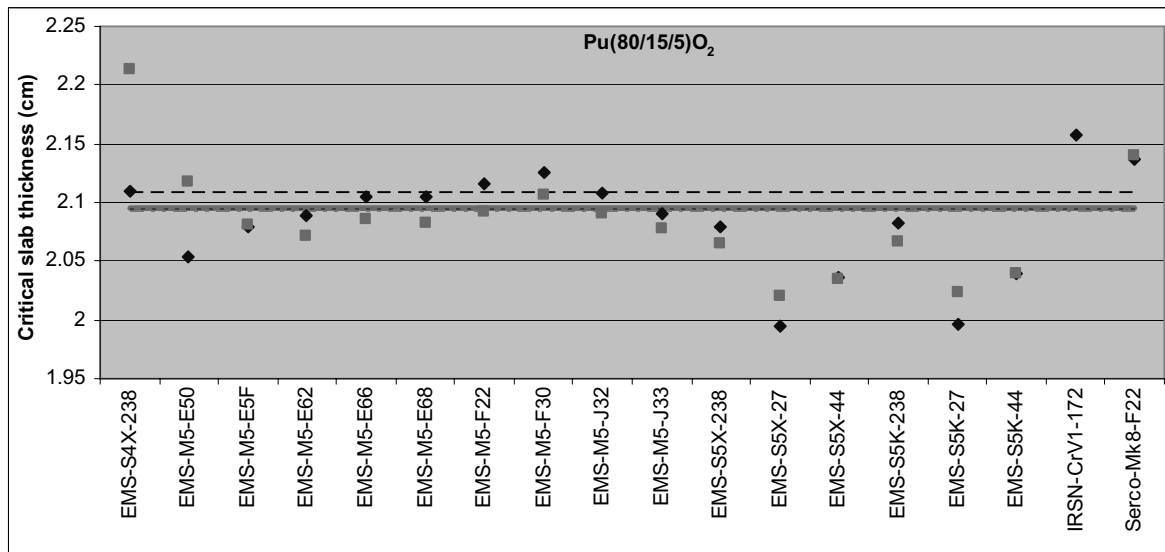


Table G87. Cylinder Pu(80/15/5/0)O₂

Critical cylinder diameter for H ₂ O-reflected Pu(80/15/5/0)O ₂ + H ₂ O systems			
EALF = 11465	Cylinder diameter (cm)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	8.23	8.42	+0.26/-0.25
EMS-M5-E50	8.15	8.27	
EMS-M5-E5F	8.23	8.23	
EMS-M5-E62	8.27	8.24	
EMS-M5-E66	8.29	8.25	
EMS-M5-E68	8.29	8.25	
EMS-M5-F22	8.30	8.26	
EMS-M5-F30	8.30	8.27	
EMS-M5-J32	8.28	8.25	
EMS-M5-J33	8.27	8.25	
EMS-S5X-238	8.25	8.23	
EMS-S5X-27	8.08	8.13	
EMS-S5X-44	8.18	8.17	
EMS-S5K-238	8.26	8.23	
EMS-S5K-27	8.09	8.14	
EMS-S5K-44	8.18	8.18	
IRSN-CrV1-172	8.33		
Serco-Mk8-F22	8.330	8.33	0.2%

Table G87. Cylinder Pu(80/15/5/0)O₂

Critical slab thickness for H ₂ O-reflected Pu(80/15/5/0)O ₂ + H ₂ O systems			
EALF = 551	Slab thickness (cm)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	2.109	2.213	+0.143/-0.138
EMS-M5-E50	2.054	2.118	
EMS-M5-E5F	2.080	2.081	
EMS-M5-E62	2.089	2.072	
EMS-M5-E66	2.104	2.085	
EMS-M5-E68	2.104	2.082	
EMS-M5-F22	2.116	2.092	
EMS-M5-F30	2.125	2.107	
EMS-M5-J32	2.108	2.090	
EMS-M5-J33	2.091	2.078	
EMS-S5X-238	2.080	2.065	
EMS-S5X-27	1.995	2.021	
EMS-S5X-44	2.036	2.035	
EMS-S5K-238	2.082	2.067	
EMS-S5K-27	1.997	2.023	
EMS-S5K-44	2.040	2.039	
IRSN-CrV1-172	2.157		
Serco-Mk8-F22	2.137	2.140	0.4%

Figure G89. Pu(80/15/5/0)O₂ – Concentration

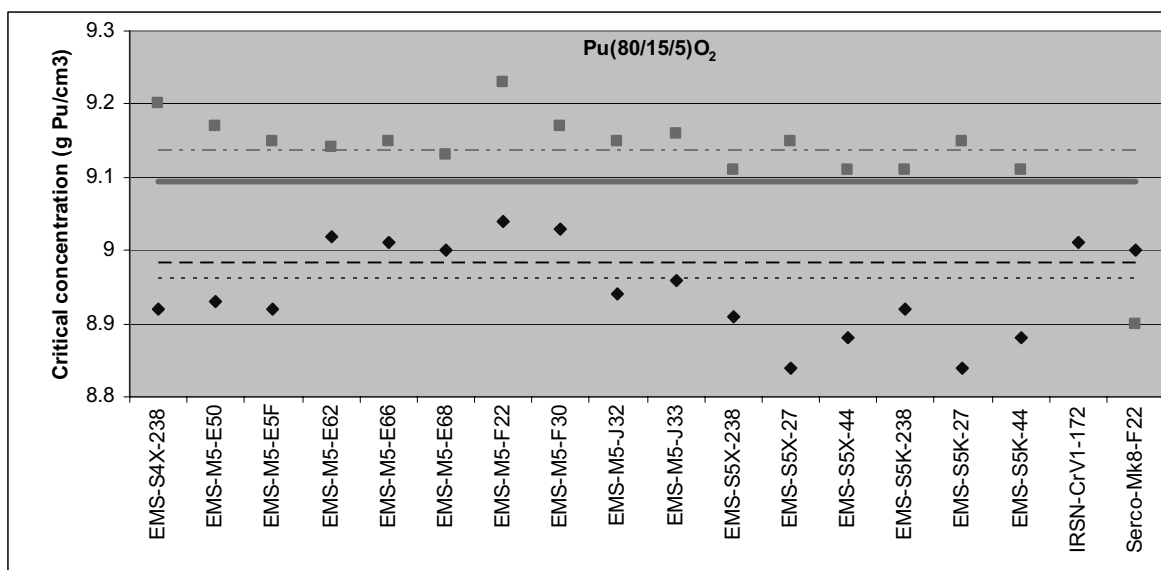


Figure G90. Pu(80/15/5/0)O₂ – Moderation H/Pu

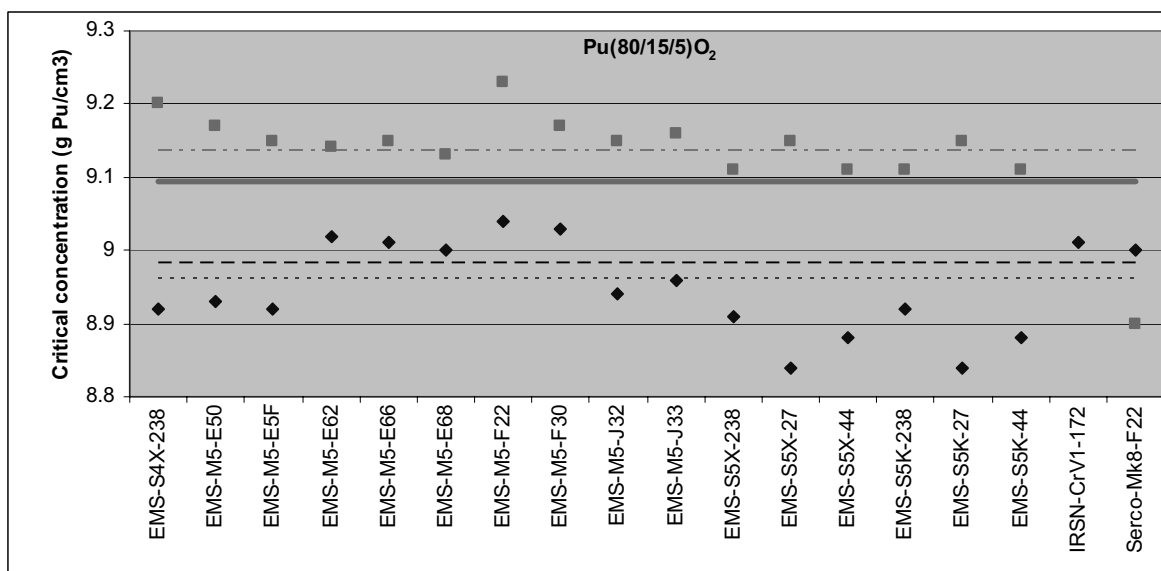


Table G89. Concentration: Pu(80/15/5/0)O₂

Critical concentration for H ₂ O-reflected Pu(80/15/5/0)O ₂ + H ₂ O systems			
EALF = 0.0196	Pu concentration (g/l)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	8.92	9.2	+0.35/-0.38
EMS-M5-E50	8.93	9.17	
EMS-M5-E5F	8.92	9.15	
EMS-M5-E62	9.02	9.14	
EMS-M5-E66	9.01	9.15	
EMS-M5-E68	9.00	9.13	
EMS-M5-F22	9.04	9.23	
EMS-M5-F30	9.03	9.17	
EMS-M5-J32	8.94	9.15	
EMS-M5-J33	8.96	9.16	
EMS-S5X-238	8.91	9.11	
EMS-S5X-27	8.84	9.15	
EMS-S5X-44	8.88	9.11	
EMS-S5K-238	8.92	9.11	
EMS-S5K-27	8.84	9.15	
EMS-S5K-44	8.88	9.11	
IRSN-CrV1-172	9.01		
Serco-Mk8-F22	9.0	8.9	0.8%

Table G90. H/Pu: Pu(80/15/5/0)O₂

Critical moderation for H ₂ O-reflected Pu(80/15/5/0)O ₂ + H ₂ O systems			
EALF = 0.0196	Moderation (H/Pu)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	2973	2880	-120/ +125
IRSN-CrV1-172	2940		

Figure G91. Pu(71/17/11/1)O₂ – Mass

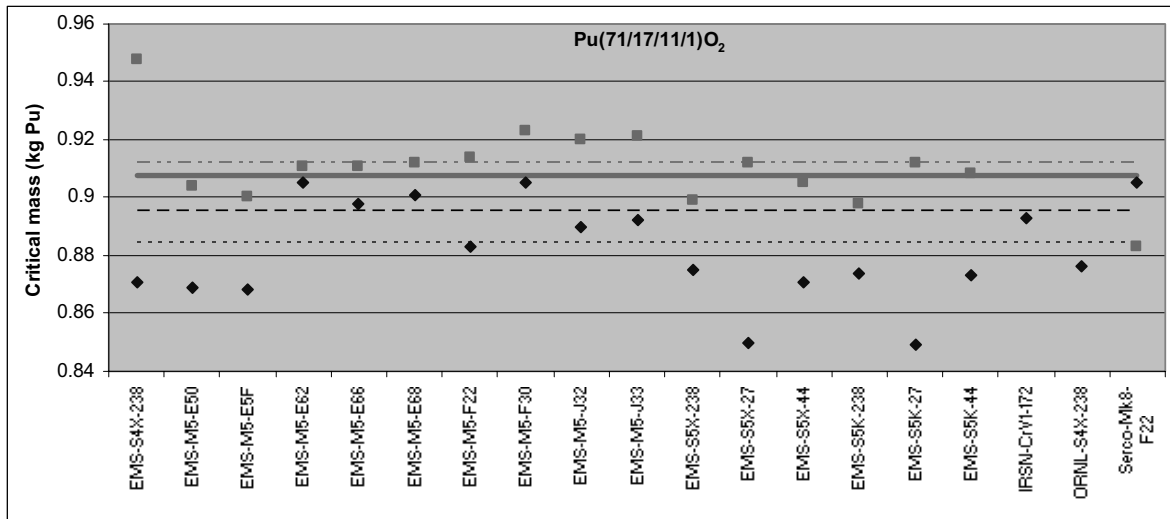


Figure G92. Pu(71/17/11/1)O₂ – Volume

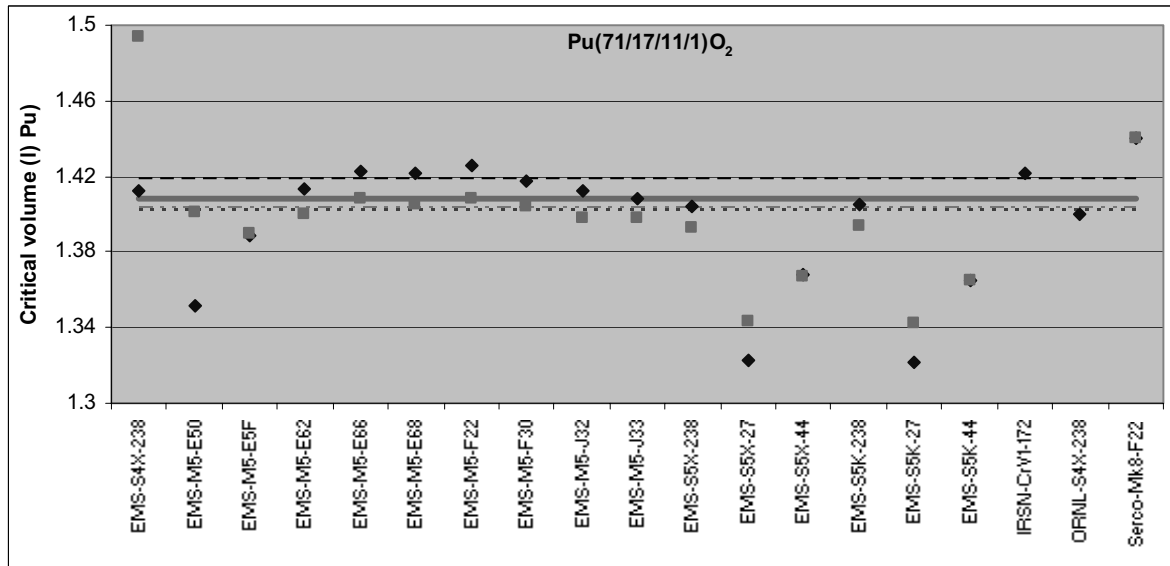


Table G91. Mass: Pu(71/17/11/1)O₂

Critical mass for H ₂ O-reflected Pu(71/17/11/1)O ₂ + H ₂ O systems			
EALF = 0.0547	Mass (kg Pu)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	0.871	0.948	+0.116/-0.101
EMS-M5-E50	0.869	0.904	
EMS-M5-E5F	0.868	0.900	
EMS-M5-E62	0.905	0.911	
EMS-M5-E66	0.898	0.911	
EMS-M5-E68	0.901	0.912	
EMS-M5-F22	0.883	0.914	
EMS-M5-F30	0.905	0.923	
EMS-M5-J32	0.890	0.920	
EMS-M5-J33	0.892	0.921	
EMS-S5X-238	0.875	0.899	
EMS-S5X-27	0.850	0.912	
EMS-S5X-44	0.871	0.905	
EMS-S5K-238	0.874	0.898	
EMS-S5K-27	0.849	0.912	
EMS-S5K-44	0.873	0.908	
IRSN-CrV1-172	0.893		
ORNL-S4X-238	0.876		
Serco-Mk8-F22	0.905	0.883	2.4%

Table G92. Volume Pu(71/17/11/1)O₂

Critical volume for H ₂ O-reflected Pu(71/17/11/1)O ₂ + H ₂ O systems			
EALF =29755	Volume (l)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	1.412	1.494	+0.115/-0.108
EMS-M5-E50	1.352	1.401	
EMS-M5-E5F	1.389	1.390	
EMS-M5-E62	1.413	1.400	
EMS-M5-E66	1.423	1.408	
EMS-M5-E68	1.422	1.405	
EMS-M5-F22	1.426	1.408	
EMS-M5-F30	1.418	1.404	
EMS-M5-J32	1.412	1.398	
EMS-M5-J33	1.408	1.398	
EMS-S5X-238	1.404	1.393	
EMS-S5X-27	1.323	1.343	
EMS-S5X-44	1.368	1.367	
EMS-S5K-238	1.405	1.394	
EMS-S5K-27	1.322	1.342	
EMS-S5K-44	1.365	1.365	
IRSN-CrV1-172	1.422		
ORNL-S4X-238	1.400		
Serco-Mk8-F22	1.44	1.44	0.4%

Figure G93. Pu(71/17/11/1)O₂ – Cylinder diameter

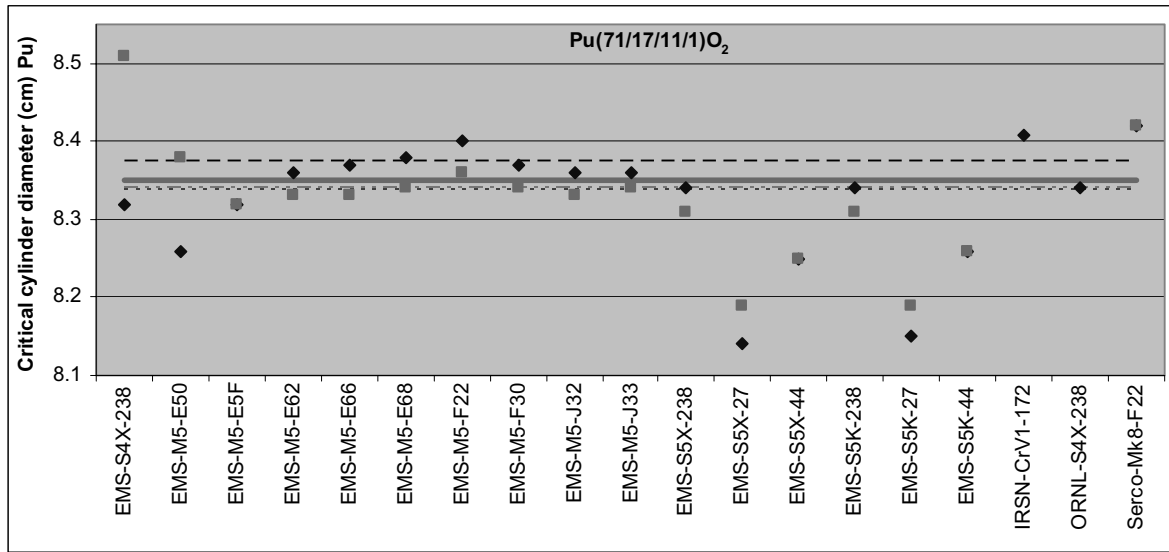


Figure G94. Pu(71/17/11/1)O₂ – Slab thickness

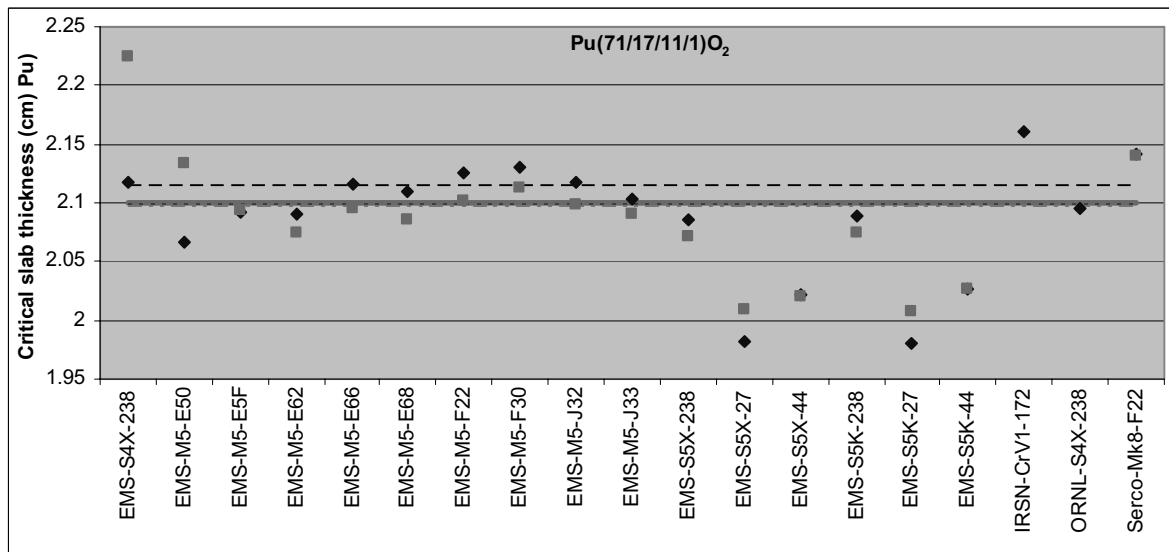


Table G93. Cylinder Pu(71/17/11/1)O₂

Critical cylinder diameter for H ₂ O-reflected Pu(71/17/11/1)O ₂ + H ₂ O systems			
EALF = 11234	Cylinder diameter (cm)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	8.32	8.51	+0.26/-0.25
EMS-M5-E50	8.26	8.38	
EMS-M5-E5F	8.32	8.32	
EMS-M5-E62	8.36	8.33	
EMS-M5-E66	8.37	8.33	
EMS-M5-E68	8.38	8.34	
EMS-M5-F22	8.40	8.36	
EMS-M5-F30	8.37	8.34	
EMS-M5-J32	8.36	8.33	
EMS-M5-J33	8.36	8.34	
EMS-S5X-238	8.34	8.31	
EMS-S5X-27	8.14	8.19	
EMS-S5X-44	8.25	8.25	
EMS-S5K-238	8.34	8.31	
EMS-S5K-27	8.15	8.19	
EMS-S5K-44	8.26	8.26	
IRSN-CrV1-172	8.41		
ORNL-S4X-238	8.34		
Serco-Mk8-F22	8.42	8.42	0.2%

Table G94. Slab Pu(71/17/11/1)O₂

Critical slab thickness for H ₂ O-reflected Pu(71/17/11/1)O ₂ + H ₂ O systems			
EALF = 542	Slab thickness (cm)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	2.117	2.225	0.147/-0.143
EMS-M5-E50	2.067	2.133	
EMS-M5-E5F	2.092	2.093	
EMS-M5-E62	2.091	2.074	
EMS-M5-E66	2.116	2.096	
EMS-M5-E68	2.109	2.086	
EMS-M5-F22	2.126	2.101	
EMS-M5-F30	2.130	2.112	
EMS-M5-J32	2.117	2.099	
EMS-M5-J33	2.103	2.090	
EMS-S5X-238	2.086	2.071	
EMS-S5X-27	1.982	2.009	
EMS-S5X-44	2.022	2.021	
EMS-S5K-238	2.089	2.074	
EMS-S5K-27	1.980	2.007	
EMS-S5K-44	2.027	2.026	
IRSN-CrV1-172	2.160		
ORNL-S4X-238	2.096		
Serco-Mk8-F22	2.142	2.140	0.4%

Figure G95. Pu(71/17/11/1)O₂ – Concentration

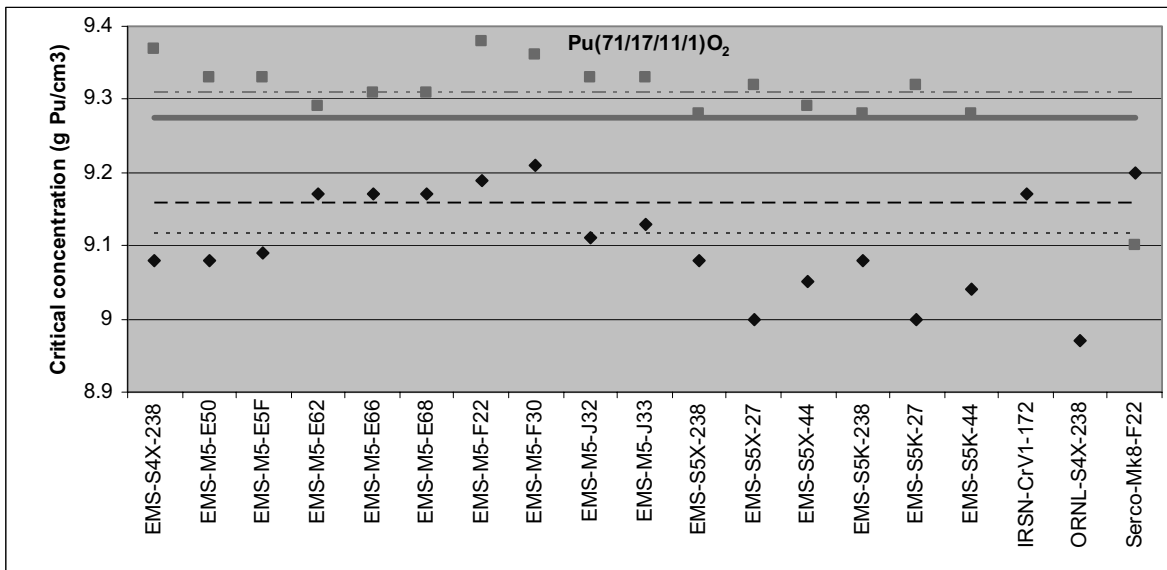


Figure G96. Pu(71/17/11/1)O₂ – Moderation H/Pu

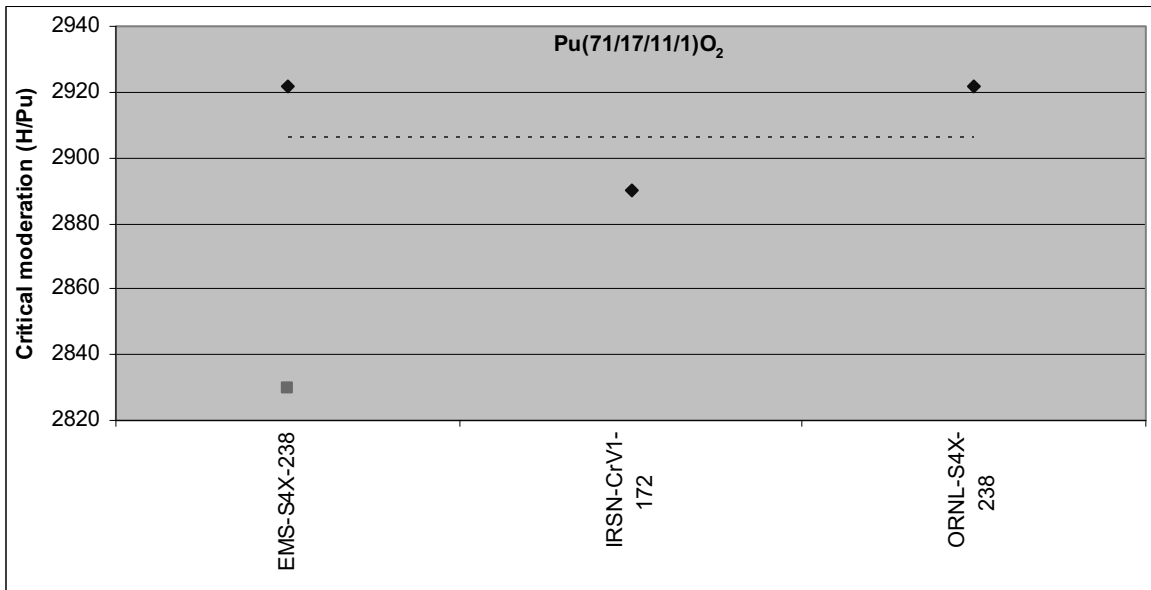


Table G95. Concentr.: Pu(71/17/11/1)O₂

Critical concentration for H ₂ O-reflected Pu(71/17/11/1)O ₂ + H ₂ O systems			
EALF = 0.0195	Pu concentration (g/l)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	9.08	9.37	+0.36/-0.40
EMS-M5-E50	9.08	9.33	
EMS-M5-E5F	9.09	9.33	
EMS-M5-E62	9.17	9.29	
EMS-M5-E66	9.17	9.31	
EMS-M5-E68	9.17	9.31	
EMS-M5-F22	9.19	9.38	
EMS-M5-F30	9.21	9.36	
EMS-M5-J32	9.11	9.33	
EMS-M5-J33	9.13	9.33	
EMS-S5X-238	9.08	9.28	
EMS-S5X-27	9.00	9.32	
EMS-S5X-44	9.05	9.29	
EMS-S5K-238	9.08	9.28	
EMS-S5K-27	9.00	9.32	
EMS-S5K-44	9.04	9.28	
IRSN-CrV1-172	9.17		
ORNL-S4X-238	8.97		
Serco-Mk8-F22	9.2	9.1	1.0%

Table G96. H/Pu: Pu(71/17/11/1)O₂

Critical moderation for H ₂ O-reflected Pu(71/17/11/1)O ₂ + H ₂ O systems			
EALF = 0.0195	Moderation (H/Pu)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	2922	2830	-120/ +123
IRSN-CrV1-172	2890		
ORNL-S4X-238	2922		

PuNHreference values

Figure G97. Pu(100/0/0)NH – Mass

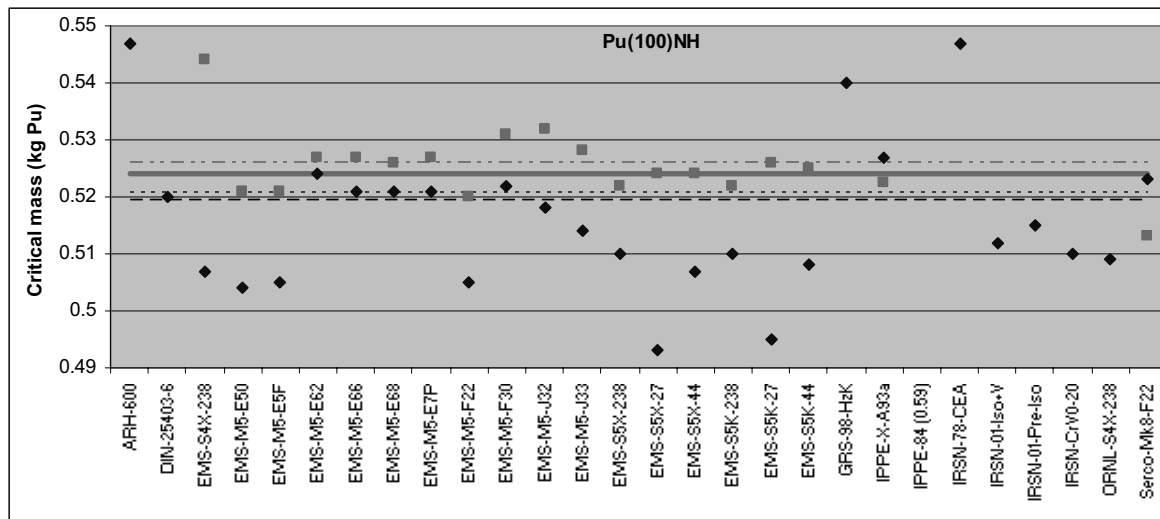


Figure G98. Pu(100/0/0)NH – Volume

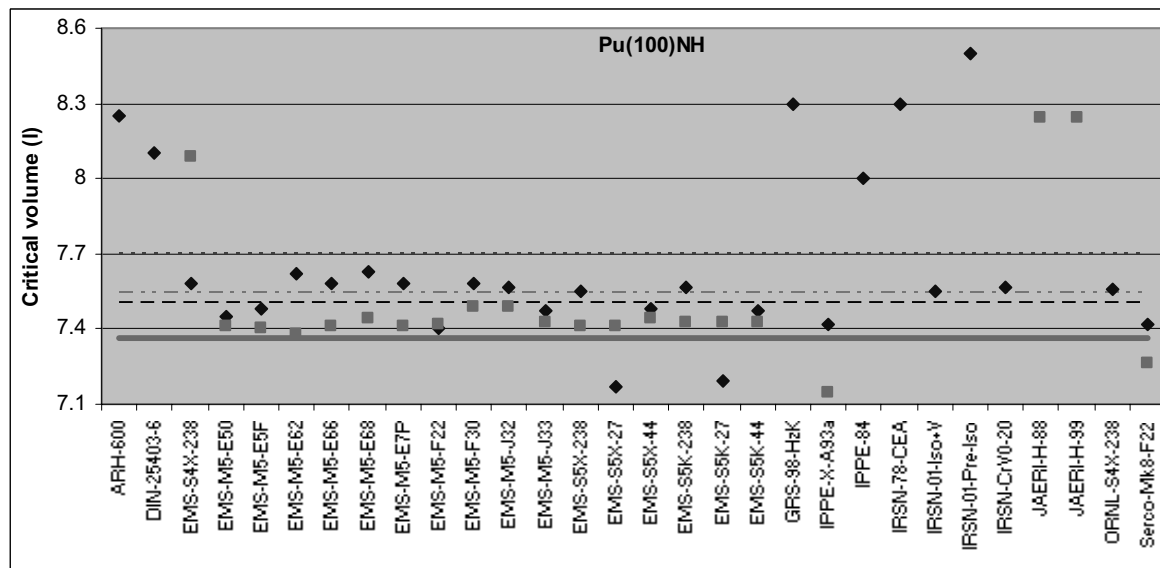


Table G97. Mass Pu(100/0/0/0)NH

Critical mass for H ₂ O-reflected Pu(100/0/0/0)NH + H ₂ O systems			
EALF = 0.0548	Mass (kg Pu)		
Source	Raw data	Best- estimate	2 σ
ARH-600	0.54		
DIN-25403-6	0.52		
EMS-S4X-238	0.507	0.544	+0.055/-0.049
EMS-M5-E50	0.504	0.521	
EMS-M5-E5F	0.505	0.521	
EMS-M5-E62	0.524	0.527	
EMS-M5-E66	0.521	0.527	
EMS-M5-E68	0.521	0.526	
EMS-M5-E7P	0.521	0.527	
EMS-M5-F22	0.505	0.520	
EMS-M5-F30	0.522	0.531	
EMS-M5-J32	0.518	0.532	
EMS-M5-J33	0.514	0.528	
EMS-S5X-238	0.510	0.522	
EMS-S5X-27	0.493	0.524	
EMS-S5X-44	0.507	0.524	
EMS-S5K-238	0.510	0.522	
EMS-S5K-27	0.495	0.526	
EMS-S5K-44	0.508	0.525	
GRS-98-HzK	0.54		
GRS-S4X-8-Iso	0.507		
GRS-M4-E6-Iso	0.524		
IPPE-ABBN93	0.527	0.523	
IPPE-84	0.59		
IRSN-78-CEA	0.547*		
IRSN-01-Iso+V	0.512		
IRSN-01-PreIso	0.515		
IRSN-CrV0-20	0.51		
ORNL-S4X-238	0.509		
Serco-Mk8-F22	0.523	0.513	1.6%

Table G98. Volume Pu(100/0/0/0)NH

Critical volume for H ₂ O-reflected Pu(100/0/0/0)NH + H ₂ O systems			
EALF=0.3097	Volume (l)		
Source	Raw data	Best- estimate	2 σ
ARH-600	8.25		
DIN-25403-6	8.1		
EMS-S4X-238	7.58	8.09	+0.74/-0.67
EMS-M5-E50	7.45	7.41	
EMS-M5-E5F	7.48	7.40	
EMS-M5-E62	7.62	7.38	
EMS-M5-E66	7.58	7.41	
EMS-M5-E68	7.63	7.44	
EMS-M5-E7P	7.58	7.41	
EMS-M5-F22	7.40	7.42	
EMS-M5-F30	7.58	7.49	
EMS-M5-J32	7.57	7.49	
EMS-M5-J33	7.47	7.43	
EMS-S5X-238	7.55	7.41	
EMS-S5X-27	7.17	7.41	
EMS-S5X-44	7.48	7.44	
EMS-S5K-238	7.57	7.43	
EMS-S5K-27	7.19	7.43	
EMS-S5K-44	7.47	7.43	
GRS-98-HzK	8.3		
GRS-S4X-8-Iso	7.56		
GRS-M4-E6-Iso	7.76		
IPPE-ABBN93	7.42	7.14	
IPPE-84	8.0		
IRSN-78-CEA	8.3		
IRSN-01-Iso+V	7.55		
IRSN-01-PreIso	8.5		
IRSN-CrV0-20	7.57		
JAERI-H-88		8.24	
JAERI-H-99		8.24	Same eval.?
ORNL-S4X-238	7.56		
Serco-Mk8-F22	7.42	7.26	1.8%

* Corrected from 0.50.

Figure G99. Pu(100/0/0/0)NH – Cylinder diameter

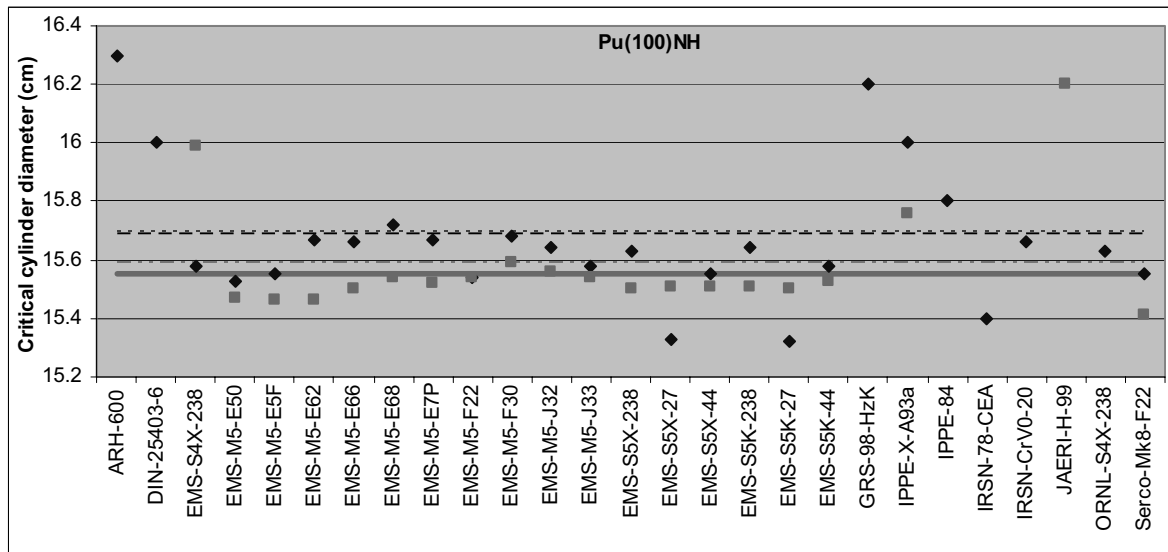


Figure G100. Pu(100/0/0/0)NH – Slab thickness

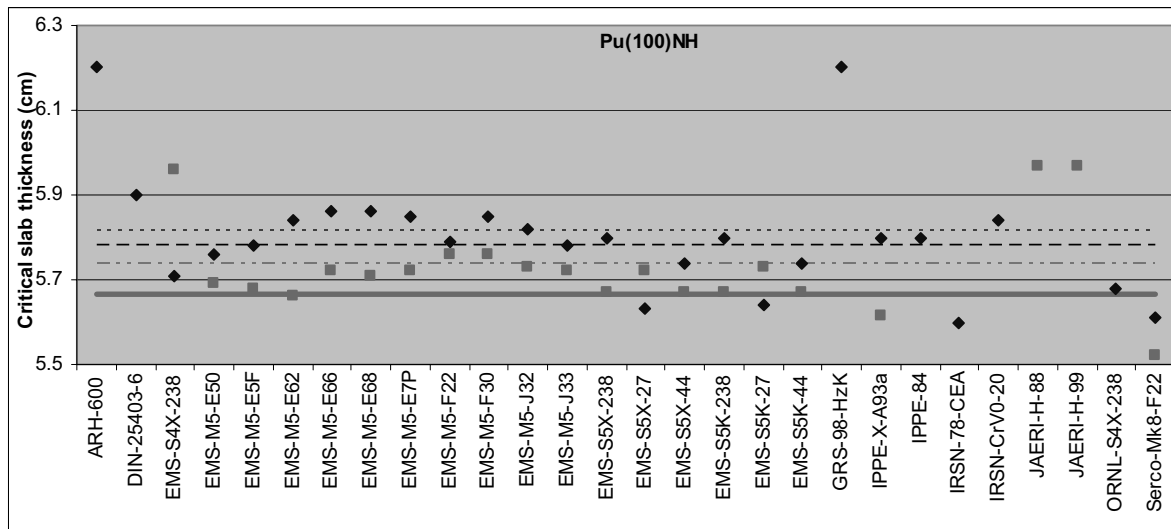


Table G99. Cylinder Pu(100/0/0/0)NH

Critical cylinder diameter for H ₂ O-reflected Pu(100/0/0/0)NH + H ₂ O systems			
EALF = 0.3562	Cylinder diameter (cm)		
Source	Raw data	Best-estimate	2 σ
ARH-600	16.3		
DIN-25403-6	16.0		
EMS-S4X-238	15.58	15.99	+0.55/-0.54
EMS-M5-E50	15.53	15.47	
EMS-M5-E5F	15.55	15.46	
EMS-M5-E62	15.67	15.46	
EMS-M5-E66	15.66	15.50	
EMS-M5-E68	15.72	15.54	
EMS-M5-E7P	15.67	15.52	
EMS-M5-F22	15.54	15.54	
EMS-M5-F30	15.68	15.59	
EMS-M5-J32	15.64	15.56	
EMS-M5-J33	15.58	15.54	
EMS-S5X-238	15.63	15.50	
EMS-S5X-27	15.33	15.51	
EMS-S5X-44	15.55	15.51	
EMS-S5K-238	15.64	15.51	
EMS-S5K-27	15.32	15.50	
EMS-S5K-44	15.58	15.53	
GRS-98-HzK	16.2		
IPPE-ABBN93	16.0	15.76	
IPPE-84	15.8		
IRSN-78-CEA	15.4		
IRSN-CrV0-20	15.66		
JAERI-H-99		16.2	
ORNL-S4X-238	15.63		
Serco-Mk8-F22	15.556	15.41	0.8%

Table G100. Slab: Pu(100/0/0/0)NH

Critical slab thickness for H ₂ O-reflected Pu(100/0/0/0)NH + H ₂ O systems			
EALF = 0.5620	Slab thickness (cm)		
Source	Raw data	Best-estimate	2 σ
ARH-600	6.2		
DIN-25403-6	5.9		
EMS-S4X-238	5.71	5.96	+0.37/-0.34
EMS-M5-E50	5.76	5.69	
EMS-M5-E5F	5.78	5.68	
EMS-M5-E62	5.84	5.66	
EMS-M5-E66	5.86	5.72	
EMS-M5-E68	5.86	5.71	
EMS-M5-E7P	5.85	5.72	
EMS-M5-F22	5.79	5.76	
EMS-M5-F30	5.85	5.76	
EMS-M5-J32	5.82	5.73	
EMS-M5-J33	5.78	5.72	
EMS-S5X-238	5.80	5.67	
EMS-S5X-27	5.63	5.72	
EMS-S5X-44	5.74	5.67	
EMS-S5K-238	5.80	5.67	
EMS-S5K-27	5.64	5.73	
EMS-S5K-44	5.74	5.67	
GRS-98-HzK	6.2		
IPPE-ABBN93	5.8	5.62	
IPPE-84	5.8		
IRSN-78-CEA	5.6		
IRSN-CrV0-20	5.84		
JAERI-H-88		5.97	
JAERI-H-99		5.97	Same eval?
ORNL-S4X-238	5.68		
Serco-Mk8-F22	5.61	5.52	1.4%

Figure G101. Pu(100/0/0/0)NH – Concentration

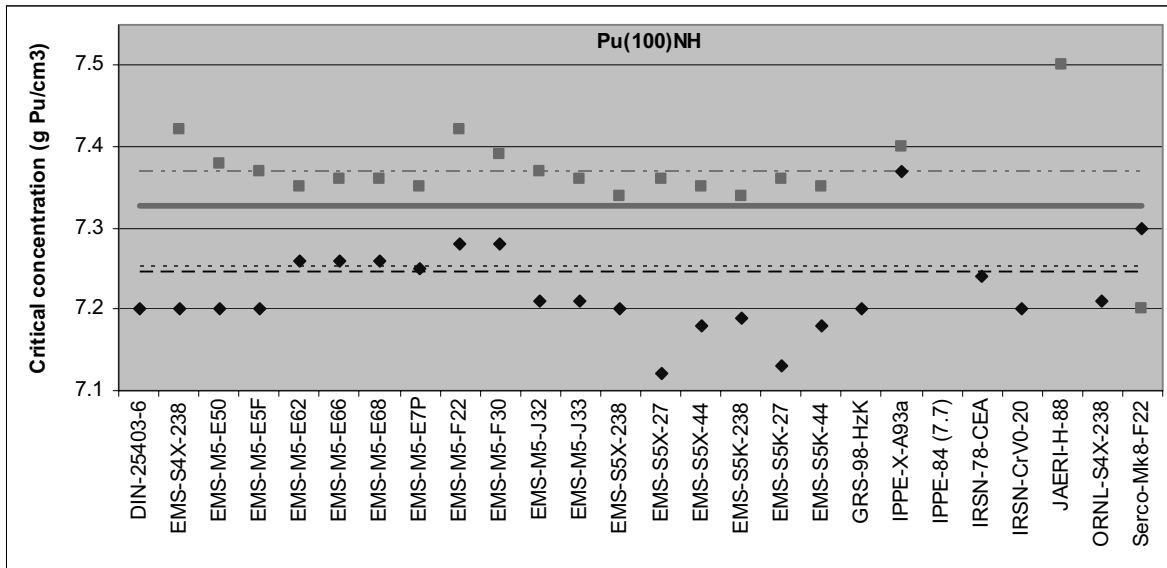


Figure G102. Pu(100/0/0/0)NH – Moderation H/Pu

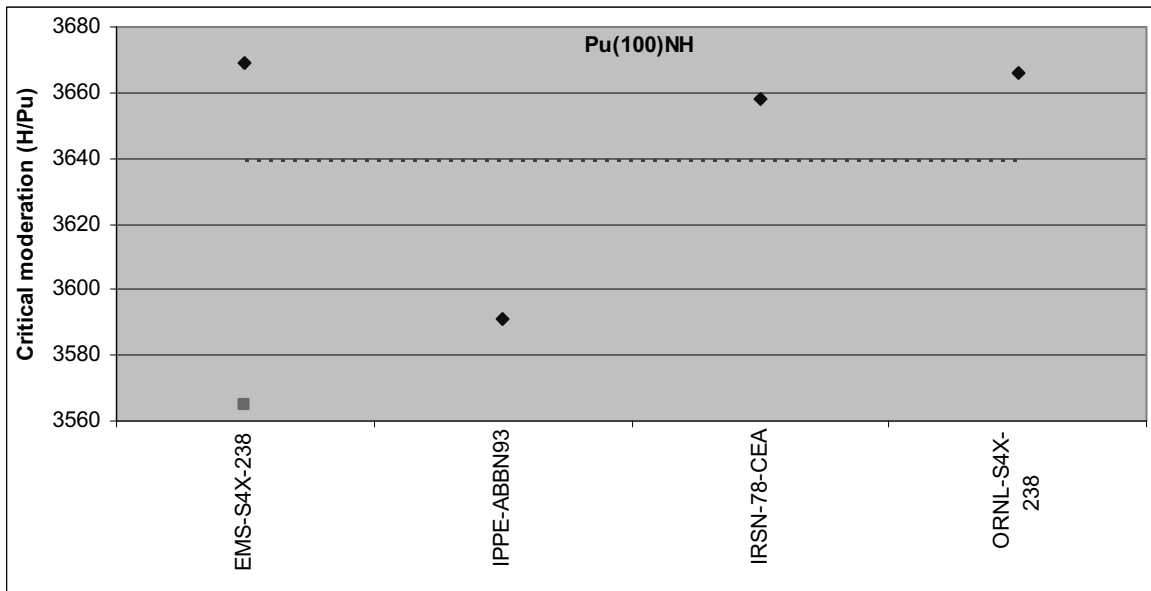


Table G101. Concentr. Pu(100/0/0/0)NH

Critical concentration for H ₂ O-reflected Pu(100/0/0/0)NH + H ₂ O systems			
EALF = 0.0194	Pu concentration (g/l)		
Source	Raw data	Best- estimate	2 σ
DIN-25403-6	7.2		
EMS-S4X-238	7.20	7.42	+0.29/-0.28
EMS-M5-E50	7.20	7.38	
EMS-M5-E5F	7.20	7.37	
EMS-M5-E62	7.26	7.35	
EMS-M5-E66	7.26	7.36	
EMS-M5-E68	7.26	7.36	
EMS-M5-E7P	7.25	7.35	
EMS-M5-F22	7.28	7.42	
EMS-M5-F30	7.28	7.39	
EMS-M5-J32	7.21	7.37	
EMS-M5-J33	7.21	7.36	
EMS-S5X-238	7.20	7.34	
EMS-S5X-27	7.12	7.36	
EMS-S5X-44	7.18	7.35	
EMS-S5K-238	7.19	7.34	
EMS-S5K-27	7.13	7.36	
EMS-S5K-44	7.18	7.35	
GRS-98-HzK	7.2		
IPPE-ABBN93	7.37	7.40	
IPPE-84	7.7		
IRSN-78-CEA	7.24		
IRSN-CrV0-20	7.2		
JAERI-H-88		7.5	
ORNL-S4X-238	7.21		
Serco-Mk8-F22	7.3*	7.2**	0.8%

Table G102. H/Pu: Pu(100/0/0/0)NH

Critical moderation for H ₂ O-reflected Pu(100/0/0/0)NH + H ₂ O systems			
EALF = 0.0194	Moderation (H/Pu)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	3669	3565	-135/ +140
IPPE-ABBN93	3591		
IRSN-78-CEA	3658		
ORNL-S4X-238	3666		

* Revised from 7.8 in March 2005.

** Revised from 7.7 in March 2005.

Figure G103. Pu(95/5/0/0)NH – Mass

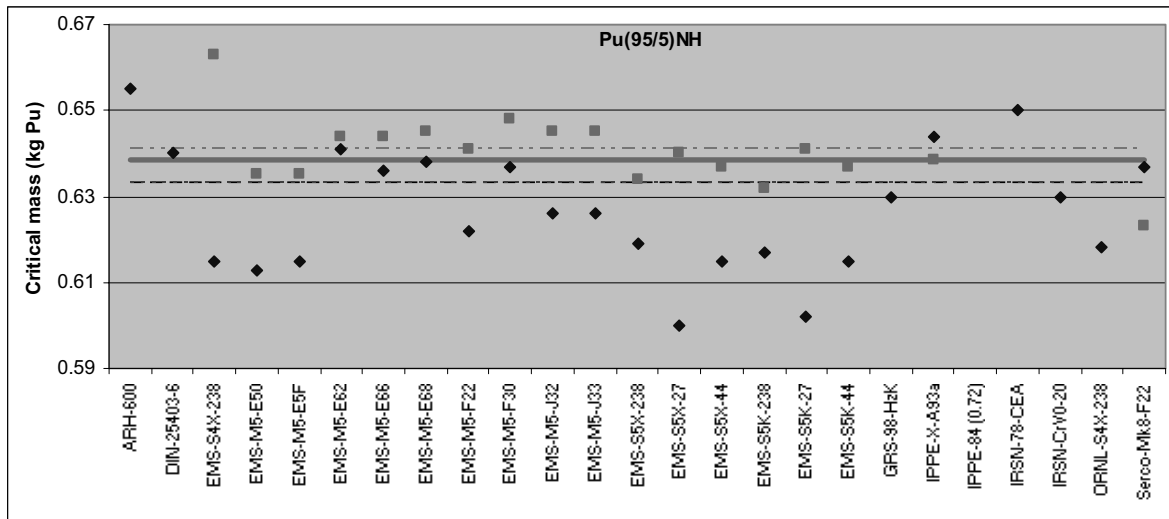


Figure G104. Pu(95/5/0/0)NH – Volume

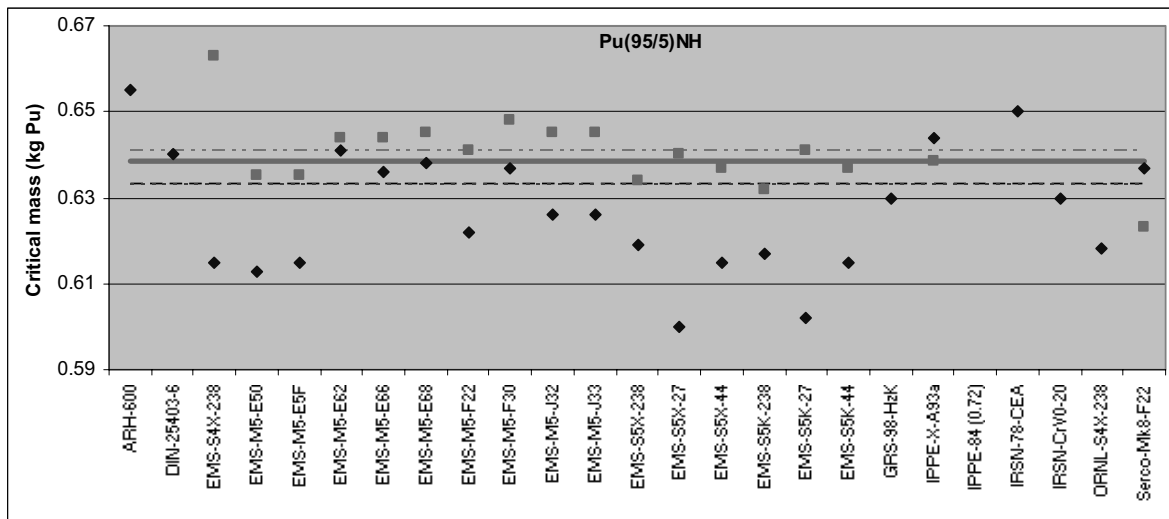


Table G103. Pu mass Pu(95/5/0/0)NH

Critical mass for H ₂ O-reflected Pu(95/5/0/0)NH + H ₂ O systems			
EALF = 0.0551	Mass (kg Pu)		
Source	Raw data	Best- estimate	2 σ
ARH-600	0.655		
DIN-25403-6	0.64		
EMS-S4X-238	0.615	0.663	+0.071/-0.063
EMS-M5-E50	0.613	0.635	
EMS-M5-E5F	0.615	0.635	
EMS-M5-E62	0.641	0.644	
EMS-M5-E66	0.636	0.644	
EMS-M5-E68	0.638	0.645	
EMS-M5-F22	0.622	0.641	
EMS-M5-F30	0.637	0.648	
EMS-M5-J32	0.626	0.645	
EMS-M5-J33	0.626	0.645	
EMS-S5X-238	0.619	0.634	
EMS-S5X-27	0.600	0.640	
EMS-S5X-44	0.615	0.637	
EMS-S5K-238	0.617	0.632	
EMS-S5K-27	0.602	0.641	
EMS-S5K-44	0.615	0.637	
GRS-98-HzK	0.63		
IPPE-ABBN93	0.644	0.638	
IPPE-84	0.72		
IRSN-78-CEA	0.65		
IRSN-CrV0-20	0.63		
ORNL-S4X-238	0.618		
Serco-Mk8-F22	0.637	0.623	2.0%

Table G104. Volume Pu(95/5/0/0)NH

Critical volume for H ₂ O-reflected Pu(95/5/0/0)NH + H ₂ O systems			
EALF=0.1443	Volume (l)		
Source	Raw data	Best- estimate	2 σ
ARH-600	11.4		
DIN-25403-6	11.4		
EMS-S4X-238	10.57	11.45	+1.16/-1.04
EMS-M5-E50	10.46	10.58	
EMS-M5-E5F	10.58	10.66	
EMS-M5-E62	11.00	10.82	
EMS-M5-E66	10.90	10.81	
EMS-M5-E68	10.91	10.79	
EMS-M5-F22	10.62	10.78	
EMS-M5-F30	10.75	10.76	
EMS-M5-J32	10.73	10.80	
EMS-M5-J33	10.68	10.78	
EMS-S5X-238	10.65	10.64	
EMS-S5X-27	10.21	10.71	
EMS-S5X-44	10.56	10.69	
EMS-S5K-238	10.68	10.67	
EMS-S5K-27	10.23	10.73	
EMS-S5K-44	10.56	10.69	
GRS-98-HzK	11.2		
IPPE-ABBN93	11.30	11.02	
IPPE-84	11.3		
IRSN-CrV0-20	10.74		
IRSN-78-CEA	11.4		
JAERI-H-88		11.3	
JAERI-H-99		11.3	
ORNL-S4X-238	10.68		
Serco-Mk8-F22	10.97	10.67	2.4%

Figure G105. Pu(95/5/0)NH – Cylinder diameter

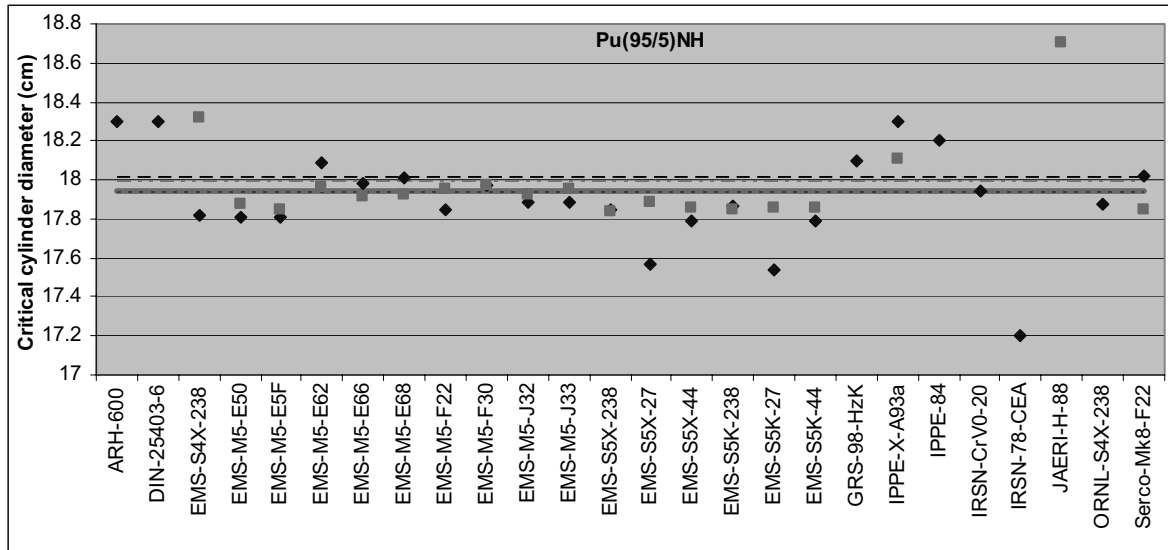


Figure G106. Pu(95/5/0)NH – Slab thickness

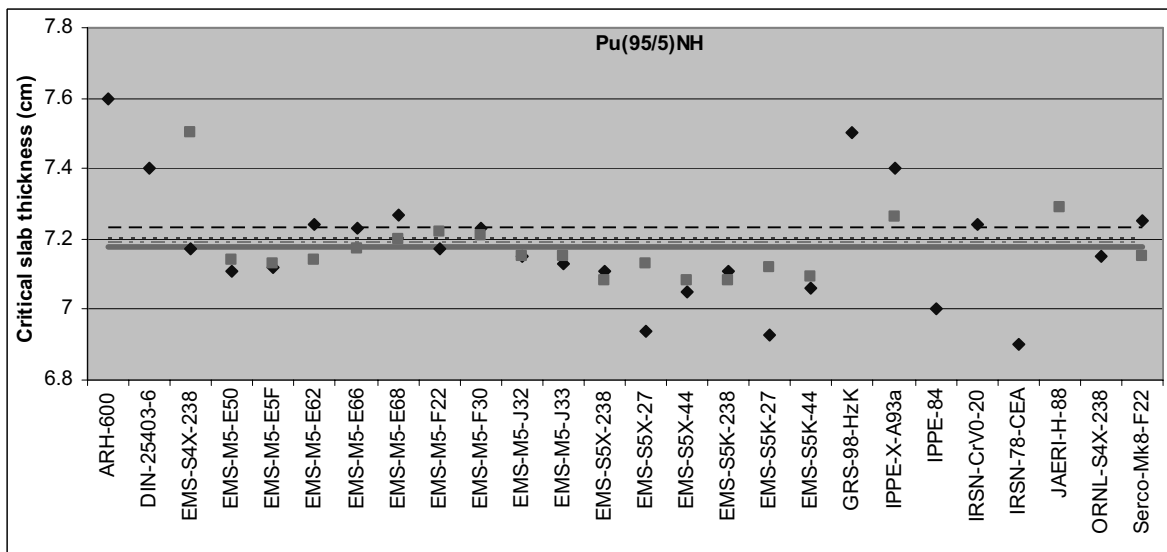


Table G105. Cylinder Pu(95/5/0/0)NH

Critical cylinder diameter for H ₂ O-reflected Pu(95/5/0/0)NH + H ₂ O systems			
EALF = 0.1525	Cylinder diameter (cm)		
Source	Raw data	Best-estimate	2 σ
ARH-600	18.3		
DIN-25403-6	18.3		
EMS-S4X-238	17.82	18.32	+0.69/-0.66
EMS-M5-E50	17.81	17.88	
EMS-M5-E5F	17.81	17.85	
EMS-M5-E62	18.09	17.96	
EMS-M5-E66	17.98	17.91	
EMS-M5-E68	18.01	17.92	
EMS-M5-F22	17.85	17.95	
EMS-M5-F30	17.97	17.97	
EMS-M5-J32	17.89	17.92	
EMS-M5-J33	17.89	17.95	
EMS-S5X-238	17.85	17.84	
EMS-S5X-27	17.57	17.89	
EMS-S5X-44	17.79	17.86	
EMS-S5K-238	17.87	17.85	
EMS-S5K-27	17.54	17.86	
EMS-S5K-44	17.79	17.86	
GRS-98-HzK	18.1		
IPPE-ABBN93	18.3	18.11	
IPPE-84	18.2		
IRSN-CrV0-20	17.94		
IRSN-78-CEA	17.2		
JAERI-H-88		18.7	
ORNL-S4X-238	17.88		
Serco-Mk8-F22	18.022	17.85	0.8%

Table G106. SlabPu(95/5/0/0)NH

Critical slab thickness for H ₂ O-reflected Pu(95/5/0/0)NH + H ₂ O systems			
EALF = 0.1811	Slab thickness (cm)		
Source	Raw data	Best-estimate	2 σ
ARH-600	7.6		
DIN-25403-6	7.4		
EMS-S4X-238	7.17	7.50	+0.45/-0.43
EMS-M5-E50	7.11	7.14	
EMS-M5-E5F	7.12	7.13	
EMS-M5-E62	7.24	7.14	
EMS-M5-E66	7.23	7.17	
EMS-M5-E68	7.27	7.20	
EMS-M5-F22	7.17	7.22	
EMS-M5-F30	7.23	7.21	
EMS-M5-J32	7.15	7.15	
EMS-M5-J33	7.13	7.15	
EMS-S5X-238	7.11	7.08	
EMS-S5X-27	6.94	7.13	
EMS-S5X-44	7.05	7.08	
EMS-S5K-238	7.11	7.08	
EMS-S5K-27	6.93	7.12	
EMS-S5K-44	7.06	7.09	
GRS-98-HzK	7.5		
IPPE-ABBN93	7.4	7.26	
IPPE-84	7		
IRSN-CrV0-20	7.24		
IRSN-78-CEA	6.9		
JAERI-H-88		7.29	
ORNL-S4X-238	7.15		
Serco-Mk8-F22	7.25	7.15	1.2%

Figure G107. Pu(95/5/0/0)NH – Concentration

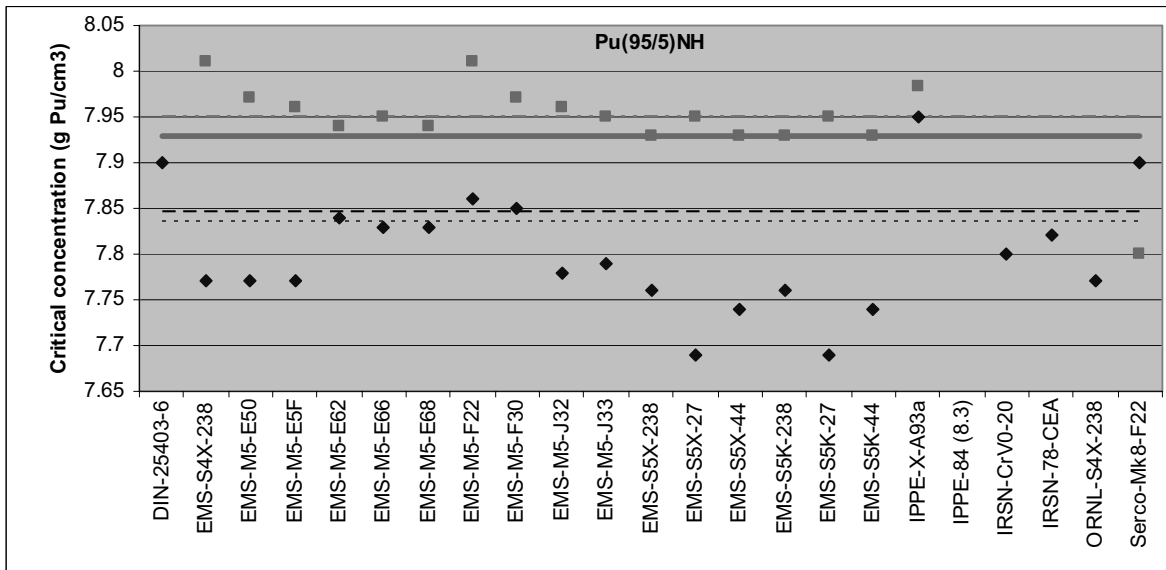


Figure G108. Pu(95/5/0/0)NH – Moderation H/Pu

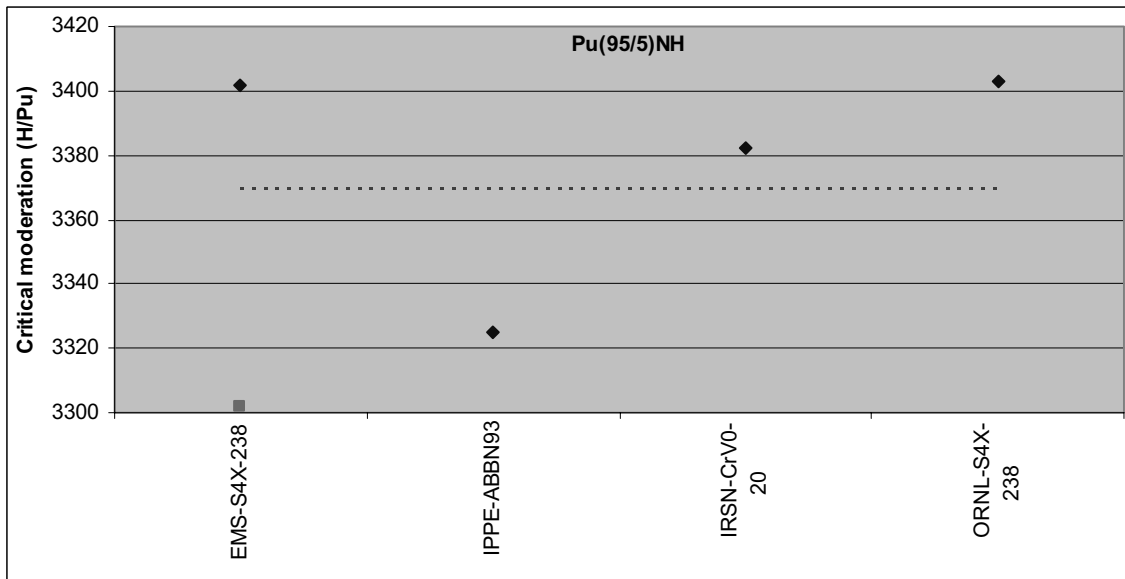


Table G107. Concentr.: Pu(95/5/0/0)NH

Critical concentration for H ₂ O-reflected Pu(95/5/0/0)NH + H ₂ O systems			
EALF = 0.0195	Pu concentration (g/l)		
Source	Raw data	Best-estimate	2 σ
DIN-25403-6	7.9		
EMS-S4X-238	7.77	8.01	+0.32/-0.32
EMS-M5-E50	7.77	7.97	
EMS-M5-E5F	7.77	7.96	
EMS-M5-E62	7.84	7.94	
EMS-M5-E66	7.83	7.95	
EMS-M5-E68	7.83	7.94	
EMS-M5-F22	7.86	8.01	
EMS-M5-F30	7.85	7.97	
EMS-M5-J32	7.78	7.96	
EMS-M5-J33	7.79	7.95	
EMS-S5X-238	7.76	7.93	
EMS-S5X-27	7.69	7.95	
EMS-S5X-44	7.74	7.93	
EMS-S5K-238	7.76	7.93	
EMS-S5K-27	7.69	7.95	
EMS-S5K-44	7.74	7.93	
IPPE-ABBN93	7.95	7.98	
IPPE-84	8.3		
IRSN-CrV0-20	7.8		
IRSN-78-CEA	7.82		
ORNL-S4X-238	7.77		
Serco-Mk8-F22	7.9	7.8	0.8%

Table G108. H/Pu: Pu(95/5/0/0)NH

Critical moderation for H ₂ O-reflected Pu(95/5/0/0)NH + H ₂ O systems			
EALF = 0.0195	Moderation (H/Pu)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	3402	3302	-131/ +135
IPPE-ABBN93	3325		
IRSN-CrV0-20	3382		
ORNL-S4X-238	3403		

Figure G109. Pu(80/10/10/0)NH – Mass

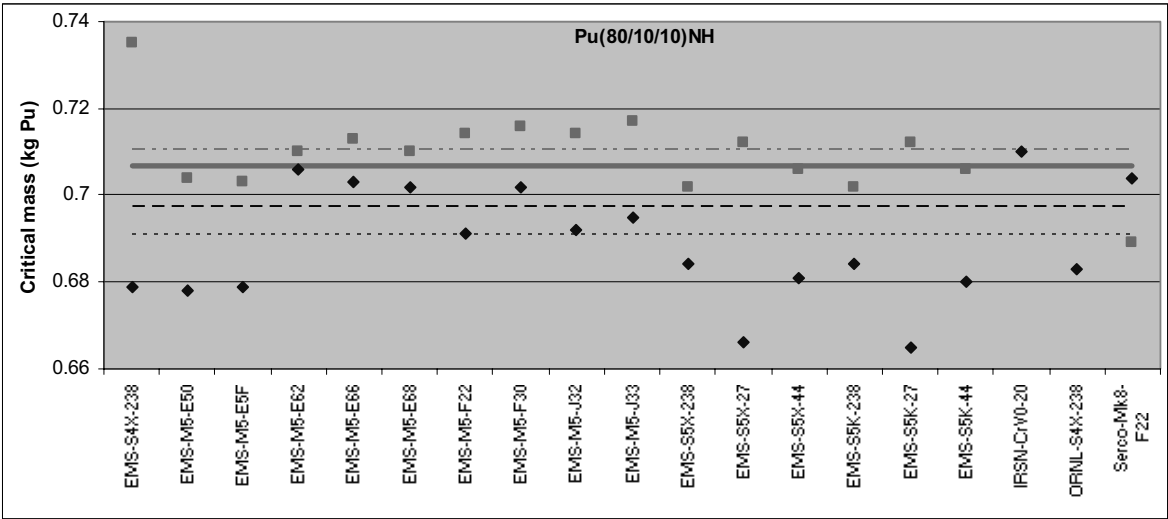


Figure G110. Pu(80/10/10/0)NH – Volume

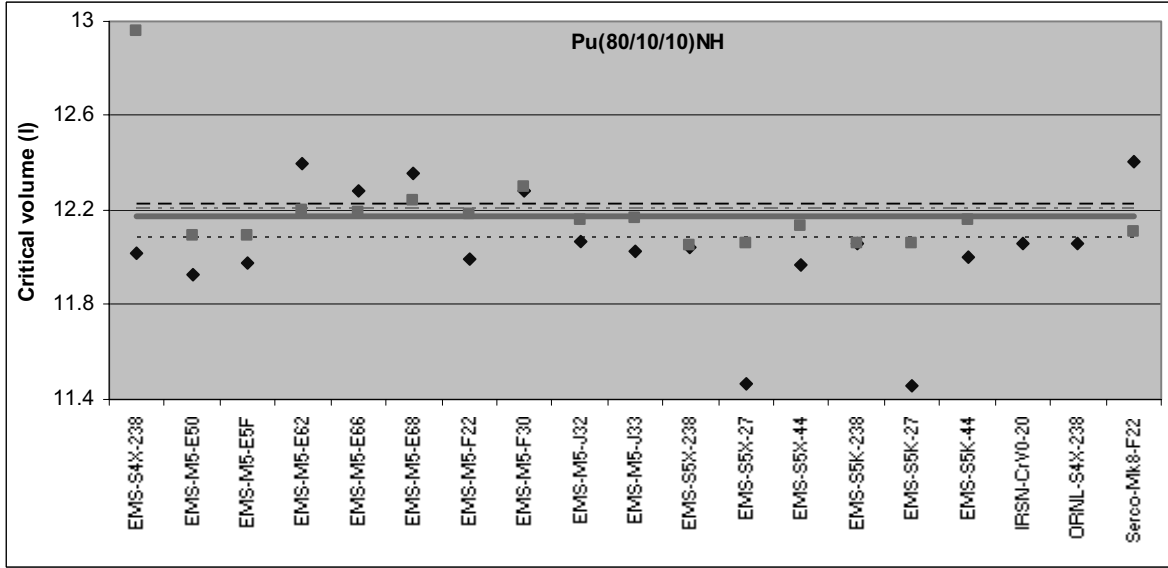


Table G109. Mass: Pu(80/10/10/0)NH

Critical mass for H ₂ O-reflected Pu(80/10/10/0)NH + H ₂ O systems			
EALF = 0.0544	Mass (kg Pu)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	0.679	0.735	+0.082/-0.073
EMS-M5-E50	0.678	0.704	
EMS-M5-E5F	0.679	0.703	
EMS-M5-E62	0.706	0.710	
EMS-M5-E66	0.703	0.713	
EMS-M5-E68	0.702	0.710	
EMS-M5-F22	0.691	0.714	
EMS-M5-F30	0.702	0.716	
EMS-M5-J32	0.692	0.714	
EMS-M5-J33	0.695	0.717	
EMS-S5X-238	0.684	0.702	
EMS-S5X-27	0.666	0.712	
EMS-S5X-44	0.681	0.706	
EMS-S5K-238	0.684	0.702	
EMS-S5K-27	0.665	0.712	
EMS-S5K-44	0.680	0.706	
IRSN-CrV0-20	0.71		
ORNL-S4X-238	0.683		
Serco-Mk8-F22	0.704	0.689	2.0%

Table G110. Volume Pu(80/10/10/0)NH

Critical volume for H ₂ O-reflected Pu(80/10/10/0)NH + H ₂ O systems			
EALF=0.1371	Volume (l)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	12.02	12.96	+1.37/-1.23
EMS-M5-E50	11.93	12.09	
EMS-M5-E5F	11.98	12.09	
EMS-M5-E62	12.40	12.20	
EMS-M5-E66	12.28	12.19	
EMS-M5-E68	12.36	12.24	
EMS-M5-F22	11.99	12.18	
EMS-M5-F30	12.28	12.30	
EMS-M5-J32	12.07	12.16	
EMS-M5-J33	12.03	12.17	
EMS-S5X-238	12.04	12.05	
EMS-S5X-27	11.47	12.06	
EMS-S5X-44	11.97	12.13	
EMS-S5K-238	12.06	12.06	
EMS-S5K-27	11.46	12.06	
EMS-S5K-44	12.00	12.16	
IRSN-CrV0-20	12.06		
ORNL-S4X-238	12.06		
Serco-Mk8-F22	12.41	12.11	2.0%

Figure G111. Pu(80/10/10/0)NH – Cylinder diameter

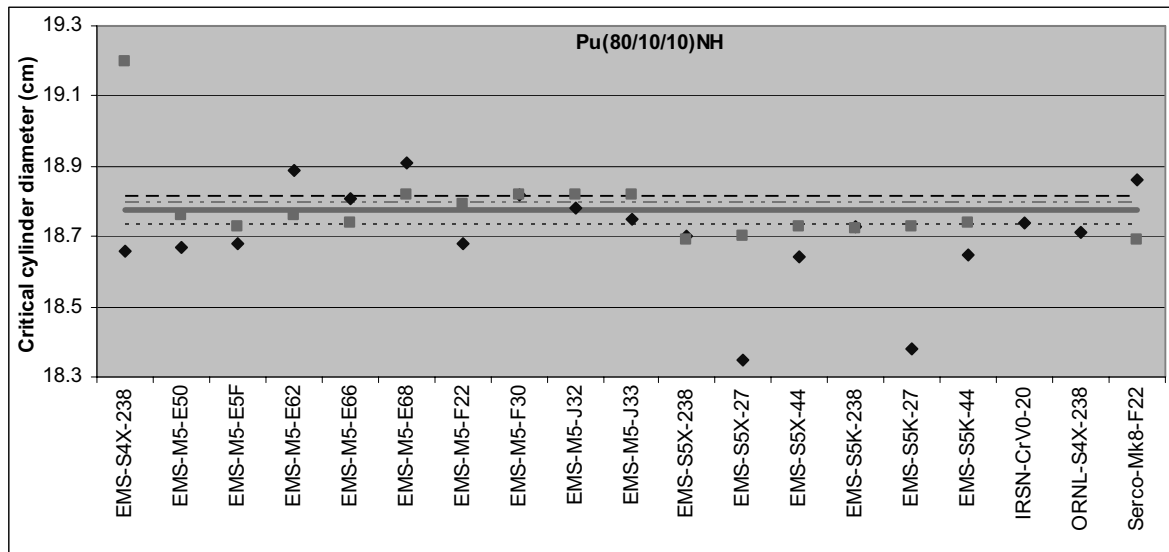


Figure G112. Pu(80/10/10/0)NH – Slab thickness

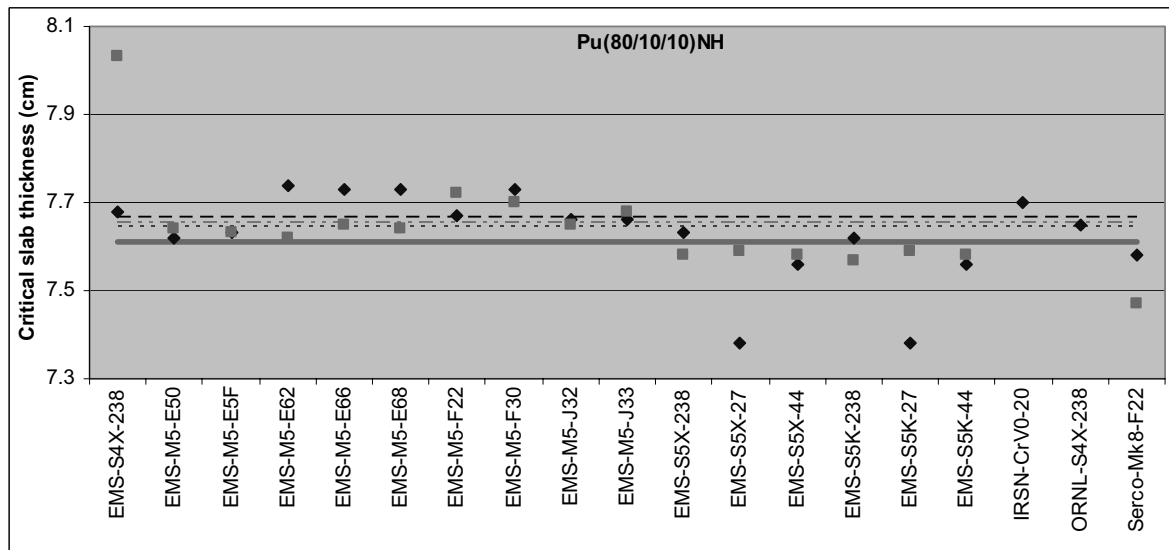


Table G111. Cylinder Pu(80/10/10/0)NH

Critical cylinder diameter for H ₂ O-reflected Pu(80/10/10/0)NH + H ₂ O systems			
EALF = 0.1470	Cylinder diameter (cm)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	18.66	19.20	+0.76/-0.72
EMS-M5-E50	18.67	18.76	
EMS-M5-E5F	18.68	18.73	
EMS-M5-E62	18.89	18.76	
EMS-M5-E66	18.81	18.74	
EMS-M5-E68	18.91	18.82	
EMS-M5-F22	18.68	18.79	
EMS-M5-F30	18.82	18.82	
EMS-M5-J32	18.78	18.82	
EMS-M5-J33	18.75	18.82	
EMS-S5X-238	18.53	18.52	
EMS-S5X-27	18.18	18.53	
EMS-S5X-44	18.47	18.56	
EMS-S5K-238	18.56	18.55	
EMS-S5K-27	18.21	18.56	
EMS-S5K-44	18.48	18.57	
IRSN-CrV0-20	18.74		
ORNL-S4X-238	18.71		
Serco-Mk8-F22	18.86	18.69	0.8%

Table G112. Slab Pu(80/10/10/0)NH

Critical slab thickness for H ₂ O-reflected Pu(80/10/10/0)NH + H ₂ O systems			
EALF = 0.2012	Slab thickness (cm)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	7.68	8.03	+0.51/-0.47
EMS-M5-E50	7.62	7.64	
EMS-M5-E5F	7.63	7.63	
EMS-M5-E62	7.74	7.62	
EMS-M5-E66	7.73	7.65	
EMS-M5-E68	7.73	7.64	
EMS-M5-F22	7.67	7.72	
EMS-M5-F30	7.73	7.70	
EMS-M5-J32	7.66	7.65	
EMS-M5-J33	7.66	7.68	
EMS-S5X-238	7.63	7.58	
EMS-S5X-27	7.38	7.59	
EMS-S5X-44	7.56	7.58	
EMS-S5K-238	7.62	7.57	
EMS-S5K-27	7.38	7.59	
EMS-S5K-44	7.56	7.58	
IRSN-CrV0-20	7.70		
ORNL-S4X-238	7.65		
Serco-Mk8-F22	7.58	7.47	1.2%

Figure G113. Pu(80/10/10/0)NH – Concentration

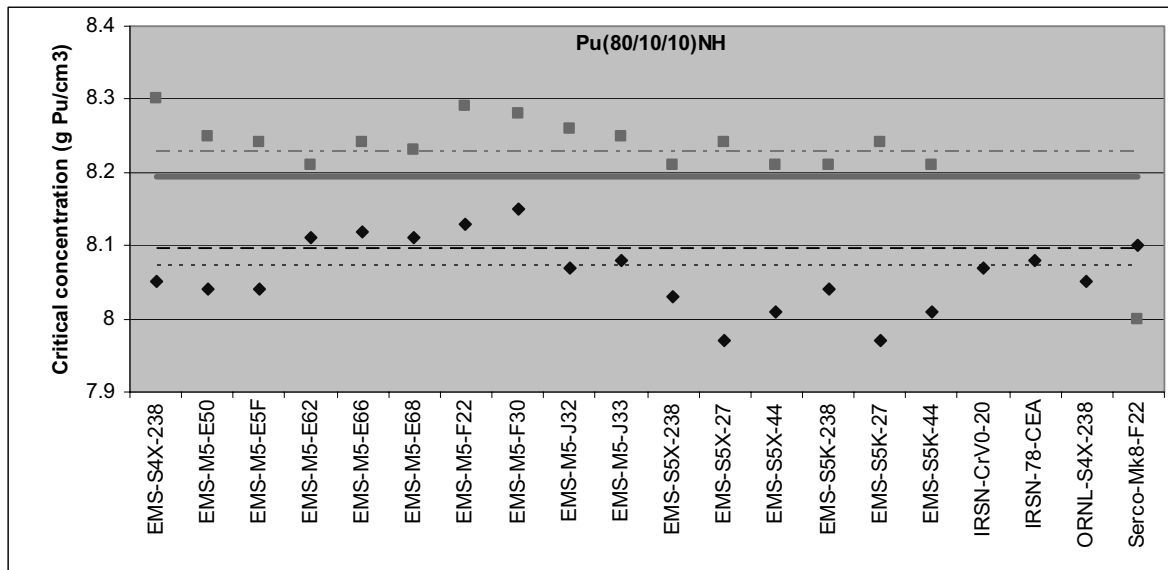


Figure G114. Pu(80/10/10/0)NH – Moderation H/Pu

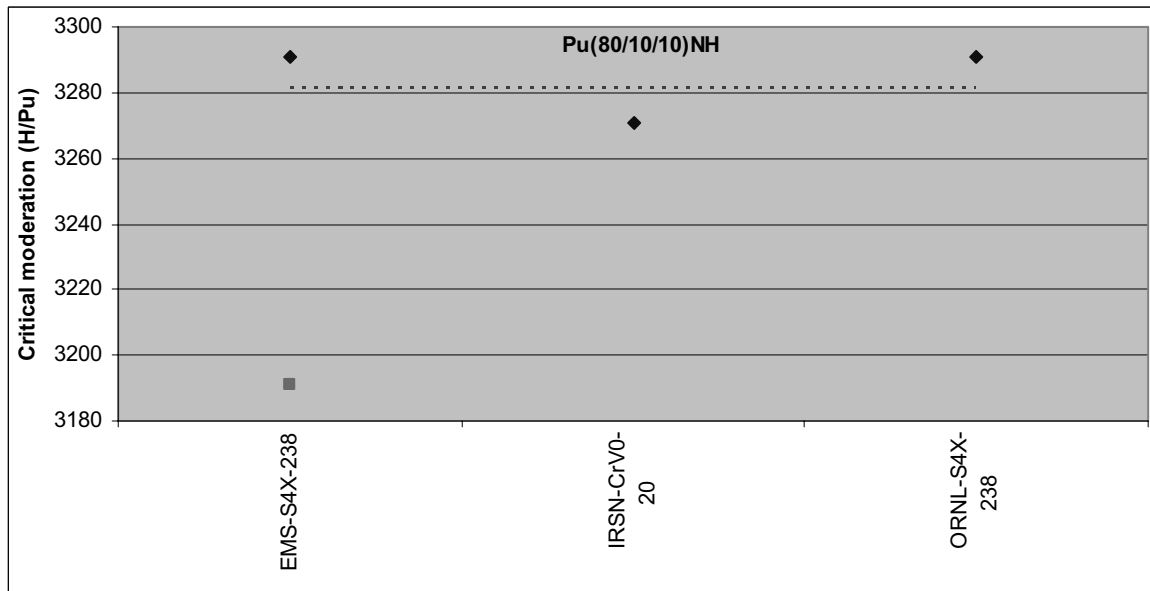


Table G113. Concentr. Pu(80/10/10/0)NH

Critical concentration for H₂O-reflected Pu(80/10/10/0)NH + H₂O systems			
EALF = 0.0193	Pu concentration (g/l)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	8.05	8.30	
EMS-M5-E50	8.04	8.25	
EMS-M5-E5F	8.04	8.24	
EMS-M5-E62	8.11	8.21	
EMS-M5-E66	8.12	8.24	
EMS-M5-E68	8.11	8.23	
EMS-M5-F22	8.13	8.29	
EMS-M5-F30	8.15	8.28	
EMS-M5-J32	8.07	8.26	
EMS-M5-J33	8.08	8.25	
EMS-S5X-238	8.03	8.21	
EMS-S5X-27	7.97	8.24	
EMS-S5X-44	8.01	8.21	
EMS-S5K-238	8.04	8.21	
EMS-S5K-27	7.97	8.24	
EMS-S5K-44	8.01	8.21	
IRSN-CrV0-20	8.07		
IRSN-78-CEA	8.08		
ORNL-S4X-238	8.05		
Serco-Mk8-F22	8.1	8.0	0.8%

Table G114. H/Pu: Pu(80/10/10/0)NH

Critical moderation for H₂O-reflected Pu(80/10/10/0)NH + H₂O systems			
EALF = 0.0193	Moderation (H/Pu)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	3291	3191	-129/134
IRSN-CrV0-20	3271		
ORNL-S4X-238	3291		

Figure G115. Pu(90/10/0/0)NH – Mass

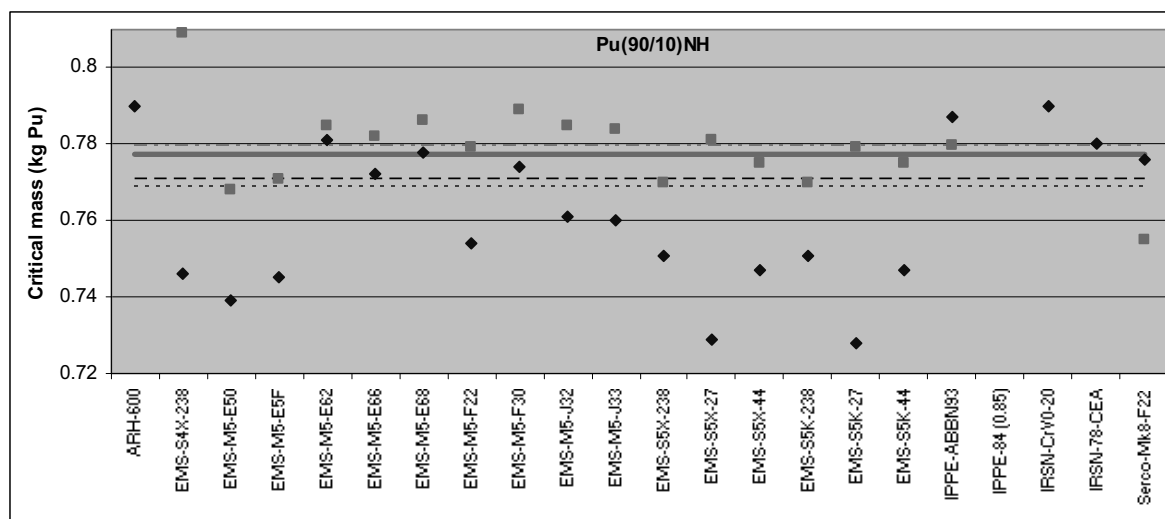


Figure G116. Pu(90/10/0/0)NH – Volume

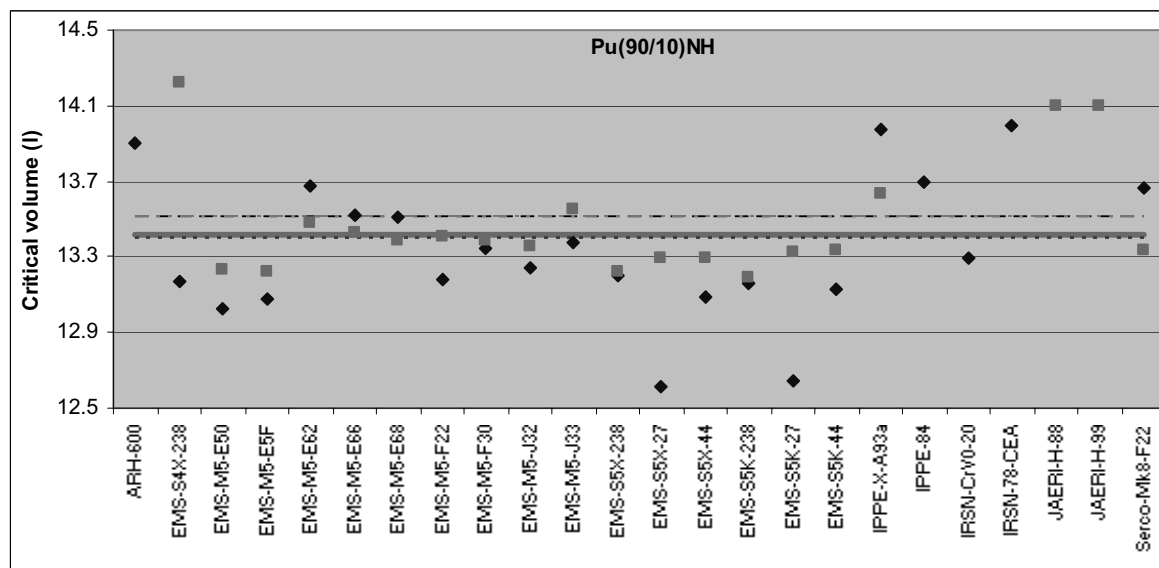


Table G115. Mass Pu(90/10/0/0)NH

Critical mass for H ₂ O-reflected Pu(90/10/0/0)NH + H ₂ O systems			
EALF = 0.0552	Mass (kg Pu)		
Source	Raw data	Best- estimate	2 σ
ARH-600	0.79		
EMS-S4X-238	0.746	0.809	+0.093/-0.082
EMS-M5-E50	0.739	0.768	
EMS-M5-E5F	0.745	0.771	
EMS-M5-E62	0.781	0.785	
EMS-M5-E66	0.772	0.782	
EMS-M5-E68	0.778	0.786	
EMS-M5-F22	0.754	0.779	
EMS-M5-F30	0.774	0.789	
EMS-M5-J32	0.761	0.785	
EMS-M5-J33	0.760	0.784	
EMS-S5X-238	0.751	0.770	
EMS-S5X-27	0.729	0.781	
EMS-S5X-44	0.747	0.775	
EMS-S5K-238	0.751	0.770	
EMS-S5K-27	0.728	0.779	
EMS-S5K-44	0.747	0.775	
IPPE-ABBN93	0.787	0.780	
IPPE-84	0.85		
IRSN-CrV0-20	0.79 *		
IRSN-78-CEA	0.780		
Serco-Mk8-F22	0.776	0.755	2.4%

Table G116. Volume Pu(90/10/0/0)NH

Critical volume for H ₂ O-reflected Pu(90/10/0/0)NH + H ₂ O systems			
EALF 0.1292	Volume (l)		
Source	Raw data	Best- estimate	2 σ
ARH-600	13.9		
EMS-S4X-238	13.17	14.22	+1.54/-1.37
EMS-M5-E50	13.03	13.23	
EMS-M5-E5F	13.08	13.22	
EMS-M5-E62	13.68	13.48	
EMS-M5-E66	13.52	13.43	
EMS-M5-E68	13.51	13.39	
EMS-M5-F22	13.18	13.41	
EMS-M5-F30	13.35	13.39	
EMS-M5-J32	13.24	13.36	
EMS-M5-J33	13.38	13.55	
EMS-S5X-238	13.20	13.22	
EMS-S5X-27	12.61	13.29	
EMS-S5X-44	13.09	13.29	
EMS-S5K-238	13.16	13.19	
EMS-S5K-27	12.64	13.32	
EMS-S5K-44	13.13	13.33	
IPPE-ABBN93	13.97	13.63	
IPPE-84	13.7		
IRSN-CrV0-20	13.29		
IRSN-78-CEA	14.0		
JAERI-H-88		14.1 *	
JAERI-H-99		14.1	
Serco-Mk8-F22	13.67	13.34	2.2%

* From report (0.77 in summary table)

* Corrected from 13.6

Figure G117. Pu(90/10/0/0)NH – Cylinder diameter

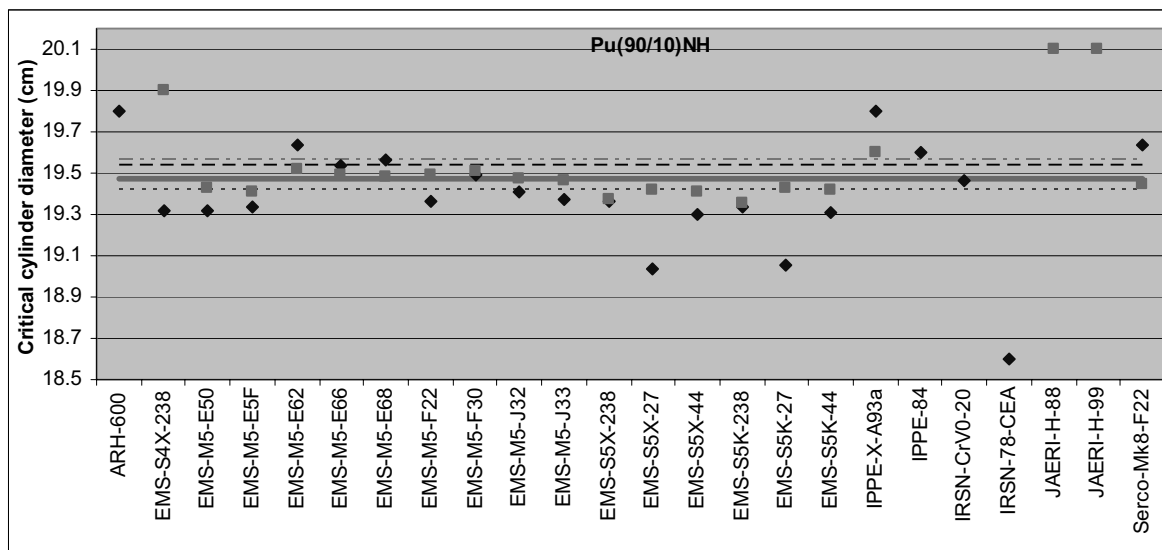


Figure G118. Pu(90/10/0/0)NH – Slab thickness

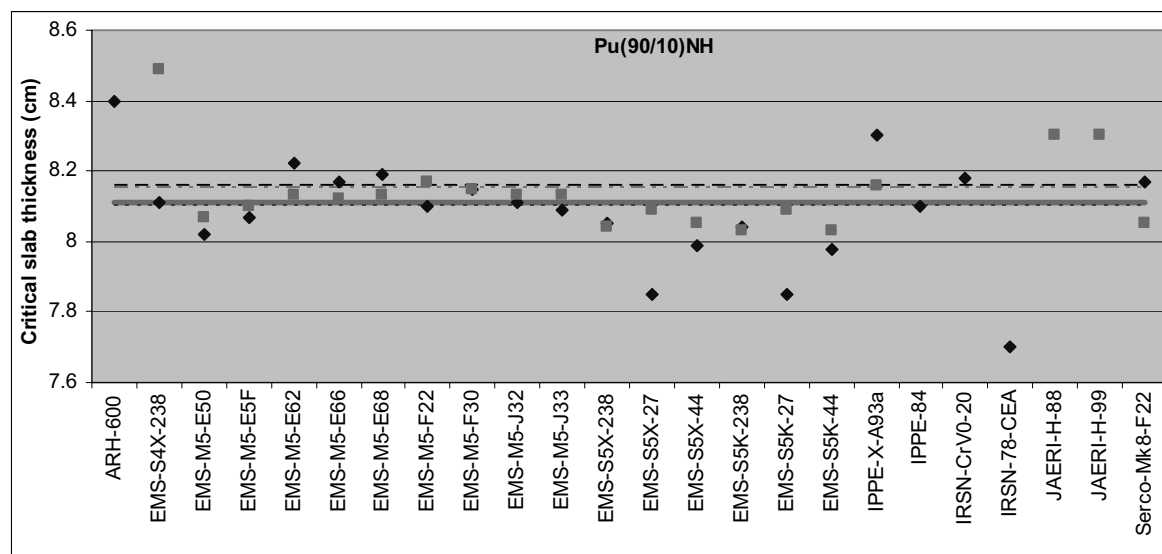


Table G117. Cylinder Pu(90/10/0/0)NH

Critical cylinder diameter for H ₂ O-reflected Pu(90/10/0/0)NH + H ₂ O systems			
EALF = 0.1342	Cylinder diameter (cm)		
Source	Raw data	Best-estimate	2 σ
ARH-600	19.8		
EMS-S4X-238	19.32	19.90	+0.79/-0.76
EMS-M5-E50	19.32	19.43	
EMS-M5-E5F	19.34	19.41	
EMS-M5-E62	19.64	19.52	
EMS-M5-E66	19.54	19.49	
EMS-M5-E68	19.56	19.48	
EMS-M5-F22	19.36	19.49	
EMS-M5-F30	19.49	19.51	
EMS-M5-J32	19.41	19.47	
EMS-M5-J33	19.37	19.46	
EMS-S5X-238	19.36	19.37	
EMS-S5X-27	19.04	19.42	
EMS-S5X-44	19.30	19.41	
EMS-S5K-238	19.34	19.35	
EMS-S5K-27	19.05	19.43	
EMS-S5K-44	19.31	19.42	
IPPE-ABBN93	19.8	19.60	
IPPE-84	19.6		
IRSN-CrV0-20	19.46		
IRSN-78-CEA	18.6		
JAERI-H-88		20.1*	
JAERI-H-99		20.1	
Serco-Mk8-F22	19.64	19.45	0.8%

Table G118. Slab: Pu(90/10/0/0)NH

Critical slab thickness for H ₂ O-reflected Pu(90/10/0/0)NH + H ₂ O systems			
EALF = 0.1537	Slab thickness (cm)		
Source	Raw data	Best-estimate	2 σ
ARH-600	8.4		
EMS-S4X-238	8.11	8.49	+0.51/-0.50
EMS-M5-E50	8.02	8.07	
EMS-M5-E5F	8.07	8.10	
EMS-M5-E62	8.22	8.13	
EMS-M5-E66	8.17	8.12	
EMS-M5-E68	8.19	8.13	
EMS-M5-F22	8.10	8.17	
EMS-M5-F30	8.15	8.15	
EMS-M5-J32	8.11	8.13	
EMS-M5-J33	8.09	8.13	
EMS-S5X-238	8.05	8.04	
EMS-S5X-27	7.85	8.09	
EMS-S5X-44	7.99	8.05	
EMS-S5K-238	8.04	8.03	
EMS-S5K-27	7.85	8.09	
EMS-S5K-44	7.98	8.03	
IPPE-ABBN93	8.3	8.16	
IPPE-84	8.1		
IRSN-CrV0-20	8.18		
IRSN-78-CEA	7.7		
JAERI-H-88		8.30*	
JAERI-H-99		8.3	
Serco-Mk8-F22	8.17	8.05	1.2%

* Corrected from 19.9

* Corrected from 8.12

Figure G119. Pu(90/10/0/0)NH – Concentration

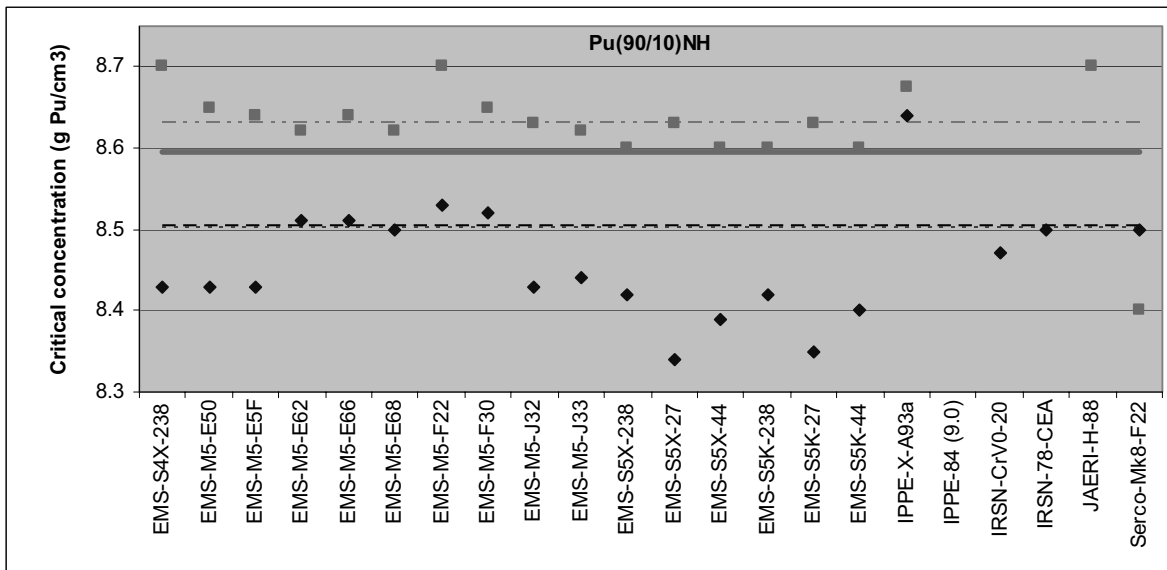


Figure G120. Pu(90/10/0/0)NH – Moderation H/Pu

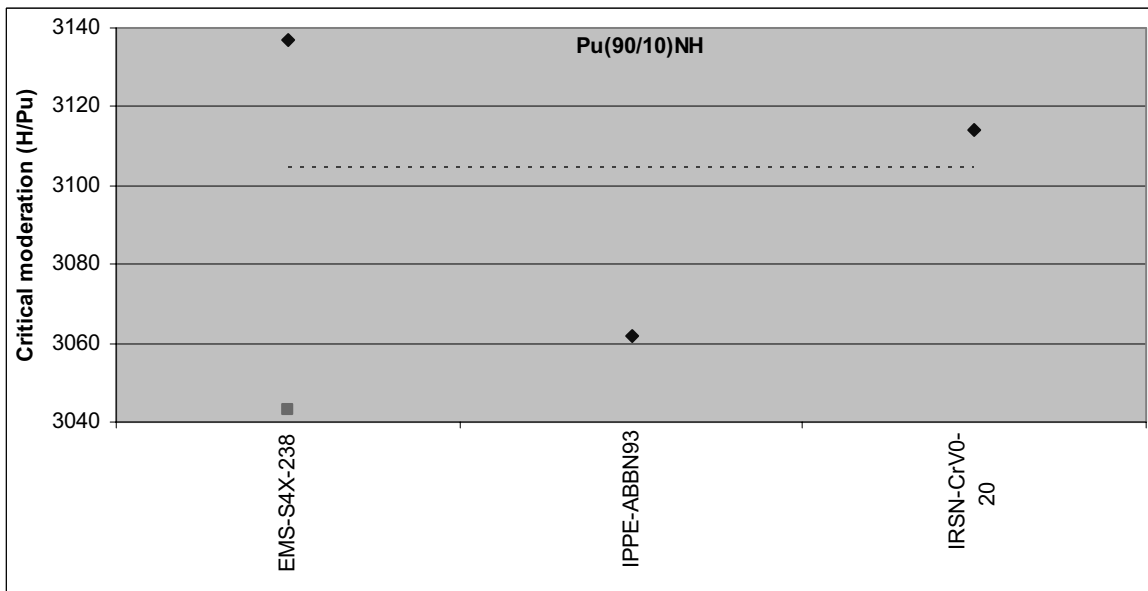


Table G119. Conc.: Pu(90/10/0/0)NH

Critical concentration for H₂O-reflected Pu(90/10/0/0)NH + H₂O systems			
EALF = 0.0196	Pu concentration (g/l)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	8.43	8.70	+0.36/-0.36
EMS-M5-E50	8.43	8.65	
EMS-M5-E5F	8.43	8.64	
EMS-M5-E62	8.51	8.62	
EMS-M5-E66	8.51	8.64	
EMS-M5-E68	8.50	8.62	
EMS-M5-F22	8.53	8.70	
EMS-M5-F30	8.52	8.65	
EMS-M5-J32	8.43	8.63	
EMS-M5-J33	8.44	8.62	
EMS-S5X-238	8.42	8.60	
EMS-S5X-27	8.34	8.63	
EMS-S5X-44	8.39	8.60	
EMS-S5K-238	8.42	8.60	
EMS-S5K-27	8.35	8.63	
EMS-S5K-44	8.40	8.60	
IPPE-ABBN93	8.64	8.68	
IPPE-84	9		
IRSN-CrV0-20	8.47		
IRSN-78-CEA	8.5		
JAERI-H-88		8.7	
Serco-Mk8-F22	8.5	8.4	1.0%

Table G120. H/Pu: Pu(90/10/0/0)NH

Critical moderation for H₂O-reflected Pu(90/10/0/0)NH + H₂O systems			
EALF = 0.0196	Moderation (H/Pu)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	3137	3043	-113/ +127
IPPE-ABBN93	3062		
IRSN-CrV0-20	3114		

Figure G121. Pu(80/15/5/0)NH – Mass

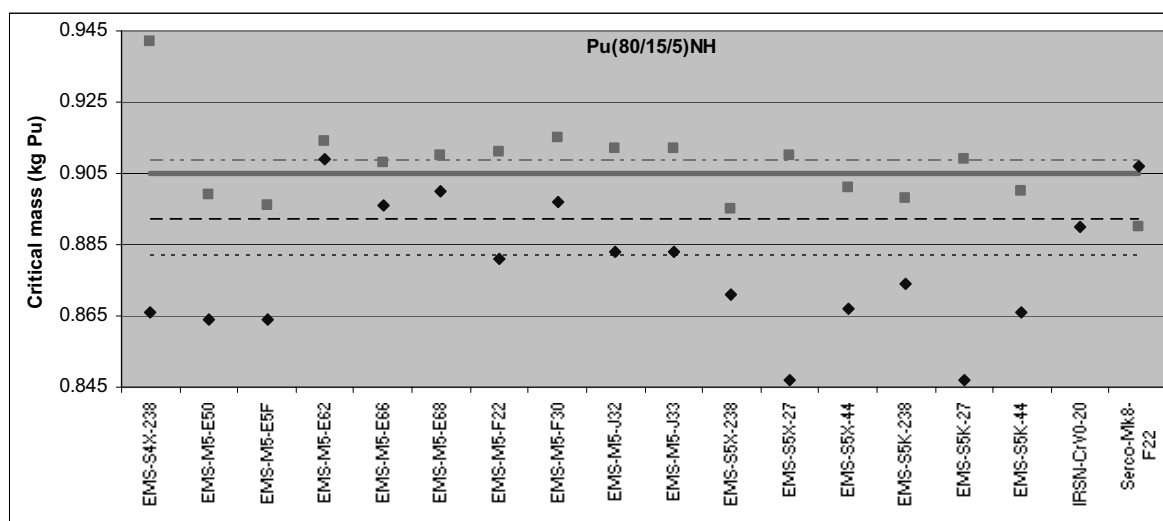


Figure G122. Pu(80/15/5/0)NH – Volume

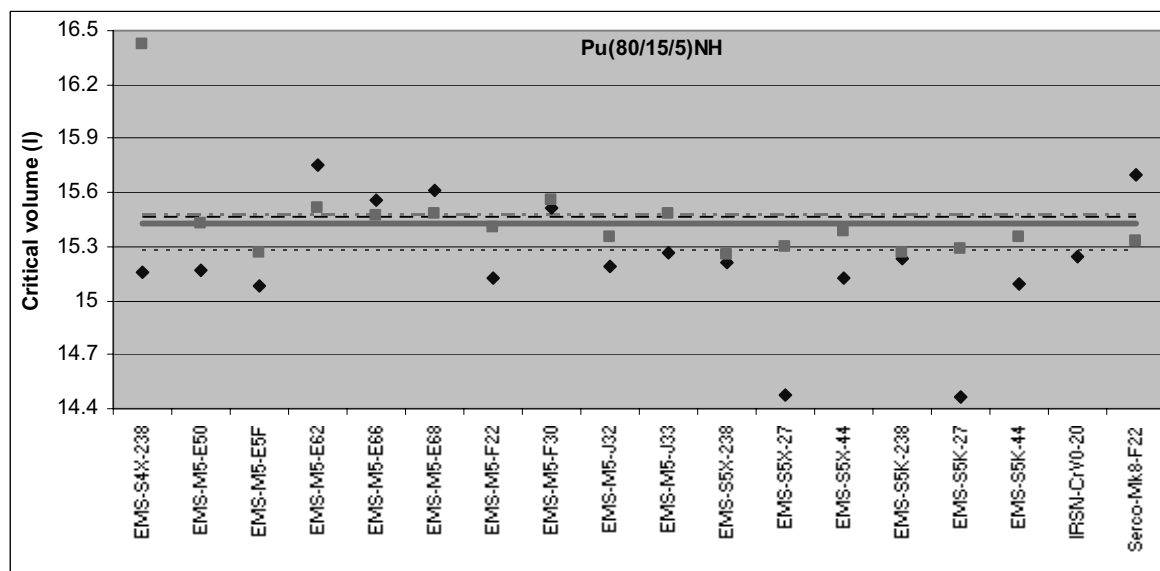


Table G121. Mass: Pu(80/15/5/0)NH

Critical mass for H ₂ O-reflected Pu(80/15/5/0)NH + H ₂ O systems			
EALF = 0.0553	Mass (kg Pu)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	0.866	0.942	+0.114/-0.100
EMS-M5-E50	0.864	0.899	
EMS-M5-E5F	0.864	0.896	
EMS-M5-E62	0.909	0.914	
EMS-M5-E66	0.896	0.908	
EMS-M5-E68	0.900	0.910	
EMS-M5-F22	0.881	0.911	
EMS-M5-F30	0.897	0.915	
EMS-M5-J32	0.883	0.912	
EMS-M5-J33	0.883	0.912	
EMS-S5X-238	0.871	0.895	
EMS-S5X-27	0.847	0.910	
EMS-S5X-44	0.867	0.901	
EMS-S5K-238	0.874	0.898	
EMS-S5K-27	0.847	0.909	
EMS-S5K-44	0.866	0.900	
IRSN-CrV0-20	0.89		
Serco-Mk8-F22	0.907	0.89	1.6%

Table G122. Volume: Pu(80/15/5/0)NH

Critical volume for H ₂ O-reflected Pu(80/15/5/0)NH + H ₂ O systems			
EALF = 0.1246	Volume (l)		
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	15.16	16.42	+1.88/-1.65
EMS-M5-E50	15.17	15.43	
EMS-M5-E5F	15.08	15.27	
EMS-M5-E62	15.75	15.52	
EMS-M5-E66	15.56	15.47	
EMS-M5-E68	15.61	15.48	
EMS-M5-F22	15.13	15.41	
EMS-M5-F30	15.51	15.56	
EMS-M5-J32	15.19	15.35	
EMS-M5-J33	15.27	15.48	
EMS-S5X-238	15.21	15.26	
EMS-S5X-27	14.48	15.30	
EMS-S5X-44	15.12	15.38	
EMS-S5K-238	15.23	15.27	
EMS-S5K-27	14.47	15.29	
EMS-S5K-44	15.09	15.35	
IRSN-CrV0-20	15.24		
Serco-Mk8-F22	15.70	15.33	2.0%

Figure G123. Pu(80/15/5/0)NH – Cylinder diameter

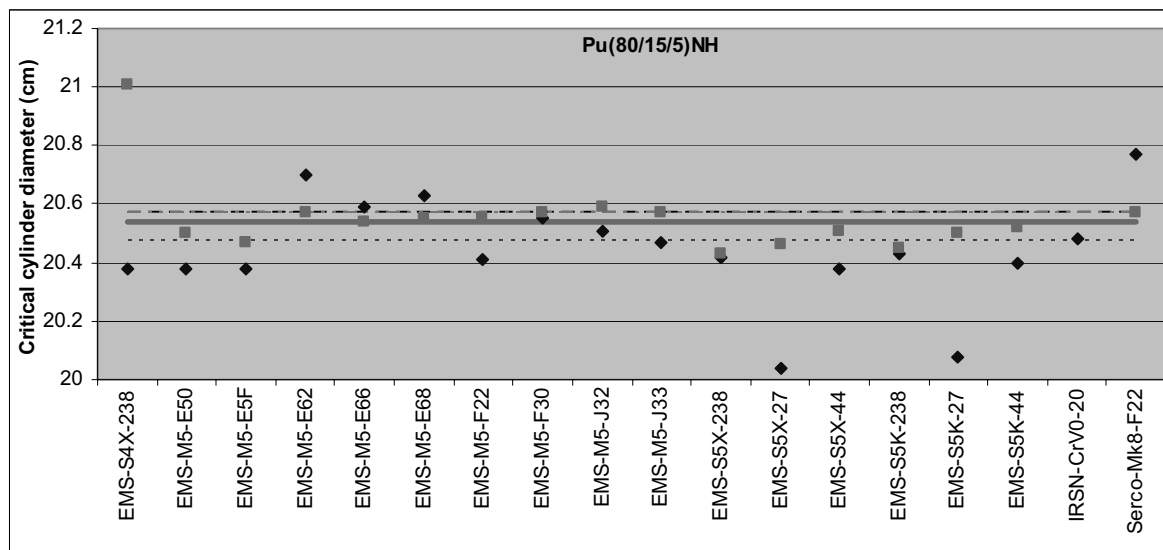


Figure G124. Pu(80/15/5/0)NH – Slab thickness

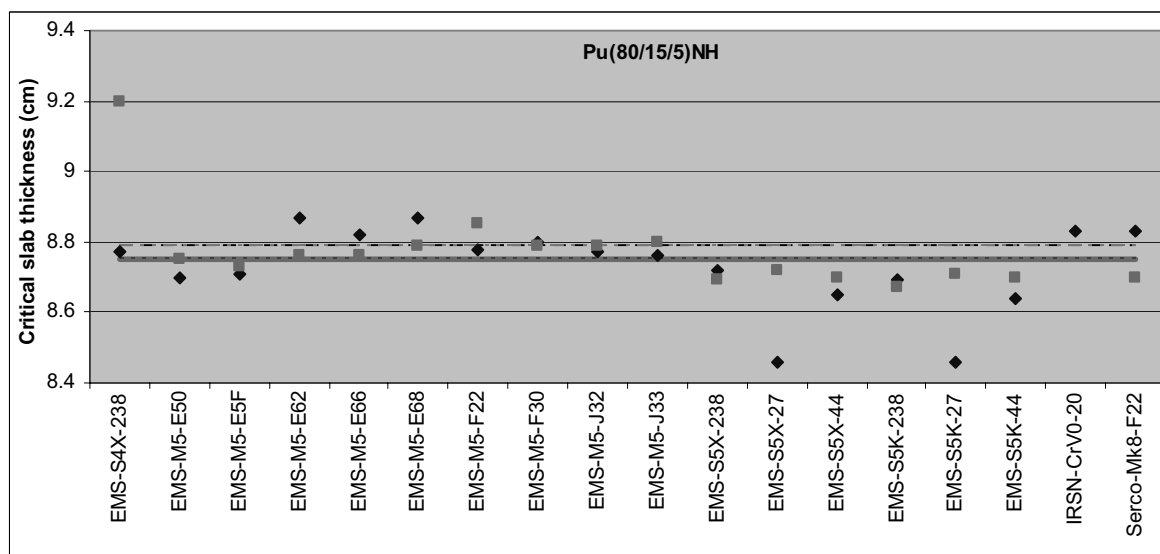


Table G123. Cylinder Pu(80/15/5/0)NH

Critical cylinder diameter for H ₂ O-reflected Pu(80/15/5/0)NH + H ₂ O systems			
EALF = 0.1304	Cylinder diameter (cm)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	20.38	21.01	+0.88/-0.84
EMS-M5-E50	20.38	20.50	
EMS-M5-E5F	20.38	20.47	
EMS-M5-E62	20.70	20.57	
EMS-M5-E66	20.59	20.54	
EMS-M5-E68	20.63	20.55	
EMS-M5-F22	20.41	20.55	
EMS-M5-F30	20.55	20.57	
EMS-M5-J32	20.51	20.59	
EMS-M5-J33	20.47	20.57	
EMS-S5X-238	20.42	20.43	
EMS-S5X-27	20.04	20.46	
EMS-S5X-44	20.38	20.51	
EMS-S5K-238	20.43	20.45	
EMS-S5K-27	20.08	20.50	
EMS-S5K-44	20.40	20.52	
IRSN-CrV0-20	20.48		
Serco-Mk8-F22	20.77	20.57	0.8%

Table G124. Slab: Pu(80/15/5/0)NH

Critical slab thickness for H ₂ O-reflected Pu(80/15/5/0)NH + H ₂ O systems			
EALF = 0.1635	Slab thickness (cm)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	8.77	9.20	+0.58/-0.56
EMS-M5-E50	8.70	8.75	
EMS-M5-E5F	8.71	8.73	
EMS-M5-E62	8.87	8.76	
EMS-M5-E66	8.82	8.76	
EMS-M5-E68	8.87	8.79	
EMS-M5-F22	8.78	8.85	
EMS-M5-F30	8.80	8.79	
EMS-M5-J32	8.77	8.79	
EMS-M5-J33	8.76	8.80	
EMS-S5X-238	8.72	8.69	
EMS-S5X-27	8.46	8.72	
EMS-S5X-44	8.65	8.70	
EMS-S5K-238	8.69	8.67	
EMS-S5K-27	8.46	8.71	
EMS-S5K-44	8.64	8.70	
IRSN-CrV0-20	8.83		
Serco-Mk8-F22	8.83	8.70	1.2%

Figure G125. Pu(80/15/5/0)NH – Concentration

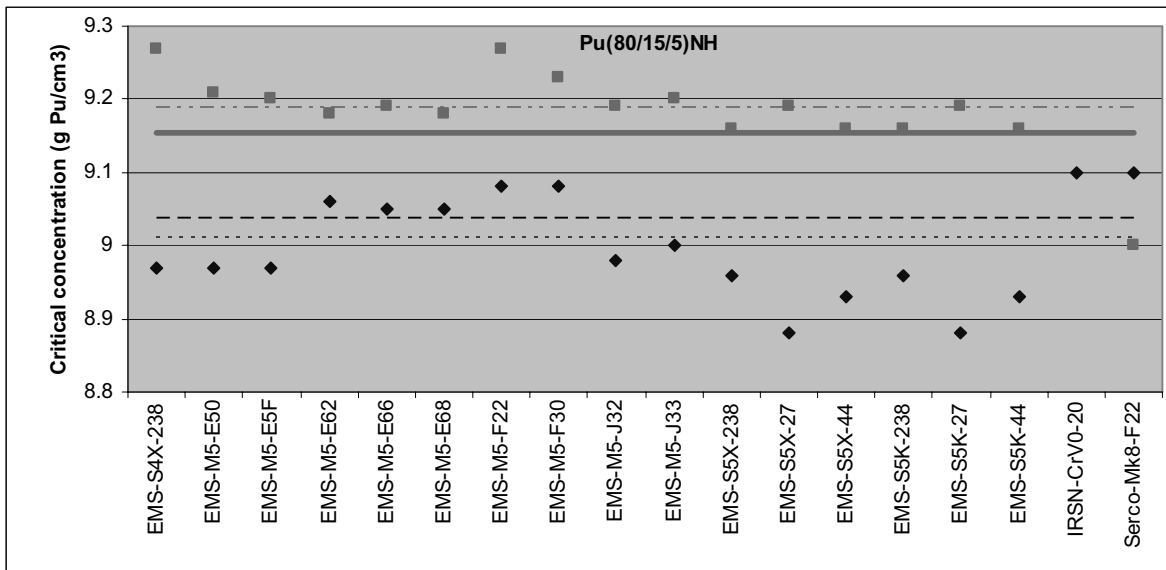


Figure G126. Pu(80/15/5/0)NH – Moderation H/Pu

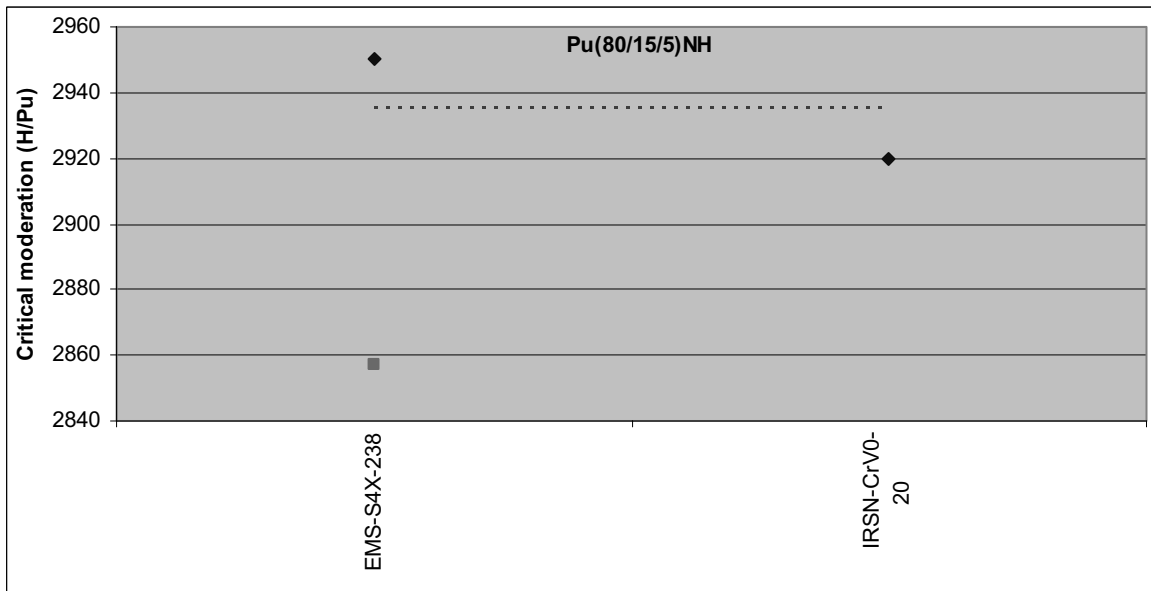


Table G125. Conc.: Pu(80/15/5/0)NH

Critical concentration for H ₂ O-reflected Pu(80/15/5/0)NH + H ₂ O systems			
EALF = 0.0196	Pu concentration (g/l)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	8.97	9.27	+0.40/-0.39
EMS-M5-E50	8.97	9.21	
EMS-M5-E5F	8.97	9.20	
EMS-M5-E62	9.06	9.18	
EMS-M5-E66	9.05	9.19	
EMS-M5-E68	9.05	9.18	
EMS-M5-F22	9.08	9.27	
EMS-M5-F30	9.08	9.23	
EMS-M5-J32	8.98	9.19	
EMS-M5-J33	9.00	9.20	
EMS-S5X-238	8.96	9.16	
EMS-S5X-27	8.88	9.19	
EMS-S5X-44	8.93	9.16	
EMS-S5K-238	8.96	9.16	
EMS-S5K-27	8.88	9.19	
EMS-S5K-44	8.93	9.16	
IRSN-CrV0-20	9.1		
Serco-Mk8-F22	9.1	9.0	1.0%

Table G126. H/Pu: Pu(80/15/5/0)NH

Critical moderation for H ₂ O-reflected Pu(80/15/5/0)NH + H ₂ O systems			
EALF = 0.0196	Moderation (H/Pu)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	2950	2857	-121/ +124
IRSN-CrV0-20	2920		

Figure G127. Pu(71/17/11/1)NH – Mass

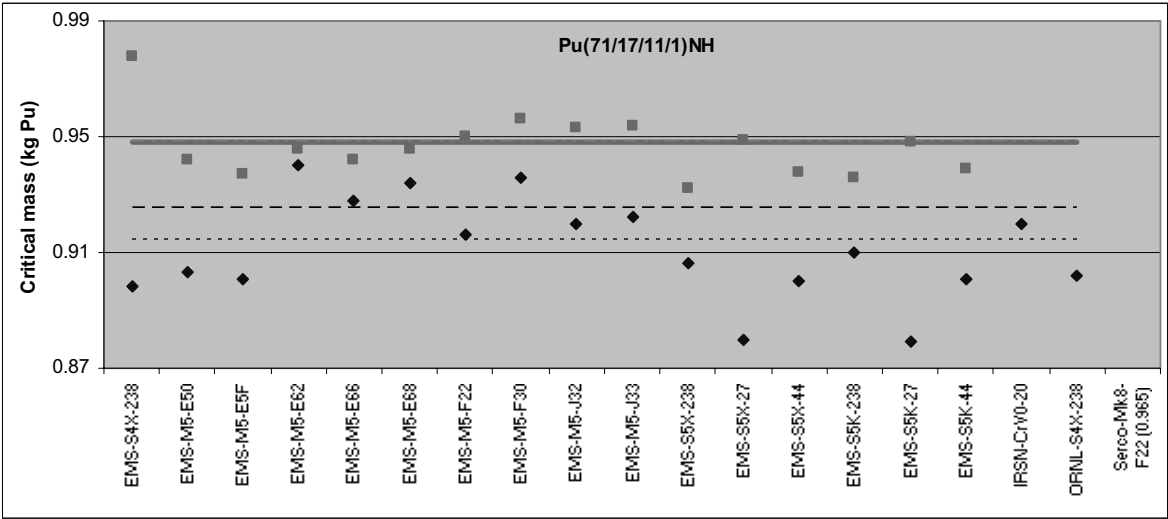


Figure G128. Pu(71/17/11/1)NH – Volume

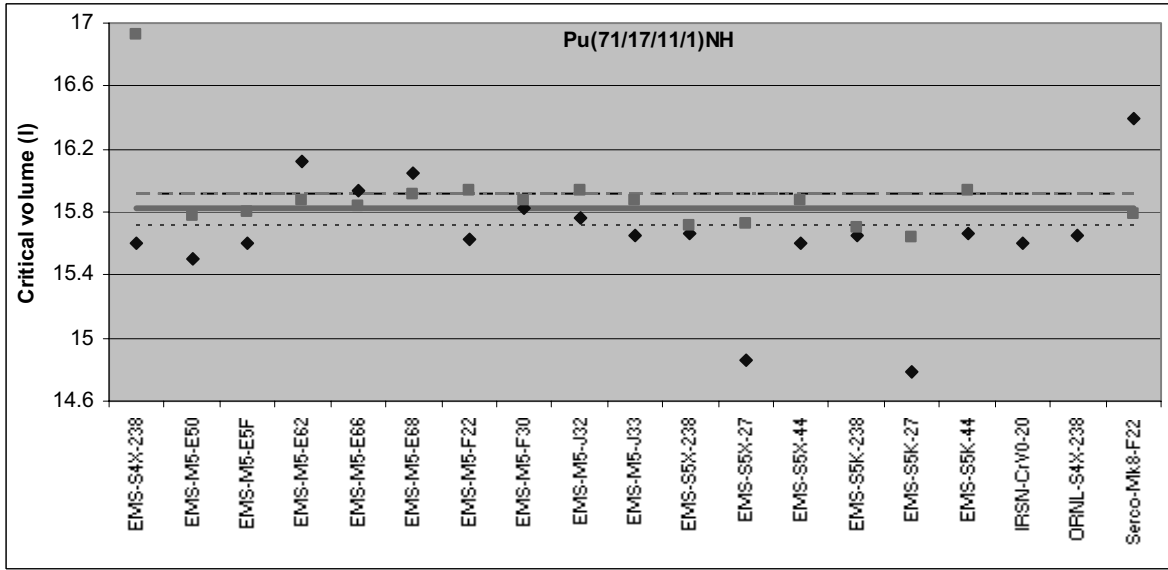


Table G127. Mass Pu(71/17/11/1)NH

Critical mass for H ₂ O-reflected Pu(71/17/11/1)NH + H ₂ O systems			
EALF = 0.0547		Mass (kg Pu)	
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	0.898	0.978	+0.121/-0.106
EMS-M5-E50	0.903	0.942	
EMS-M5-E5F	0.901	0.937	
EMS-M5-E62	0.940	0.946	
EMS-M5-E66	0.928	0.942	
EMS-M5-E68	0.934	0.946	
EMS-M5-F22	0.916	0.950	
EMS-M5-F30	0.936	0.956	
EMS-M5-J32	0.920	0.953	
EMS-M5-J33	0.922	0.954	
EMS-S5X-238	0.906	0.932	
EMS-S5X-27	0.880	0.949	
EMS-S5X-44	0.900	0.938	
EMS-S5K-238	0.910	0.936	
EMS-S5K-27	0.879	0.948	
EMS-S5K-44	0.901	0.939	
IRSN-CrV0-20	0.92		
ORNL-S4X-238	0.902		
Serco-Mk8-F22	0.965*	0.948	1.6%

Table G128. Volume Pu(71/17/11/1)NH

Critical volume for H ₂ O-reflected Pu(71/17/11/1)NH + H ₂ O systems			
EALF =0.1247		Volume (l)	
Source	Raw data	Best- estimate	2 σ
EMS-S4X-238	15.60	16.92	+1.75/-1.73
EMS-M5-E50	15.50	15.77	
EMS-M5-E5F	15.60	15.80	
EMS-M5-E62	16.12	15.88	
EMS-M5-E66	15.93	15.84	
EMS-M5-E68	16.05	15.91	
EMS-M5-F22	15.63	15.93	
EMS-M5-F30	15.82	15.88	
EMS-M5-J32	15.76	15.93	
EMS-M5-J33	15.65	15.87	
EMS-S5X-238	15.66	15.71	
EMS-S5X-27	14.86	15.72	
EMS-S5X-44	15.60	15.87	
EMS-S5K-238	15.65	15.70	
EMS-S5K-27	14.78	15.64	
EMS-S5K-44	15.66	15.93	
IRSN-CrV0-20	15.6		
ORNL-S4X-238	15.65		
Serco-Mk8-F22	16.39	15.79	3.2%

* Not credible, compare with other MONK results

Figure G129. Pu(71/17/11/1)NH – Cylinder diameter

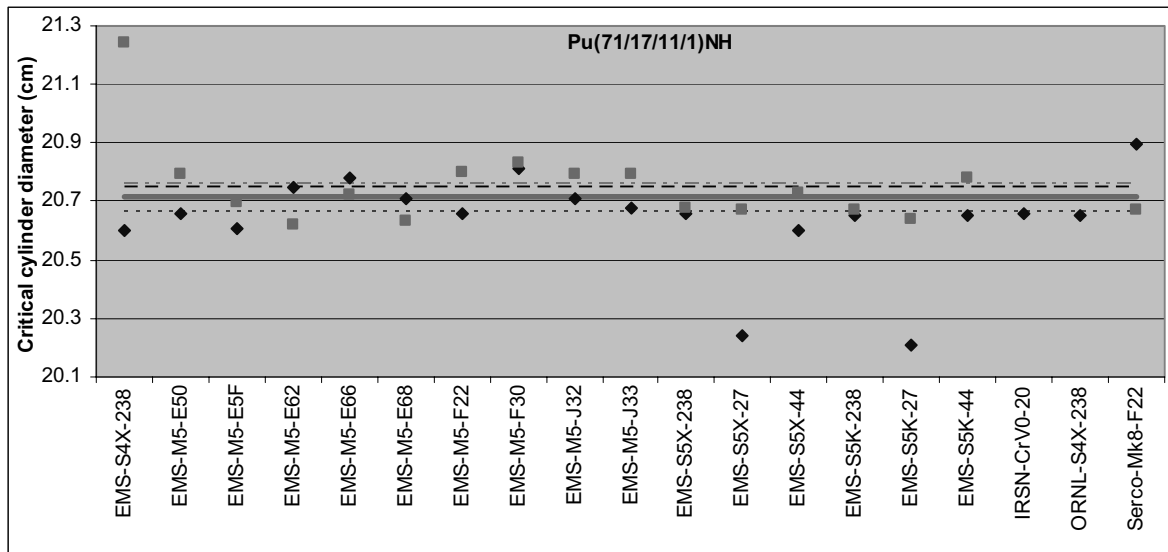


Figure G130. Pu(71/17/11/1)NH – Slab thickness

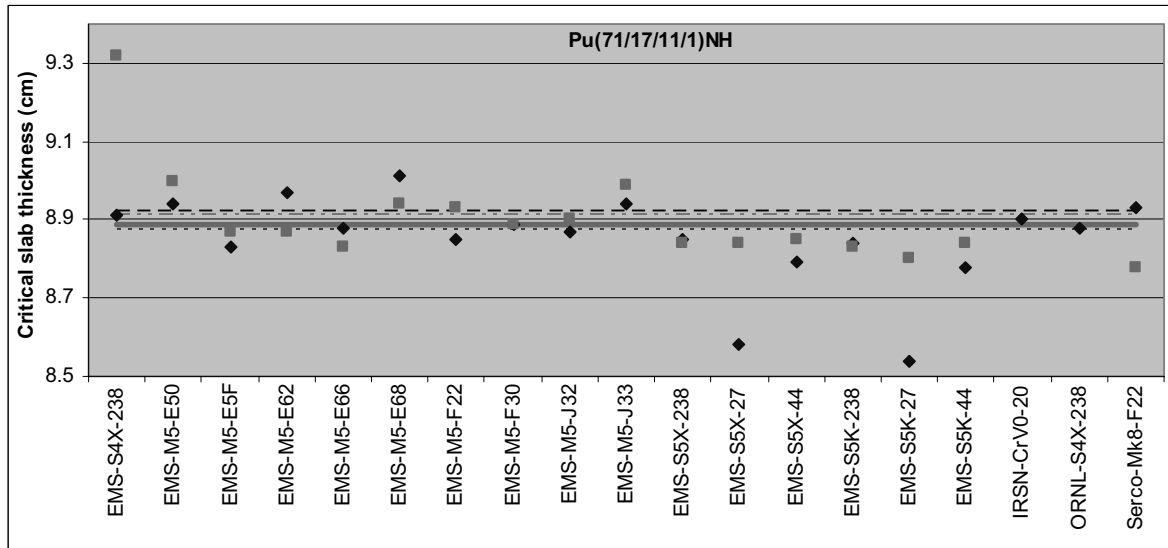


Table G129. Cylinder Pu(71/17/11/1)NH

Critical cylinder diameter for H ₂ O-reflected Pu(71/17/11/1)NH + H ₂ O systems			
EALF = 0.1298	Cylinder diameter (cm)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	20.60	21.24	+0.90/-0.85
EMS-M5-E50	20.66	20.79	
EMS-M5-E5F	20.61	20.70	
EMS-M5-E62	20.75	20.62	
EMS-M5-E66	20.78	20.72	
EMS-M5-E68	20.71	20.63	
EMS-M5-F22	20.66	20.80	
EMS-M5-F30	20.81	20.83	
EMS-M5-J32	20.71	20.79	
EMS-M5-J33	20.68	20.79	
EMS-S5X-238	20.66	20.68	
EMS-S5X-27	20.24	20.67	
EMS-S5X-44	20.60	20.73	
EMS-S5K-238	20.65	20.67	
EMS-S5K-27	20.21	20.64	
EMS-S5K-44	20.65	20.78	
IRSN-CrV0-20	20.66		
ORNL-S4X-238	20.65		
Serco-Mk8-F22	20.896	20.67	1.0%

Table G130. Slab Pu(71/17/11/1)NH

Critical slab thickness for H ₂ O-reflected Pu(71/17/11/1)NH + H ₂ O systems			
EALF = 0.1473	Slab thickness (cm)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	8.91	9.32	+0.59/-0.55
EMS-M5-E50	8.94	9.00	
EMS-M5-E5F	8.83	8.87	
EMS-M5-E62	8.97	8.87	
EMS-M5-E66	8.88	8.83	
EMS-M5-E68	9.01	8.94	
EMS-M5-F22	8.85	8.93	
EMS-M5-F30	8.89	8.89	
EMS-M5-J32	8.87	8.90	
EMS-M5-J33	8.94	8.99	
EMS-S5X-238	8.85	8.84	
EMS-S5X-27	8.58	8.84	
EMS-S5X-44	8.79	8.85	
EMS-S5K-238	8.84	8.83	
EMS-S5K-27	8.54	8.80	
EMS-S5K-44	8.78	8.84	
IRSN-CrV0-20	8.90		
ORNL-S4X-238	8.88		
Serco-Mk8-F22	8.93	8.78	1.4%

Figure G131. Pu(71/17/11/1)NH – Concentration

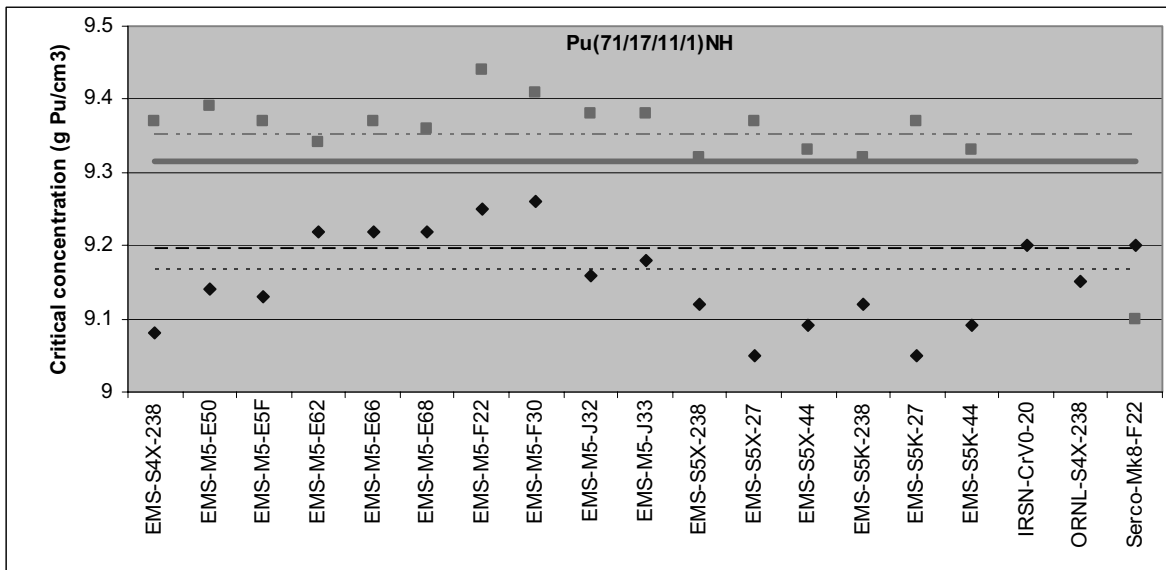


Figure G132. Pu(71/17/11/1)NH – Moderation H/Pu

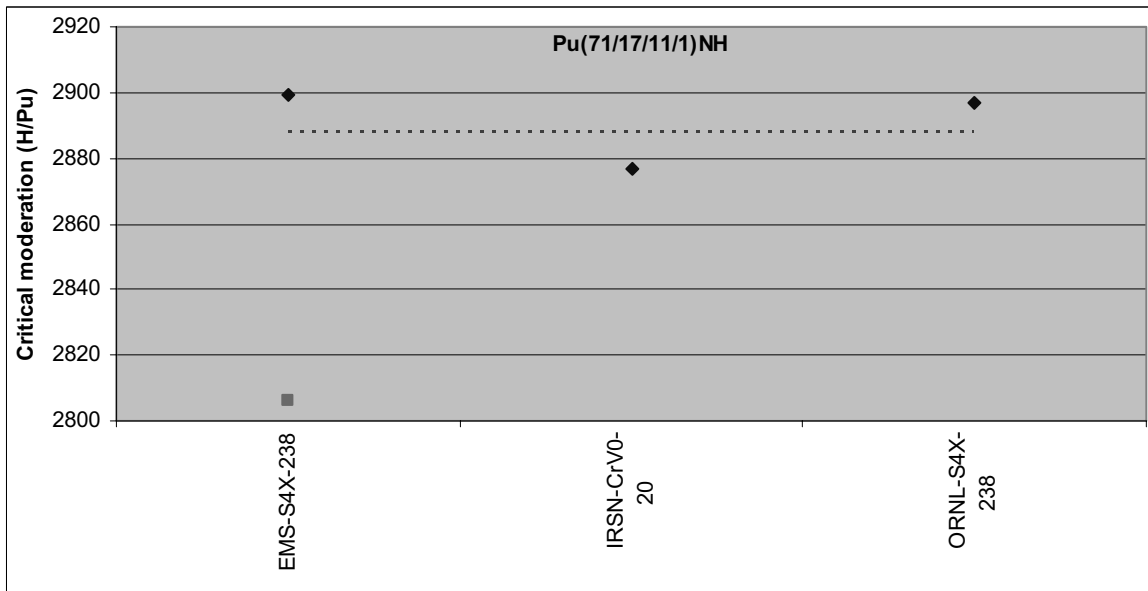


Table G131. Concentration Pu(71/17/11/1)NH

Critical concentration for H₂O-reflected Pu(71/17/11/1)NH + H₂O systems			
EALF = 0.0195	Pu concentration (g/l)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	9.08	9.37	+0.36/-0.40
EMS-M5-E50	9.14	9.39	
EMS-M5-E5F	9.13	9.37	
EMS-M5-E62	9.22	9.34	
EMS-M5-E66	9.22	9.37	
EMS-M5-E68	9.22	9.36	
EMS-M5-F22	9.25	9.44	
EMS-M5-F30	9.26	9.41	
EMS-M5-J32	9.16	9.38	
EMS-M5-J33	9.18	9.38	
EMS-S5X-238	9.12	9.32	
EMS-S5X-27	9.05	9.37	
EMS-S5X-44	9.09	9.33	
EMS-S5K-238	9.12	9.32	
EMS-S5K-27	9.05	9.37	
EMS-S5K-44	9.09	9.33	
IRSN-CrV0-20	9.2		
ORNL-S4X-238	9.15		
Serco-Mk8-F22	9.2	9.1	1.0%

Table G132. H/Pu: Pu(71/17/11/1)NH

Critical moderation for H₂O-reflected Pu(71/17/11/1)NH + H₂O systems			
EALF = 0.0195	Moderation (H/Pu)		
Source	Raw data	Best-estimate	2 σ
EMS-S4X-238	2899	2806	-119/ +124
IRSN-CrV0-20	2877		
ORNL-S4X-238	2897		

Appendix H

SIMILARITIES BETWEEN APPLICATIONS AND BENCHMARKS

The TSUNAMI calculation sequences ([86]-[88]) in the recently released SCALE 5 code package [79] were applied to evaluate a number of critical experiment specifications from the ICSBEP Handbook, 2004 edition. Due to a lack of resources, primarily time, published input data released together with the Handbook have been used (files on the CD-ROM or scanned text from the Handbook).

The sensitivity assessments performed by various TSUNAMI sequences involve adjoint calculations, sometimes by the 1-dimensional deterministic code XSDRNPM/S and sometimes by the 3-dimensional Monte Carlo code KENOvA. The adjoint calculations usually require much better statistics than the forward calculations to give the same accuracy. The importance of such accuracy has not been studied.

Some of the sensitivities that are important for selecting certain critical experiment specifications rely on good source convergence. This includes the very important fact that in Monte Carlo calculations, enough initial generations must be skipped to exclude the transient effects due to the initial neutron source. E.g., a flat initial neutron distribution may result in many reactions, such as absorptions, in regions that may not be significant in the converged neutron distribution. This issue is problem dependent and is often not easy to detect from the convergence behaviour of k_{eff} .

The summary coefficients c_k , E_{sum} and G are primarily used to classify the similarity between applications and experiments. High values (maximum 1.0) indicate close similarity.

There are several parameters that may be used to find trends in the calculation results. Examples are enrichment ^{235}U , moderation (atomic ratio H/X , volume ratio or concentration for well-defined systems), average energy causing fission, Energy corresponding to Average Lethargy causing Fission (EALF), thermal neutron leakage rate, absorption ratios, etc.

Both SCALE 5 (XSDRNPM/S and KENOvA) and MCNP5 report EALF values by default for each calculation. For the simple and clean systems covered by this study, EALF is expected to be a significant trending parameter. Its sensitivity to initial neutron source distribution transients have not been studied, but in general many more initial neutron histories have been skipped in this study than in the ICSBEP Handbook examples.

The ICSBEP Benchmark models selected in the following tables are intended as a starting point for further comparisons and evaluations. The input data used by EMS for MCNP 5 and SCALE 5 calculations were first found from a search in the INPUT directory on the 2004 edition of the ICSBEP Handbook CD-ROM. If the input data were not found there, they were scanned from the appropriate appendix of the main handbook specifications. Agreement between the input data and the benchmark model has only rarely been confirmed. Further, it appears that the CD-ROM files are not updated as often as the main handbook text.

Uncertainties are taken from the ICSBEP handbook text, as they are often more accurate and more recent than in the DICE database (a utility tool released with the Handbook).

Some experiments with very large uncertainties are included. How useful can they be for validation? When there are many experiments with a correlated (systematic) error, the differences between the results as a function of a specified parameter change could be valuable for validation (trends). The differential uncertainty can be much lower than the total uncertainty.

The applications involve four chemical forms of fissionable (and fissile) materials to be evaluated: UO_2 , UNH , PuO_2 and PuNH . They are homogeneously and uniformly mixed with or dissolved in pure water in concentrations determined by a selection of conditions. Those conditions are minimum critical mass, minimum critical volume, minimum critical cylinder diameter, minimum critical slab thickness, minimum critical concentration and maximum critical hydrogen moderation. Full water reflection is required.

The fissile nuclides included in the selected applications are ^{235}U , ^{239}Pu and ^{241}Pu . Other fissionable nuclides that contribute to criticality in fast neutron energy systems are ^{240}Pu and ^{242}Pu but in moderated systems they make criticality more difficult to occur. ^{238}U , the most common fissionable nuclide, is always a negative factor on the potential for criticality. In some of the critical experiment benchmarks included in the evaluation, other fissionable nuclides such as ^{234}U , ^{238}Pu and ^{241}Pu are present in low concentrations.

In the evaluation of biases and uncertainties, the only parameters selected are ratios $^{235}\text{U}/\text{U}_{\text{total}}$, moderation of uranium and moderation of plutonium. Variation of the plutonium isotope distribution is not evaluated at this time. The bias influence of nitrogen in nitrate systems is not evaluated.

A parameter that is not included is water reflection. Many of the benchmark models based on critical experiments have little or essentially no reflection at all. In particular for metal systems, the moderation in the reflector changes the average system properties significantly. Biases for internally and externally moderated systems may be quite different, even when average properties are similar.

Biases and uncertainties due to calculation methods are not considered. Instead discrepancies are identified and explained when possible. Calculation results that are not considered correct may be corrected or removed from evaluations of best estimate values.

Biases and uncertainties due to different geometries are not considered. Discrepancies are more likely related to convergence, geometry mesh, angular quadrature order, etc.

Cross-sections that are processed in essentially identical ways are expected to give very close results, independent of whether Monte Carlo or deterministic codes are used. This is based on the expectation that the codes can take advantage of the properties of the cross section libraries and that the codes are used properly to take this into account. These properties of cross-sections and the appropriate use of codes need to be verified.

Five different groups of biases and uncertainties are involved:

- Fast systems with high-enriched uranium.
- Slow (usually thermal) systems with high-enriched uranium.
- Slow (usually thermal) systems with low-enriched uranium.

- Fast systems with plutonium.
- Slow (usually thermal) systems with plutonium.

The moderation parameter is considered in the form of EALF; the energy corresponding to average lethargy of neutrons causing fission. The logarithmic weighting of the neutron energy makes it easier to compare moderated systems. A new parameter, R_{en} is introduced to demonstrate the similarity of EALF values for an application and for a benchmark. R_{en} is defined to give values between zero and one. In this way, display and comparison with other similarity indices such as c_k , E_{sum} and G are simplified. They all (maybe except for c_k for some very dissimilar systems) have values between zero and one.

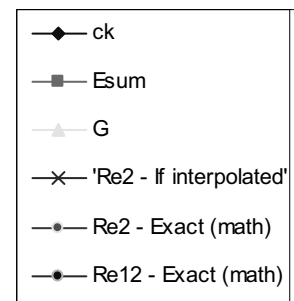
$$R_{en} = (EALF_e / EALF_a)^{sign(1-EALF_e / EALF_a) / n} \quad \text{or} \quad R_{en} = e^{-|\ln(EALF_e / EALF_a)| / n}$$

The number n has been arbitrarily chosen to be 2 in the tables included in this evaluation. That makes R_{e2} equal to the square root (negative) of the EALF ratio or of the inverse EALF ratio (positive). In many figures, results for $n=12$ has also been included. No effort has been made to quantify grades of similarity (such as perfect fit, very good, acceptable, etc.). Different values of n could easily be applied for different EALF values and for different fissionable materials. R_{en} is not expected to be very useful for complicated systems, since the similarity of the values depend on properties of the system being evaluated. Closeness of neutron energies to physical properties such as cadmium cut-off, fission thresholds of non-fissile nuclides, resonances, iron window, etc. makes small changes of the neutron energy spectrum significant. Average properties may not be appropriate. For the selected very simple systems, as well as for other systems where EALF is used, R_{en} is useful.

It is important to notice that EALF depends on the cross-section energy structure. Continuous-energy cross-sections and calculations should give the best results. Very fine-group cross-sections will also give good results. The group structure and the application determine the deviation from the correct answer. In this evaluation it is clearly shown that the SCALE 27-group library gives very large deviations, the 44-group library gives much smaller deviations while the 238-group library results that are almost identical to continuous-energy calculations. If EALF is used to select benchmarks for testing broad-group cross-section libraries, the same method should be applied when determining EALF values for the benchmarks and for the application.

In the charts, the legend on this page applies. The application EALF can be seen in the chart when R_{en} is exactly one (independent of n). For each application there is at least one chart with the most interesting EALF areas included. For uranium, the cylinder and slab charts are quite similar to the volume charts. For PuO_2 , the slabs have properties that separate them, not only from volume and cylinder systems, but also from benchmarks.

After most of the charts had been generated, it was decided to add first one, and then another new curve. They correspond to the R_{en} with the number n as 2 and 12 respectively and are based on values calculated specifically to mathematically support an accurate curve. The parameters are identified as “ $R_{e2} - \text{Exact (math)}$ ” and “ $R_{e12} - \text{Exact (math)}$ ”. The first “ $R_{e2} - \text{If interpolated}$ ” curve was generated with support of only benchmark EALF-values. Large gaps lead to incorrect curves. These are still of interest since differences between the exact (mathematical) and the interpolated curved lines also indicate uncertainties in the SCALE 5 TSUNAMI indices when interpolated. The PuO_2 slab systems are the best examples of differences, indicating uncertainties.



UO₂ applications and uranium benchmarks

Figure H1. U(100)O₂ mass indices

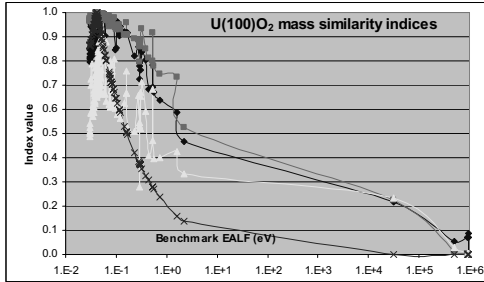


Figure H5. U(100)O₂ slab

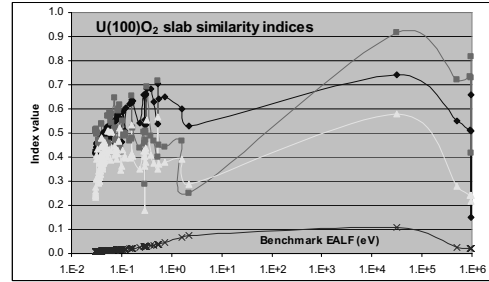


Figure H2. U(100)O₂ mass, enlarged

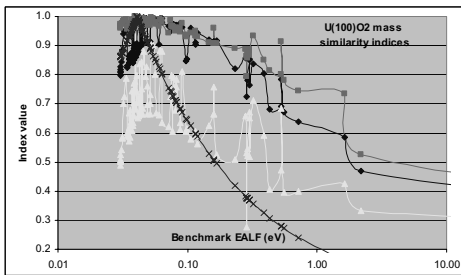


Figure H6. U(100)O₂ slab

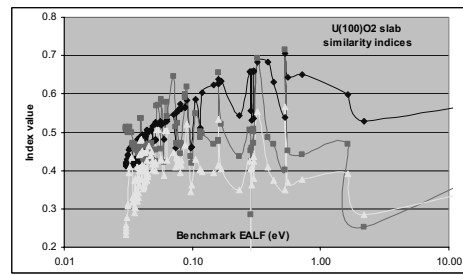


Figure H3. U(100)O₂ volume indices

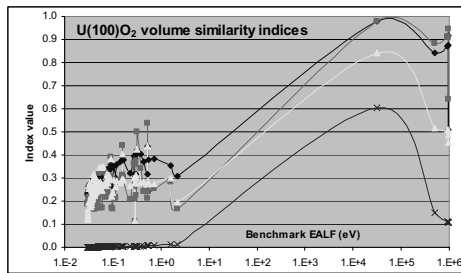


Figure H7. U(100)O₂ concentration

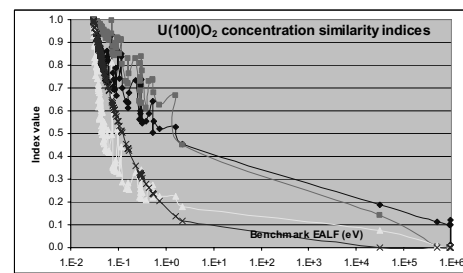


Figure H4. U(100)O₂ cylinder

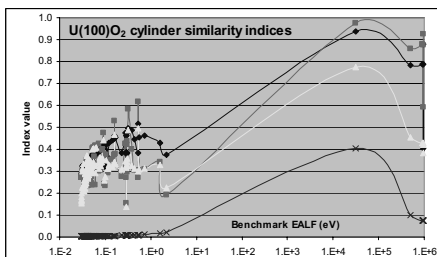


Figure H8. U(100)O₂ concentration

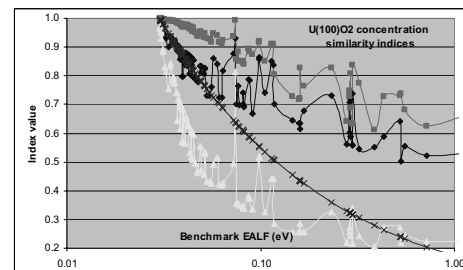


Table H1. U(100)O₂ – c_k, E_{sum}, G and R_{e2}

U(100)O ₂ applications and experiments similarities – c _k , E _{sum} , G and R _{e2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}
HMF01-1	7	0	0	0	87	91	51	11	79	88	43	7	51	73	24	2	10	0	0	0
HMF04-1	22	23	23	0	98	98	84	61	94	98	78	40	74	92	58	11	19	14	8	0
HMF08-1	7	0	0	0	87	91	51	11	79	88	43	7	51	73	24	2	10	0	0	0
HMF15-1	9	0	0	0	92	95	49	11	88	93	42	7	66	82	24	2	12	0	0	0
HMF18-1	7	0	0	0	87	91	51	11	79	88	43	7	51	73	24	2	10	0	0	0
HMF20-1	5	1	3	0	84	89	52	15	78	86	45	10	55	72	28	3	11	0	1	0
HMF65-1	9	0	0	0	92	95	49	11	88	93	42	7	66	82	24	2	12	0	0	0
HCT11-1	64	75	40	24	38	25	28	1	46	31	31	1	65	44	38	4	52	62	22	20
HCT11-2	67	78	40	27	38	24	28	1	46	30	31	1	64	45	37	4	55	68	25	23
HCT11-3	68	81	41	31	37	24	28	1	45	31	31	1	63	47	37	3	59	73	27	26
HMT11-1	94	93	56	59	36	28	29	0	43	35	33	0	60	50	40	2	70	80	29	50
HMT11-3	97	97	61	73	33	26	28	0	39	34	34	0	56	52	42	1	77	88	36	62
HMT11-5	98	98	64	80	31	25	27	0	38	34	32	0	53	54	43	1	82	92	43	69
HMT11-7	98	97	67	84	30	27	27	0	37	37	32	0	52	59	43	1	86	95	49	72
HMT11-35	92	91	52	49	38	31	29	0	45	38	33	1	63	52	40	2	68	76	26	42
HMT11-37	96	94	58	62	35	29	29	0	42	38	35	0	59	55	43	2	74	85	33	53
HMT11-39	97	95	61	68	34	31	30	0	40	40	36	0	57	60	47	2	79	88	37	58
HMT11-41	97	94	62	75	32	32	29	0	39	42	34	0	55	65	45	1	88	94	50	65
HMT11-43	98	96	64	69	34	31	29	0	40	40	35	0	56	59	47	2	79	89	38	59
HST01-1	97	96	76	71	34	27	30	0	40	34	34	0	56	47	41	1	69	84	34	61
HST01-2	86	89	66	38	40	36	30	0	47	42	34	1	66	51	42	3	56	64	22	33
HST01-3	97	96	76	71	34	27	30	0	40	33	34	0	56	47	41	1	70	85	34	61
HST01-4	85	88	65	37	40	36	30	1	48	42	34	1	66	50	42	3	56	63	22	32
HST01-5	99	99	84	98	29	22	28	0	35	29	33	0	49	46	45	1	81	96	53	84
HST01-6	99	99	84	96	30	22	28	0	36	29	34	0	50	47	45	1	80	95	51	82
HST01-7	98	96	79	72	34	28	31	0	40	34	36	0	55	47	43	1	70	85	35	62
HST01-8	97	96	78	70	34	28	31	0	40	35	36	0	56	47	43	1	69	84	34	60
HST01-9	85	89	67	37	40	38	31	1	48	44	36	1	66	51	44	3	56	63	22	32
HST01-10	100	99	88	94	30	23	29	0	36	30	35	0	50	47	46	1	79	95	49	81
HST09-1	79	91	68	28	44	54	44	1	52	62	50	1	70	72	57	4	50	74	22	24
HST09-2	84	93	71	36	42	50	42	1	50	58	49	1	68	69	55	3	55	78	24	30
HST09-3	91	96	76	51	39	44	41	0	46	53	47	1	64	65	53	2	61	83	29	43
HST09-4	96	98	81	67	36	39	38	0	42	47	44	0	58	62	52	2	67	87	34	57
HST10-1	99	100	90	88	32	32	34	0	38	40	40	0	52	57	51	1	73	93	43	76
HST10-2	99	99	90	86	32	32	34	0	38	41	40	0	52	57	51	1	73	93	43	74
HST10-3	99	99	89	82	32	33	35	0	38	42	41	0	53	58	50	1	73	92	42	70
HST10-4	99	99	88	80	32	34	35	0	38	42	41	0	53	58	50	1	72	91	42	69
HST11-1	100	100	97	98	29	27	31	0	35	35	37	0	49	54	48	1	80	97	57	87
HST11-1	100	100	97	98	29	27	31	0	35	35	37	0	49	54	48	1	80	97	57	87
HST12-1	95	99	73	89	27	22	27	0	32	30	31	0	46	51	41	1	93	99	81	96
HST25-1	98	99	74	100	29	20	26	0	35	27	31	0	49	46	41	1	84	97	56	86
HST27-1	98	97	80	74	33	28	31	0	40	34	36	0	55	47	43	1	70	86	36	63
HST28-1	99	99	80	93	30	22	28	0	36	29	34	0	51	46	44	1	78	94	47	80
HST28-9	92	91	63	53	37	29	28	0	44	36	32	1	62	47	39	2	64	73	26	45
HST29-1	91	91	67	51	38	31	30	0	45	38	34	1	63	48	41	2	64	72	26	44
HST30-1	99	99	83	92	30	23	29	0	36	30	35	0	50	47	45	1	78	94	46	79

Table H1. U(100)O₂ – c_k, E_{sum}, G and R_{e2} (Cont'd)

U(100)O ₂ applications and experiments similarities – c _k , E _{sum} , G and R _{e2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}
HST30-4	91	91	67	51	38	31	30	0	45	37	34	1	63	48	41	2	64	72	26	43
HST33-11A	79	86	55	37	39	28	28	1	46	34	32	1	66	46	41	3	59	69	24	32
HST33-11B	79	87	53	38	38	26	28	0	46	33	32	1	66	45	40	3	60	73	26	32
HST35-1	97	99	74	96	28	19	26	0	34	27	31	0	48	46	41	1	89	98	64	90
HST35-5	98	99	76	91	30	21	27	0	37	28	32	0	52	45	43	1	81	94	47	78
HST35-7	96	95	68	71	34	24	28	0	41	30	32	0	57	44	39	1	74	85	35	61
HST36-1	99	98	80	85	31	23	28	0	38	30	34	0	53	46	43	1	76	92	43	73
HST37-1	98	99	74	97	28	19	25	0	34	27	31	0	49	46	41	1	88	98	62	89
HST37-3	98	99	75	96	29	20	26	0	36	28	32	0	51	46	43	1	84	96	52	83
HST37-6	98	99	73	89	31	21	26	0	37	28	32	0	53	45	42	1	81	93	46	77
HST38-1	80	85	59	32	41	34	28	1	49	40	32	1	68	49	41	3	55	61	21	28
HST42-1	88	98	59	88	25	19	19	0	30	27	23	0	44	50	31	1	98	100	88	98
HST42-2	88	97	58	87	25	19	19	0	30	27	23	0	44	50	31	1	98	100	89	98
HST42-3	84	97	54	87	24	19	16	0	29	28	20	0	43	51	28	1	99	100	93	99
HST42-4	83	97	52	86	23	19	15	0	29	28	18	0	42	51	26	1	100	100	95	99
HST42-5	81	97	50	86	23	19	13	0	28	27	16	0	42	51	24	1	100	100	96	99
HST42-6	82	97	51	86	23	19	14	0	29	27	17	0	42	51	25	1	100	100	96	99
HST42-7	81	97	50	86	23	19	13	0	28	27	16	0	42	51	24	1	100	100	97	99
HST42-8	80	96	49	86	23	19	12	0	28	27	16	0	41	51	23	1	100	100	97	100
HST43-1	95	99	73	74	27	22	27	0	32	30	31	0	46	51	41	1	93	99	81	64
HST43-2	97	99	79	91	27	22	28	0	33	30	33	0	46	50	44	1	90	99	75	95
HST43-3	94	98	70	89	26	21	25	0	32	29	30	0	45	50	39	1	94	100	83	97
LCT01-1	85	93	61	64	27	17	24	0	33	23	28	0	46	42	36	2	86	92	51	55
LCT01-2	85	94	61	65	27	17	22	0	32	24	26	0	46	44	34	2	86	92	52	55
LCT02-1	91	95	60	59	30	21	26	0	36	29	31	0	51	49	40	2	84	91	44	51
LCT02-4	90	93	59	60	30	22	26	0	36	30	31	0	51	50	40	2	85	91	44	51
LCT13-1	76	87	52	37	32	22	28	1	38	29	33	1	54	47	38	3	74	84	34	32
LCT14-1	78	87	52	38	32	21	28	1	38	27	32	1	53	42	36	3	72	81	32	32
LCT14-6	69	80	47	28	32	21	27	1	38	27	30	1	54	40	35	4	64	73	27	24
LCT39-1	82	89	51	42	32	21	27	0	39	27	31	1	54	44	35	3	73	83	33	36
LCT49-1	47	52	33	14	31	17	20	1	37	19	22	2	53	25	29	8	45	45	18	12
LCT61-1	72	80	28	38	32	11	12	0	39	15	14	1	56	29	18	3	71	75	27	32
LCT70-1	59	73	43	16	36	28	30	1	43	34	33	2	60	47	39	7	53	67	22	14
LST01-1	90	97	66	83	28	17	24	0	34	24	29	0	48	42	39	1	84	94	52	71
LST03-1	91	98	80	100	27	19	30	0	32	26	35	0	45	44	45	1	85	97	65	86
LST03-2	90	98	78	98	26	20	30	0	32	27	35	0	44	46	44	1	86	98	69	88
LST03-3	90	98	77	97	26	20	29	0	32	27	34	0	44	47	44	1	87	98	69	88
LST03-4	89	97	71	97	26	18	26	0	31	25	31	0	44	44	40	1	88	98	70	88
LST03-5	87	97	68	94	25	19	25	0	30	26	29	0	43	46	38	1	91	99	78	92
LST03-6	86	97	67	93	25	19	25	0	30	26	29	0	43	46	38	1	92	99	79	92
LST03-7	85	96	62	93	24	18	22	0	30	25	26	0	43	46	34	1	92	99	79	92
LST03-8	83	96	60	92	24	18	21	0	29	26	24	0	42	47	33	1	94	99	84	94
LST03-9	82	97	59	92	24	18	20	0	29	25	24	0	42	47	32	1	94	99	84	94
LST07-1	88	97	72	98	26	18	26	0	31	24	31	0	44	42	41	1	83	97	63	84
LST07-2	87	97	71	100	25	18	25	0	31	25	30	0	44	44	40	1	84	97	65	86
LST07-3	86	98	68	98	25	17	24	0	30	24	29	0	43	44	38	1	85	98	68	87
LST07-4	85	97	66	97	25	17	23	0	30	24	28	0	43	45	36	1	86	98	69	88
LST07-5	84	97	63	97	24	17	22	0	29	24	26	0	42	44	34	1	86	98	71	88

Table H1. $U(100)O_2 - c_k, E_{sum}, G$ and R_{e2} (Cont'd)

U(100)O ₂ applications and experiments similarities – c _k , E _{sum} , G and R _{e2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}
LST16-1	91	98	70	89	28	18	27	0	34	25	32	0	48	42	42	1	82	95	53	76
LST16-2	91	98	70	91	28	18	27	0	34	24	32	0	47	43	42	1	84	96	56	78
LST16-3	91	98	68	95	27	17	25	0	33	24	30	0	47	43	39	1	86	97	60	82
LST16-4	90	98	68	97	27	17	24	0	32	24	29	0	46	43	38	1	87	97	61	83
LST16-5	90	98	67	98	27	17	24	0	32	24	29	0	46	44	37	1	87	97	63	84
LST16-6	89	98	66	99	26	17	23	0	32	23	28	0	45	43	36	1	88	98	65	85
LST16-7	89	98	65	100	26	16	22	0	32	23	27	0	45	43	35	1	88	98	66	86
LST17-1	91	97	66	89	28	17	25	0	34	24	30	0	48	42	40	1	83	95	53	76
LST17-2	91	97	67	91	28	17	25	0	33	24	30	0	48	43	40	1	83	95	55	78
LST17-3	91	97	67	95	27	17	24	0	33	24	29	0	47	43	38	1	85	97	59	82
LST17-4	90	98	66	96	27	17	24	0	32	24	28	0	46	44	37	1	86	97	60	83
LST17-5	90	97	67	98	26	17	23	0	32	24	28	0	46	43	37	1	87	97	62	84
LST17-6	89	97	66	99	26	17	22	0	32	24	27	0	46	43	36	1	87	98	64	85
LST20-1	88	98	66	96	25	18	23	0	31	25	28	0	44	46	36	1	90	98	72	89
LST20-2	87	97	64	95	25	17	22	0	30	25	26	0	44	45	34	1	91	99	74	90
LST20-3	85	97	61	94	24	17	20	0	30	25	24	0	43	46	32	1	92	99	78	92
LST20-4	84	97	59	93	24	17	19	0	29	25	22	0	42	46	30	1	92	99	79	92
LST21-1	87	98	62	96	25	17	21	0	31	25	25	0	44	46	33	1	90	99	72	89
LST21-2	87	97	61	95	25	17	20	0	30	24	24	0	44	45	32	1	91	99	74	90
LST21-3	85	97	59	94	24	17	18	0	30	24	22	0	43	46	30	1	92	99	77	91
LST21-4	84	98	57	93	24	17	17	0	29	25	21	0	42	47	29	1	92	99	79	92

Figure H9. $U(20)O_2$ mass indices

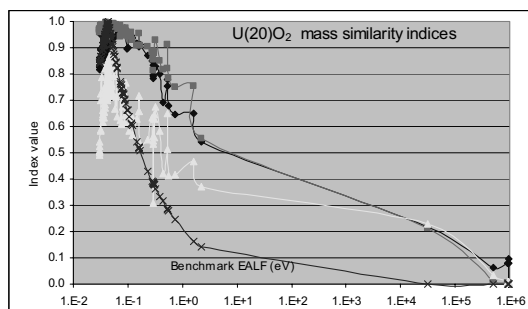


Figure H13. $U(20)O_2$ cylinder

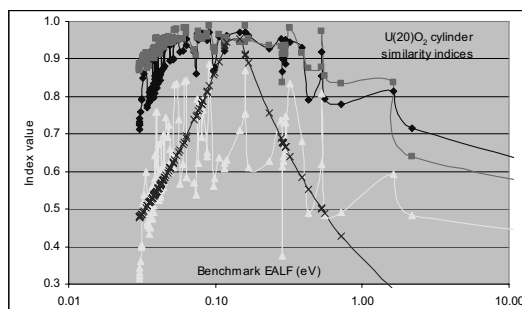


Figure H10. $U(20)O_2$ mass, enlarged

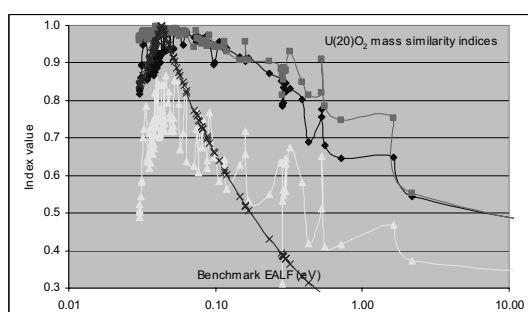


Figure H14. $U(20)O_2$ slab

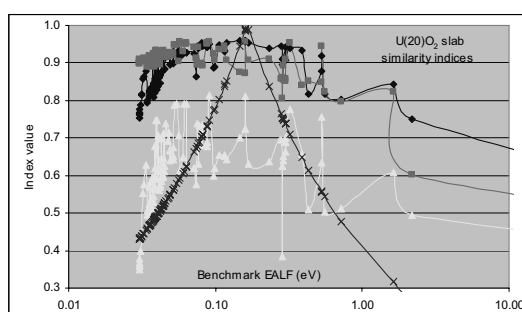


Figure H11. $U(20)O_2$ volume indices

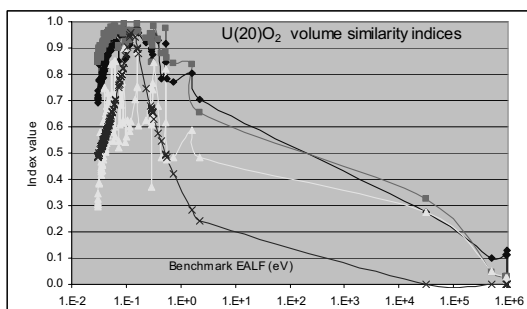


Figure H15. $U(20)O_2$ concentration

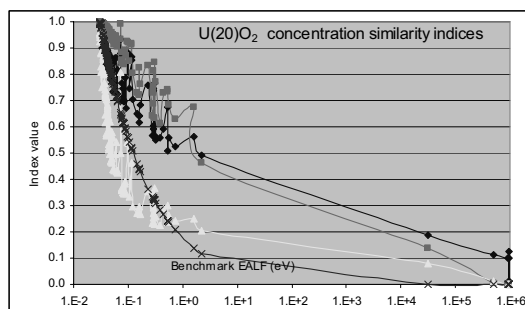


Figure H12. $U(20)O_2$ volume, enlarged

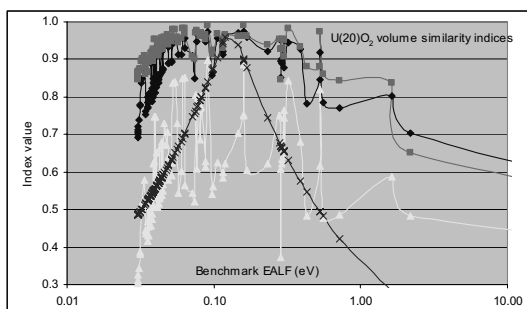


Figure H16. $U(20)O_2$ concentration

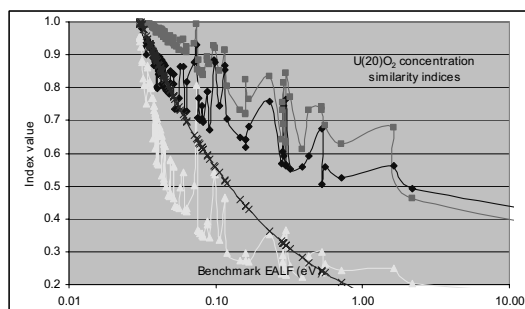


Table H2. $U(20)O_2 - c_k, E_{sum}, G$ and R_{e2}

U(20)O ₂ applications and experiments similarities – c _k , E _{sum} , G and R _{e2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}
HMF01-1	8	0	1	0	11	3	2	0	12	3	2	0	13	3	2	0	10	0	0	0
HMF04-1	22	21	23	0	28	33	28	0	28	33	28	0	29	35	29	0	19	14	8	0
HMF08-1	8	0	1	0	11	3	2	0	12	3	2	0	13	3	2	0	10	0	0	0
HMF15-1	9	0	1	0	13	3	2	0	14	3	2	0	15	4	2	0	12	0	0	0
HMF18-1	8	0	1	0	11	3	2	0	12	3	2	0	13	3	2	0	10	0	0	0
HMF20-1	6	1	3	0	10	4	5	0	10	4	5	0	12	5	5	0	11	0	1	0
HMF65-1	9	0	1	0	13	3	2	0	14	3	2	0	15	4	2	0	12	0	0	0
HCT11-1	65	75	42	24	77	84	49	42	78	83	49	43	80	80	51	48	53	63	24	21
HCT11-2	68	78	41	28	79	86	48	48	79	85	48	49	82	82	50	54	56	68	26	24
HCT11-3	69	82	42	32	78	88	48	55	79	88	49	55	82	85	51	61	59	73	29	27
HMT11-1	94	93	57	60	96	97	62	96	96	96	63	95	95	91	64	85	70	80	30	51
HMT11-3	97	96	61	75	95	98	61	77	95	97	62	76	94	94	63	69	77	88	36	63
HMT11-5	98	98	64	82	93	97	56	70	94	97	59	69	93	95	62	63	82	92	43	69
HMT11-7	98	97	67	87	91	94	55	67	92	95	57	66	92	96	61	59	86	94	50	73
HMT11-35	91	91	53	51	96	96	60	88	96	95	61	89	95	91	63	99	68	76	27	43
HMT11-37	96	94	58	64	96	97	63	90	96	97	64	89	95	94	65	80	75	85	33	54
HMT11-39	97	95	62	70	95	95	61	83	95	96	64	81	94	95	68	73	79	88	38	59
HMT11-41	97	94	62	77	91	91	54	75	92	92	57	74	92	94	62	66	88	93	50	65
HMT11-43	97	96	64	70	95	96	63	82	95	97	65	81	94	95	69	73	79	89	39	59
HST01-1	96	96	73	72	97	97	77	80	97	95	76	79	95	89	72	71	70	84	35	61
HST01-2	85	88	64	39	95	95	75	68	95	93	74	69	94	86	69	76	57	64	23	33
HST01-3	96	96	74	73	97	97	77	79	97	96	77	78	95	90	72	70	70	84	35	62
HST01-4	85	88	63	38	95	95	74	66	95	93	73	67	94	85	69	74	57	63	23	32
HST01-5	99	99	84	100	93	95	66	58	93	95	68	57	91	92	70	51	81	96	53	85
HST01-6	99	99	84	98	93	96	68	59	93	95	70	58	91	92	71	52	80	95	51	83
HST01-7	97	96	76	74	97	97	80	78	97	96	79	77	94	90	73	69	70	85	36	63
HST01-8	96	96	75	72	97	97	80	80	97	96	79	79	95	90	74	71	70	84	35	61
HST01-9	85	88	65	38	95	95	77	66	95	93	75	67	94	86	70	74	56	63	23	32
HST01-10	99	99	87	97	94	96	73	60	94	96	74	59	92	92	74	53	79	95	50	82
HST09-1	78	91	65	29	92	97	82	49	92	97	81	50	92	94	76	56	51	73	24	24
HST09-2	83	93	68	36	95	98	84	63	95	98	83	64	94	95	78	71	55	77	26	31
HST09-3	91	96	72	52	97	99	89	90	97	99	87	91	96	96	81	99	62	82	30	44
HST09-4	95	97	77	69	98	99	90	84	97	99	89	83	95	96	81	75	67	87	34	58
HST10-1	99	99	86	90	95	98	84	64	95	98	83	63	92	95	79	57	73	93	44	76
HST10-2	99	99	85	89	95	98	84	65	95	98	83	64	92	95	79	58	73	92	44	75
HST10-3	98	99	84	84	96	98	85	69	95	98	84	68	93	95	79	61	73	91	43	71
HST10-4	98	98	83	82	96	98	85	70	95	98	84	69	93	95	79	62	73	91	42	70
HST11-1	99	100	95	96	93	95	75	55	93	96	76	55	90	93	75	49	80	97	57	88
HST11-1	99	100	94	96	93	95	75	55	93	95	76	55	90	93	75	49	80	97	57	88
HST12-1	96	98	72	87	85	90	52	50	86	91	54	49	86	91	58	45	93	99	81	98
HST25-1	98	98	75	97	91	93	56	56	91	93	58	55	90	91	61	50	84	97	57	87
HST27-1	97	96	77	76	97	97	81	76	97	96	79	75	94	90	74	68	71	86	37	64
HST28-1	99	99	79	95	94	96	67	61	94	95	69	60	92	92	69	54	78	94	47	81
HST28-9	92	91	63	54	97	96	70	94	97	94	71	95	96	87	70	94	65	73	27	46
HST29-1	91	91	66	52	97	96	75	90	97	94	75	91	96	87	73	99	64	72	27	44
HST30-1	99	99	82	95	94	97	71	61	94	96	72	60	92	92	72	54	78	94	47	80

Table H2. $U(20)O_2 - c_k, E_{sum}, G$ and R_{e2} (Cont'd)

U(20)O ₂ applications and experiments similarities – c _k , E _{sum} , G and R _{e2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}
HST30-4	91	91	66	52	97	96	75	90	97	94	75	91	96	87	73	99	64	72	27	44
HST33-11A	79	86	55	38	90	93	62	66	90	91	63	67	91	85	64	75	59	69	25	33
HST33-11B	79	87	53	39	89	93	61	67	90	91	61	68	91	86	62	75	61	73	27	33
HST35-1	97	99	74	93	89	92	54	54	90	92	56	53	89	91	60	48	89	98	64	91
HST35-5	98	99	76	93	93	96	64	62	94	95	66	61	92	92	67	55	81	94	48	79
HST35-7	96	95	68	73	96	96	69	79	97	95	69	78	95	90	68	70	74	85	36	62
HST36-1	98	98	79	88	95	96	73	66	95	95	74	65	93	91	71	59	77	91	43	74
HST37-1	98	99	74	94	90	92	54	55	90	92	56	54	90	91	60	48	88	98	62	90
HST37-3	98	99	76	99	92	96	59	59	93	95	61	58	92	93	65	52	84	96	52	83
HST37-6	98	98	73	92	94	96	63	63	94	96	65	62	93	92	65	56	81	93	46	78
HST38-1	80	85	58	33	93	93	68	58	93	92	68	58	93	84	66	65	56	61	22	28
HST42-1	90	97	59	85	78	88	39	49	80	89	40	49	82	90	44	44	98	100	88	99
HST42-2	89	97	58	85	78	87	38	49	79	89	40	49	82	90	44	44	98	100	88	99
HST42-3	86	97	54	85	74	87	34	49	76	89	36	48	79	91	40	43	99	100	92	100
HST42-4	85	97	53	84	72	87	33	49	74	89	34	48	78	91	38	43	99	100	94	100
HST42-5	83	96	50	84	71	85	31	49	73	87	32	48	76	90	36	43	100	100	95	99
HST42-6	84	97	51	84	71	86	31	49	73	88	33	48	77	90	37	43	100	100	95	100
HST42-7	83	96	50	84	70	85	30	49	72	87	32	48	76	90	36	43	100	100	96	99
HST42-8	82	96	49	84	69	85	30	49	71	87	31	48	75	90	35	43	100	100	96	99
HST43-1	96	98	72	76	85	90	52	76	86	91	54	75	86	91	58	67	93	99	81	65
HST43-2	98	99	79	88	88	91	58	51	88	92	60	50	88	91	63	45	90	99	75	96
HST43-3	95	98	70	87	84	89	50	50	85	90	51	49	86	91	55	44	94	99	83	98
LCT01-1	90	94	66	66	87	91	56	87	88	92	58	86	89	91	62	78	88	92	54	56
LCT01-2	89	95	65	66	86	92	54	87	87	93	56	86	89	92	60	77	88	93	54	56
LCT02-1	94	96	64	61	92	95	60	95	93	96	62	94	93	94	65	84	85	91	46	52
LCT02-4	94	94	63	61	91	93	58	94	92	94	61	93	93	94	65	84	87	91	46	52
LCT13-1	82	88	56	38	88	91	64	66	89	91	65	67	91	91	66	74	77	84	37	32
LCT14-1	83	89	56	39	89	93	64	67	90	92	64	68	91	89	65	75	75	81	35	33
LCT14-6	75	82	51	29	85	88	62	50	86	88	62	50	88	85	63	56	67	74	30	24
LCT39-1	87	91	55	43	92	94	62	74	93	94	63	76	94	91	64	84	76	84	35	36
LCT49-1	54	55	37	14	70	65	48	24	71	64	48	25	75	60	50	27	49	46	20	12
LCT61-1	78	81	31	39	85	85	37	67	87	84	37	68	90	81	38	75	74	76	29	33
LCT70-1	65	75	47	16	80	84	59	28	81	84	59	29	84	82	61	32	56	68	25	14
LST01-1	95	98	71	85	91	96	60	68	92	95	62	67	92	93	65	61	86	95	54	72
LST03-1	93	99	85	98	86	93	65	56	87	93	67	56	87	90	71	50	86	98	68	87
LST03-2	93	99	83	95	85	92	63	55	86	93	65	54	86	91	68	49	87	98	71	89
LST03-3	93	99	82	95	85	93	62	55	86	93	64	54	86	92	68	49	88	98	71	89
LST03-4	92	97	76	95	84	89	56	55	85	90	58	54	85	89	62	49	89	98	72	89
LST03-5	90	98	73	91	81	89	52	53	82	90	54	52	83	90	58	47	92	99	80	93
LST03-6	89	98	71	91	80	89	51	53	81	90	53	52	83	90	57	47	92	99	81	93
LST03-7	88	96	66	91	79	87	47	52	80	88	49	52	82	89	52	47	93	99	81	93
LST03-8	86	96	65	89	76	86	45	52	78	88	47	51	80	89	51	46	94	99	86	95
LST03-9	85	97	64	89	75	88	44	52	77	89	46	51	79	90	49	46	95	99	87	95
LST07-1	90	98	78	99	84	91	59	57	84	91	61	57	85	89	64	51	84	97	66	85
LST07-2	89	98	75	98	83	91	56	56	83	92	58	56	84	91	62	50	85	97	68	87
LST07-3	89	98	73	96	81	92	53	56	82	92	55	55	83	91	59	49	86	98	71	88
LST07-4	87	98	71	95	80	92	51	55	81	92	53	54	82	91	57	49	87	98	72	89
LST07-5	87	97	68	94	79	90	49	55	80	91	51	54	81	91	54	48	87	98	73	90

Table H2. U(20)O₂ – c_k, E_{sum}, G and Re₂ (Cont'd)

U(20)O ₂ applications and experiments similarities – c _k , E _{sum} , G and R _{e2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}
LST16-1	94	99	75	91	90	96	62	63	90	95	64	62	90	93	67	56	84	95	56	77
LST16-2	94	99	75	94	89	95	61	62	90	95	63	61	90	93	66	55	85	96	58	79
LST16-3	93	99	74	98	87	94	57	59	88	95	59	58	88	93	62	53	87	97	62	83
LST16-4	93	99	73	99	86	93	55	58	87	94	57	58	88	92	61	52	88	97	64	84
LST16-5	93	99	73	100	86	94	54	58	87	94	56	57	87	93	59	51	88	98	66	85
LST16-6	92	99	71	99	85	93	52	57	86	93	54	56	87	92	58	51	89	98	67	86
LST16-7	91	98	70	98	84	92	51	56	85	93	52	56	86	92	56	50	89	98	68	87
LST17-1	94	98	72	91	89	95	59	63	90	95	61	62	90	92	64	56	84	95	56	77
LST17-2	94	98	72	93	89	94	58	62	90	94	60	61	90	92	64	55	85	96	58	79
LST17-3	93	98	72	98	87	93	55	59	88	93	57	58	88	92	61	53	87	97	62	83
LST17-4	93	99	72	99	87	94	54	58	88	95	56	58	88	93	60	52	87	97	63	84
LST17-5	93	98	72	100	86	92	53	58	87	93	55	57	87	92	59	51	88	98	65	85
LST17-6	92	98	71	99	85	92	51	57	86	92	53	56	87	91	57	51	88	98	66	86
LST20-1	91	99	71	94	82	92	51	54	83	93	53	53	85	92	56	48	91	99	74	90
LST20-2	90	98	69	93	81	90	49	54	82	91	50	53	84	91	54	48	92	99	77	91
LST20-3	88	98	66	91	79	89	45	53	80	90	47	52	82	91	51	47	93	99	80	93
LST20-4	87	98	63	91	77	89	43	52	79	90	45	52	81	91	49	47	93	99	82	93
LST21-1	90	99	67	94	82	92	47	54	83	93	49	54	84	93	53	48	91	99	74	90
LST21-2	89	98	66	93	80	90	46	54	82	91	48	53	83	91	51	48	92	99	77	91
LST21-3	88	98	63	92	78	90	43	53	80	91	45	52	82	91	49	47	93	99	80	92
LST21-4	87	98	62	91	77	90	42	53	79	91	43	52	81	92	47	47	93	99	82	93

Figure H17. U(5)O₂ mass indices

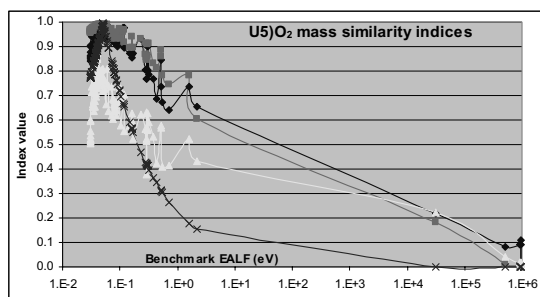


Figure H21. U(5)O₂ cylinder

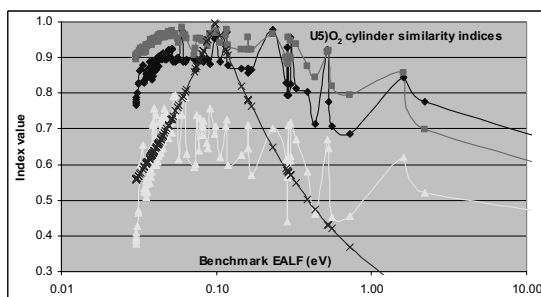


Figure H18. U(5)O₂ mass, enlarged

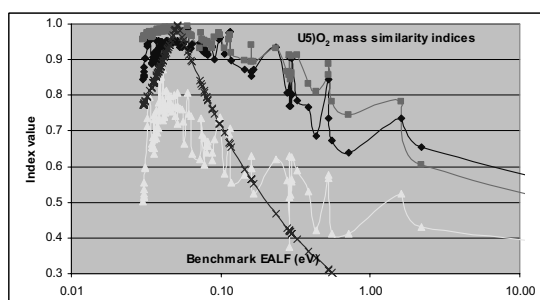


Figure H22. U(5)O₂ slab

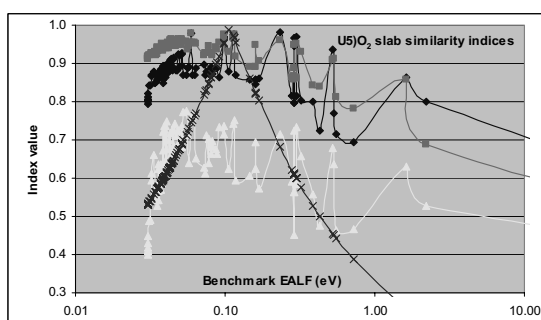


Figure H19. U(5)O₂ volume indices

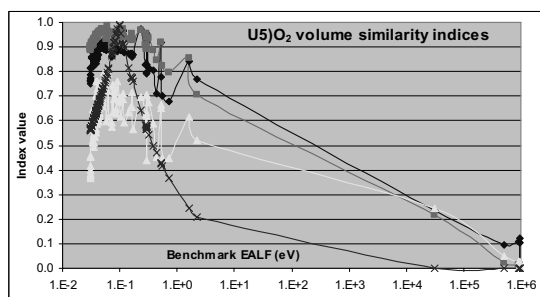


Figure H23. U(5)O₂ concentration

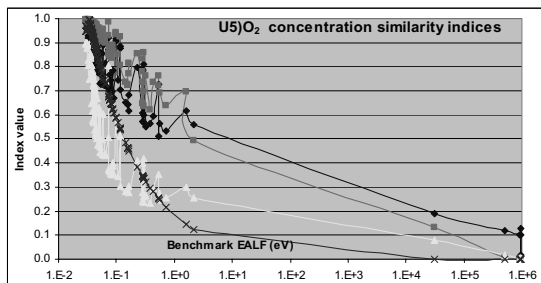


Figure H20. U(5)O₂ volume, enlarged

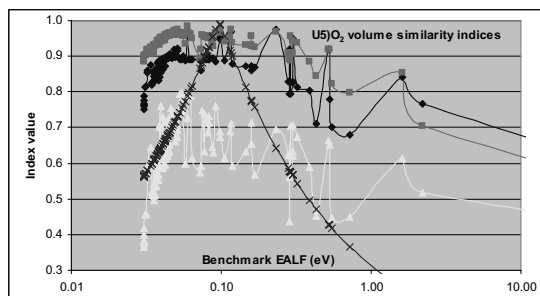


Figure H24. U(5)O₂ concentration

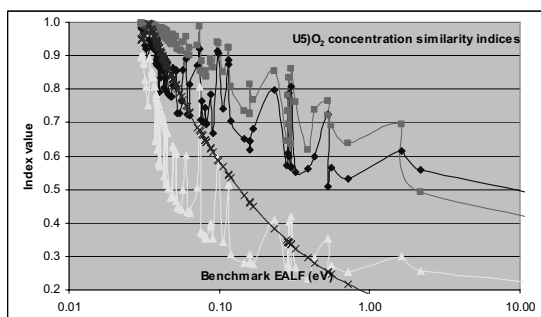


Table H3. $U(5)O_2 - c_k, E_{sum}, G$ and Re_2

U(5)O ₂ applications and experiments similarities – c _k , E _{sum} , G and Re ₂ in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c _k	E _s	G	Re ₂	c _k	E _s	G	Re ₂	c _k	E _s	G	Re ₂	c _k	E _s	G	Re ₂	c _k	E _s	G	Re ₂
HMF01-1	9	0	1	0	10	1	2	0	11	1	2	0	11	1	2	0	10	0	0	0
HMF04-1	22	18	22	0	24	22	25	0	24	22	25	0	24	23	27	0	19	13	8	0
HMF08-1	9	1	2	0	11	1	3	0	11	1	3	0	12	1	2	0	10	0	0	0
HMF15-1	11	0	1	0	12	1	1	0	12	1	1	0	13	1	1	0	13	0	0	0
HMF18-1	9	1	2	0	11	1	3	0	11	1	3	0	12	1	2	0	10	0	0	0
HMF20-1	8	1	4	0	10	2	5	0	10	2	5	0	11	2	5	0	12	0	2	0
HMF65-1	11	0	1	0	12	1	1	0	12	1	1	0	13	1	1	0	13	0	0	
HCT11-1	64	74	41	27	68	80	45	37	69	79	45	37	70	78	47	39	53	64	25	22
HCT11-2	67	78	41	30	70	82	45	42	71	82	45	42	72	81	46	44	56	69	27	25
HCT11-3	69	81	42	34	71	85	45	47	71	85	46	47	73	84	47	50	60	74	30	28
HMT11-1	90	92	56	66	88	94	59	90	88	94	60	91	87	92	59	96	70	81	30	54
HMT11-3	93	95	60	81	89	95	63	90	89	95	64	89	88	95	64	84	76	88	37	66
HMT11-5	94	97	64	89	89	95	62	82	89	95	63	81	89	95	65	77	81	92	44	73
HMT11-7	95	96	66	94	89	93	60	77	89	94	61	77	89	95	64	73	86	94	50	77
HMT11-35	87	90	52	55	87	93	57	76	87	92	57	76	86	91	57	80	68	77	28	45
HMT11-37	92	93	58	70	89	94	61	96	89	94	62	96	88	93	62	99	74	85	34	57
HMT11-39	93	93	62	76	89	93	63	96	89	93	64	95	89	94	66	90	78	88	39	62
HMT11-41	95	93	62	84	89	90	57	87	89	91	59	86	90	92	63	82	87	93	51	69
HMT11-43	94	95	64	76	90	94	65	95	90	94	66	95	89	94	68	90	79	89	40	62
HST01-1	91	95	66	79	89	95	71	92	89	95	71	92	87	92	68	87	70	84	35	64
HST01-2	81	87	56	43	83	91	62	59	83	90	61	59	82	86	59	62	57	65	24	35
HST01-3	92	95	66	79	89	96	72	92	89	95	71	91	87	93	69	86	70	84	36	65
HST01-4	80	86	56	41	83	91	62	57	82	90	61	57	81	86	59	60	57	64	24	34
HST01-5	95	98	81	92	89	95	72	67	89	95	72	66	88	94	72	63	81	96	54	89
HST01-6	95	98	80	94	89	96	73	68	89	96	73	68	88	95	73	64	79	95	52	87
HST01-7	92	95	68	81	89	96	74	90	89	95	73	89	87	93	70	85	70	85	36	66
HST01-8	92	95	67	79	89	96	73	93	89	95	72	92	87	93	70	87	69	84	35	64
HST01-9	80	86	57	41	83	91	63	57	83	90	62	57	82	86	59	60	57	64	24	34
HST01-10	95	98	80	95	90	96	75	69	90	96	76	69	88	95	74	65	79	94	50	86
HST09-1	74	89	57	31	78	92	65	43	78	92	65	43	77	91	64	45	51	72	25	25
HST09-2	78	91	59	40	81	94	67	54	81	94	67	55	80	93	66	58	55	76	27	32
HST09-3	85	94	63	56	86	96	71	77	86	96	71	78	84	95	69	82	62	82	31	46
HST09-4	90	96	68	75	88	96	76	97	88	97	76	97	86	96	73	92	67	86	35	61
HST10-1	93	98	76	98	89	97	80	74	89	97	79	74	87	96	77	70	73	92	45	80
HST10-2	93	98	76	96	89	97	80	76	89	97	79	75	87	96	77	71	73	92	44	79
HST10-3	93	97	75	91	89	96	79	80	89	97	79	79	87	96	77	75	72	91	43	75
HST10-4	93	97	74	90	89	96	79	81	89	96	79	81	87	95	76	76	72	90	43	73
HST11-1	95	99	85	88	89	95	76	64	89	95	76	64	88	95	74	61	79	96	57	93
HST11-1	95	99	85	88	89	95	76	64	89	95	76	64	87	95	74	60	79	96	58	93
HST12-1	94	97	74	80	86	92	59	58	87	92	60	58	87	93	61	55	92	99	81	98
HST25-1	95	98	76	89	88	94	63	65	89	94	64	65	88	94	65	61	83	97	57	91
HST27-1	92	96	69	83	90	96	75	88	89	95	74	88	88	93	71	83	71	85	37	67
HST28-1	95	98	75	96	89	96	72	70	89	96	73	70	88	94	71	66	78	94	48	85
HST28-9	87	90	58	59	87	93	63	81	87	92	63	82	86	89	61	86	65	74	28	48
HST29-1	87	89	60	57	87	93	65	78	87	92	65	78	86	89	62	82	64	72	28	46
HST30-1	95	98	77	97	90	96	74	71	90	96	75	70	88	95	72	67	78	93	47	84

Table H3. $U(5)O_2 - c_k, E_{sum}, G$ and Re_2 (Cont'd)

U(5)O ₂ applications and experiments similarities – c _k , E _{sum} , G and R _{e2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}
HST30-4	87	90	59	56	87	93	66	78	87	92	65	78	86	89	62	82	64	73	28	46
HST33-11A	77	84	52	42	79	89	57	57	80	88	57	58	80	86	56	61	60	70	26	34
HST33-11B	77	86	51	42	79	89	56	58	80	89	56	58	80	87	56	61	61	74	28	34
HST35-1	95	98	76	86	88	93	61	62	89	94	63	62	89	93	64	59	88	98	65	95
HST35-5	95	98	74	99	90	96	70	72	90	96	71	71	89	95	69	68	81	94	48	83
HST35-7	92	94	64	79	90	95	69	92	90	95	68	91	89	93	66	86	74	85	36	65
HST36-1	94	97	73	95	90	96	74	76	90	95	74	76	89	94	71	72	76	91	44	78
HST37-1	95	98	76	87	89	94	61	63	89	94	62	63	89	94	64	60	87	98	62	94
HST37-3	95	98	76	93	89	96	66	68	90	96	67	67	89	95	68	64	83	96	52	88
HST37-6	95	98	72	100	90	96	69	73	90	96	70	73	89	95	68	69	81	93	47	81
HST38-1	77	83	53	36	80	89	59	50	80	88	58	50	80	84	56	53	56	62	23	30
HST42-1	90	97	60	79	82	90	46	57	83	91	47	57	84	92	49	54	97	99	87	96
HST42-2	90	97	60	78	81	90	45	57	82	91	47	57	84	92	49	54	97	99	88	96
HST42-3	88	96	56	78	79	90	42	57	80	91	43	56	82	92	45	53	98	100	90	95
HST42-4	87	96	54	78	77	90	40	56	79	91	41	56	81	92	43	53	98	100	90	95
HST42-5	85	96	52	77	76	89	38	56	78	90	39	56	80	91	41	53	98	100	90	95
HST42-6	86	96	52	77	77	89	38	56	78	90	40	56	81	92	42	53	98	100	90	95
HST42-7	85	96	51	77	76	89	38	56	77	90	39	56	80	91	41	53	98	100	90	95
HST42-8	84	96	50	77	75	89	37	56	77	90	38	56	79	91	40	53	98	100	89	95
HST43-1	94	97	74	83	86	92	59	88	87	92	60	87	87	93	61	83	92	99	81	68
HST43-2	95	98	79	81	88	93	65	59	88	93	65	59	88	93	66	56	89	98	75	100
HST43-3	94	97	71	80	86	92	57	58	86	92	58	58	87	92	59	55	93	99	83	97
LCT01-1	96	97	74	72	95	97	69	99	96	97	71	99	97	97	74	96	91	94	59	59
LCT01-2	96	97	73	72	95	97	67	99	95	98	69	100	97	98	71	95	92	94	59	59
LCT02-1	98	97	71	66	97	97	71	91	97	98	73	92	98	98	75	97	87	92	51	54
LCT02-4	98	96	69	67	96	96	69	92	97	96	71	92	97	97	74	97	89	92	51	54
LCT13-1	90	91	63	41	95	94	71	57	96	95	72	57	97	95	73	60	81	86	42	34
LCT14-1	91	91	63	42	95	96	71	58	96	96	71	58	97	95	72	61	79	83	40	34
LCT14-6	84	86	58	31	92	92	66	43	92	92	67	43	94	91	68	45	73	76	35	25
LCT39-1	93	93	62	47	97	97	70	64	98	97	70	65	98	96	71	68	80	85	41	38
LCT49-1	65	61	43	15	77	70	52	21	78	70	52	21	80	69	53	22	56	49	26	12
LCT61-1	87	86	38	42	92	90	44	58	93	90	44	58	95	89	45	61	78	78	34	34
LCT70-1	74	78	52	18	84	86	62	24	85	86	62	24	86	86	63	26	62	70	30	14
LST01-1	99	99	81	92	97	99	73	79	97	99	74	78	98	98	76	74	89	96	60	75
LST03-1	94	99	87	90	89	95	73	65	90	95	74	65	90	95	75	62	87	98	72	91
LST03-2	94	99	85	88	89	95	71	64	89	95	72	63	89	95	73	60	88	98	76	93
LST03-3	94	99	84	87	89	95	70	64	89	95	71	63	89	95	72	60	89	98	76	93
LST03-4	93	98	78	87	88	93	64	63	88	93	65	63	89	93	67	60	90	98	77	94
LST03-5	92	98	75	84	86	93	60	61	87	93	61	61	88	93	63	58	92	99	84	97
LST03-6	92	98	73	84	85	93	59	61	86	93	60	60	87	93	62	57	93	99	84	98
LST03-7	91	97	68	83	84	91	54	61	85	92	56	60	87	92	58	57	94	99	85	98
LST03-8	89	96	66	82	82	91	52	60	84	91	53	59	85	92	56	56	95	99	89	99
LST03-9	89	97	65	82	82	92	51	60	83	92	53	59	85	93	55	56	95	99	89	99
LST07-1	92	98	81	91	87	94	67	66	88	94	68	66	88	94	70	63	86	97	71	90
LST07-2	91	98	78	90	86	94	64	65	87	95	65	65	87	94	68	62	86	98	72	91
LST07-3	90	98	76	88	85	95	61	64	86	95	62	64	87	95	65	61	87	98	75	92
LST07-4	89	98	73	87	84	94	59	64	85	95	61	63	86	95	63	60	87	98	76	93
LST07-5	89	98	71	87	83	93	57	63	84	94	58	63	85	94	60	60	88	98	77	94

Table H3. $U(5)O_2 - c_k, E_{sum}, G$ and Re_2 (Cont'd)

U(5)O ₂ applications and experiments similarities – c _k , E _{sum} , G and Re ₂ in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c _k	E _s	G	Re ₂	c _k	E _s	G	Re ₂	c _k	E _s	G	Re ₂	c _k	E _s	G	Re ₂	c _k	E _s	G	Re ₂
LST16-1	95	99	81	99	92	97	71	73	93	97	72	73	93	97	74	69	86	96	61	81
LST16-2	95	99	80	98	92	97	69	71	92	97	70	71	92	96	72	67	86	96	63	83
LST16-3	95	99	78	94	91	97	65	69	91	97	66	68	92	96	68	65	88	97	67	87
LST16-4	95	99	77	93	90	96	63	68	91	96	64	67	91	96	67	64	89	98	69	88
LST16-5	94	99	76	92	90	96	62	67	90	96	63	66	91	96	65	63	90	98	70	89
LST16-6	94	99	74	91	89	95	60	66	89	96	61	65	90	95	63	62	90	98	72	90
LST16-7	93	99	73	90	88	95	59	65	89	95	60	65	90	95	62	62	90	98	73	91
LST17-1	95	98	77	99	92	97	67	73	92	97	69	73	92	96	71	69	86	96	61	81
LST17-2	95	98	77	98	91	96	66	72	92	96	67	71	92	96	70	68	86	96	63	83
LST17-3	95	98	76	94	90	96	63	69	91	96	65	68	91	95	67	65	88	97	67	87
LST17-4	95	99	76	93	90	96	62	68	91	96	63	67	91	96	65	64	88	97	68	88
LST17-5	94	98	75	92	90	95	61	67	90	95	62	66	91	95	65	63	89	98	70	89
LST17-6	94	98	74	91	89	95	60	66	89	95	61	66	90	95	63	62	89	98	71	90
LST20-1	93	99	73	86	87	94	59	63	88	95	60	62	89	95	62	59	91	99	78	95
LST20-2	92	98	71	85	86	93	56	62	87	94	58	62	88	94	60	58	92	99	81	96
LST20-3	91	98	68	84	84	93	53	61	85	93	55	61	87	94	57	58	93	99	84	97
LST20-4	90	98	65	83	83	93	51	61	84	93	52	60	86	94	54	57	94	99	85	98
LST21-1	92	98	70	86	86	94	55	63	87	95	57	62	88	95	59	59	92	99	79	94
LST21-2	92	98	68	85	85	93	54	62	86	94	55	62	88	94	57	59	92	99	81	96
LST21-3	90	98	65	84	84	93	51	61	85	93	52	61	86	94	54	58	93	99	84	97
LST21-4	90	98	64	84	83	93	50	61	84	94	51	60	86	94	53	57	94	99	85	98

Figure H25. U(4)O₂ mass indices

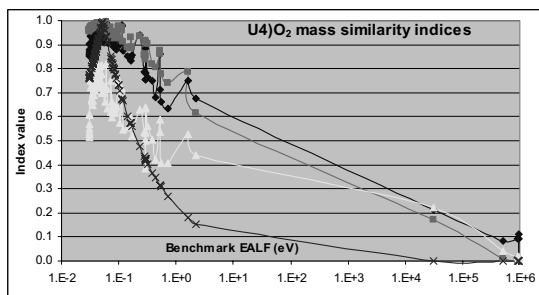


Figure H29. U(4)O₂ cylinder

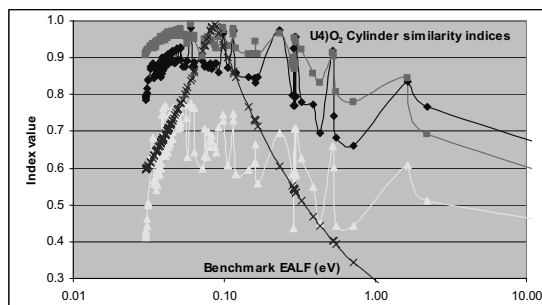


Figure H26. U(4)O₂ mass, enlarged

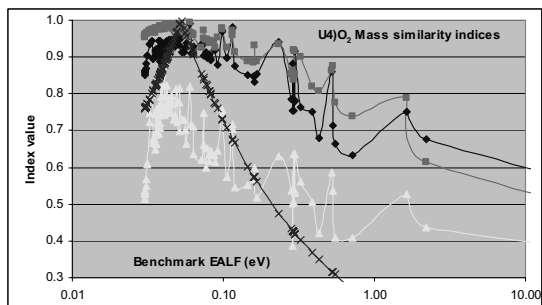


Figure H30. U(4)O₂ slab

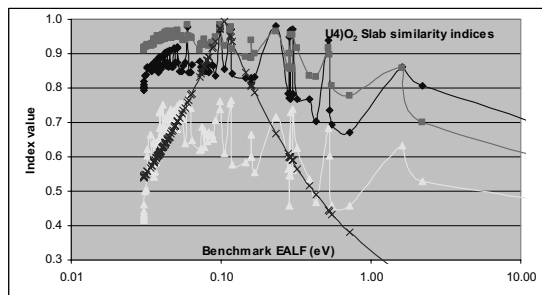


Figure H27. U(4)O₂ volume indicesa

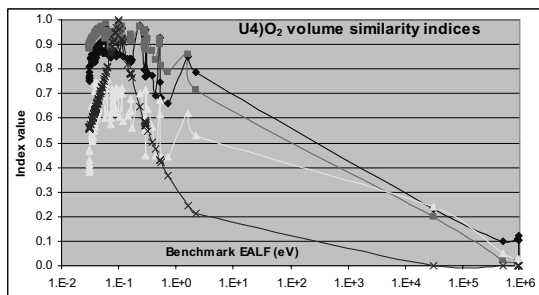


Figure H31. U(4)O₂ concentration

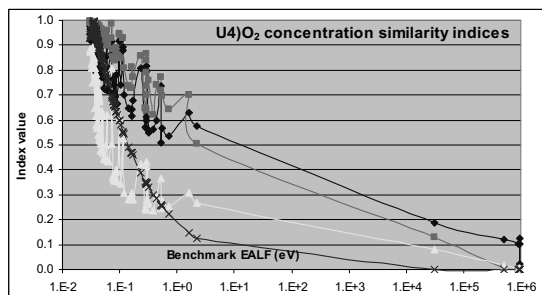


Figure H28. U(4)O₂ volume, enlarged

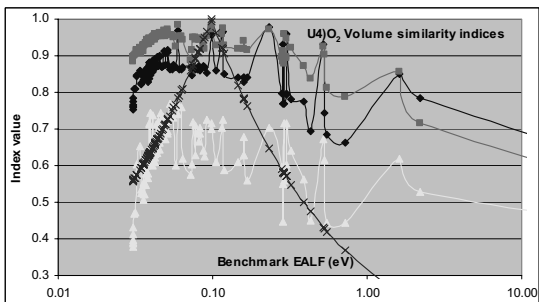


Figure H32. U(4)O₂ concentration

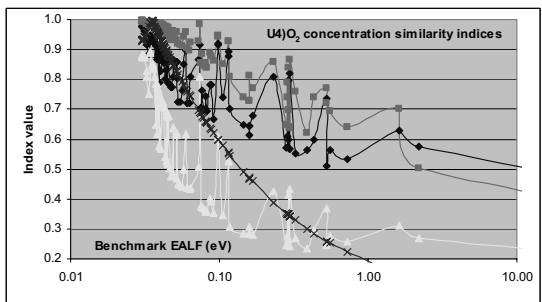


Table H4. $U(4)O_2 - c_k, E_{sum}, G$ and R_{e2}

U(4)O ₂ applications and experiments similarities – c _k , E _{sum} , G and R _{e2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}
HMF01-1	9	0	1	0	10	1	2	0	10	1	2	0	11	1	2	0	10	0	1	0
HMF04-1	22	17	22	0	23	20	24	0	23	20	24	0	23	21	26	0	19	13	8	0
HMF08-1	9	1	2	0	11	1	3	0	11	1	2	0	11	1	2	0	10	0	1	0
HMF15-1	11	0	1	0	12	1	1	0	12	1	1	0	13	1	1	0	13	0	0	0
HMF18-1	9	1	2	0	11	1	3	0	11	1	2	0	11	1	2	0	10	0	1	0
HMF20-1	9	1	4	0	10	2	5	0	10	2	5	0	11	2	5	0	12	0	2	0
HMF65-1	11	0	1	0	12	1	1	0	12	1	1	0	13	1	1	0	13	0	0	0
HCT11-1	63	74	41	27	66	79	44	37	66	78	44	34	67	78	46	38	53	64	26	22
HCT11-2	66	78	41	31	68	81	44	42	68	81	44	39	69	81	46	43	57	69	27	25
HCT11-3	68	81	42	35	69	84	45	47	70	83	45	44	70	83	47	49	60	74	30	29
HMT11-1	88	91	55	67	85	93	59	91	86	93	58	85	84	91	58	94	70	81	31	55
HMT11-3	91	95	60	83	86	94	63	89	88	95	63	95	86	94	63	86	76	88	37	68
HMT11-5	93	96	64	91	87	94	62	81	89	95	64	87	87	95	65	78	81	92	44	74
HMT11-7	94	96	66	96	87	92	60	77	89	94	63	82	87	94	64	74	85	94	50	78
HMT11-35	86	89	52	56	84	91	56	76	85	91	56	71	83	90	56	79	68	77	28	46
HMT11-37	90	92	57	71	86	93	61	96	87	93	61	90	85	92	61	99	74	85	34	58
HMT11-39	92	93	61	77	87	92	62	95	88	93	64	98	87	93	65	92	78	88	39	63
HMT11-41	94	93	62	85	87	89	57	86	89	90	60	92	88	91	62	83	87	93	51	70
HMT11-43	92	94	63	78	87	93	64	95	89	94	66	99	87	93	66	92	78	89	40	64
HST01-1	89	94	63	80	86	94	69	92	87	94	67	98	85	92	66	89	69	84	36	65
HST01-2	78	86	53	43	80	90	60	59	80	89	58	55	78	86	57	61	57	65	24	35
HST01-3	90	94	64	81	86	95	69	91	87	95	68	97	85	93	66	88	70	84	36	66
HST01-4	78	85	53	42	79	89	59	57	79	88	58	53	78	85	56	59	57	64	24	34
HST01-5	94	98	79	91	87	95	71	66	89	96	74	71	86	94	72	64	80	95	54	90
HST01-6	93	98	77	92	87	95	72	68	89	96	75	72	86	95	72	66	79	95	52	89
HST01-7	90	95	65	82	86	95	71	89	87	95	70	96	85	93	68	87	70	85	37	67
HST01-8	89	94	64	80	86	95	70	92	87	95	69	98	85	92	67	89	69	84	36	65
HST01-9	78	85	54	42	80	90	60	57	80	88	59	53	78	86	57	59	57	64	24	34
HST01-10	93	98	77	94	87	95	74	69	89	96	77	74	86	95	74	67	78	94	50	87
HST09-1	72	88	54	32	74	90	62	43	74	90	60	40	74	90	60	44	51	72	25	26
HST09-2	76	90	56	40	78	92	64	55	78	92	63	51	77	92	63	57	55	76	27	33
HST09-3	83	93	60	57	83	94	68	78	83	94	67	73	81	94	66	81	62	81	31	47
HST09-4	88	95	64	76	85	95	73	97	86	96	71	97	84	95	71	94	67	86	35	62
HST10-1	91	97	73	100	86	96	77	74	88	96	77	79	85	95	75	71	73	92	45	82
HST10-2	91	97	73	98	86	96	77	75	88	96	77	80	85	95	75	73	73	92	44	80
HST10-3	91	97	72	93	86	95	76	79	88	96	77	85	85	95	75	77	72	90	44	76
HST10-4	91	96	71	91	86	95	76	80	87	96	76	86	85	95	74	78	72	90	43	75
HST11-1	93	98	82	87	87	95	74	64	88	96	76	68	86	95	73	62	79	96	57	94
HST11-1	93	98	83	87	86	94	74	64	88	96	76	68	86	95	73	62	79	96	58	95
HST12-1	94	97	75	79	85	91	60	58	87	93	63	62	86	93	62	56	92	99	81	96
HST25-1	93	98	76	88	86	94	63	64	88	95	67	69	86	94	65	62	83	97	57	93
HST27-1	90	95	66	84	87	95	72	88	88	95	71	94	85	93	69	85	71	85	37	69
HST28-1	93	97	73	95	87	95	72	70	89	96	74	74	86	94	71	67	78	93	48	86
HST28-9	85	89	55	60	84	92	61	82	85	91	60	77	83	89	58	84	65	74	28	49
HST29-1	85	89	57	57	84	92	63	78	85	91	61	73	83	89	60	81	64	73	28	47
HST30-1	93	98	74	95	87	96	74	70	89	96	75	75	86	95	72	68	77	93	48	86

Table H4. $U(4)O_2 - c_k, E_{sum}, G$ and R_{e2} (Cont'd)

U(4)O ₂ applications and experiments similarities – c _k , E _{sum} , G and R _{e2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}
HST30-4	85	89	57	57	84	92	63	78	85	91	62	73	83	89	60	81	64	73	28	47
HST33-11A	75	84	51	42	77	88	56	58	77	87	55	54	77	85	54	60	60	70	26	35
HST33-11B	76	85	50	43	77	88	55	58	77	88	54	54	77	86	55	60	61	74	28	35
HST35-1	94	98	77	84	87	93	62	62	89	94	66	66	87	94	64	60	88	98	65	97
HST35-5	93	97	72	97	88	95	70	71	89	96	72	76	87	95	69	69	81	94	48	84
HST35-7	91	94	62	81	87	94	67	91	88	94	66	97	87	93	65	88	74	85	37	66
HST36-1	93	97	70	97	88	95	73	76	89	96	73	81	87	94	71	73	76	91	44	79
HST37-1	94	98	77	85	87	93	62	63	89	95	65	67	87	94	64	61	87	98	62	96
HST37-3	94	98	75	92	87	95	67	67	89	96	70	72	87	95	68	65	83	96	53	89
HST37-6	93	97	70	99	88	96	69	72	89	96	71	78	87	95	68	70	80	93	47	83
HST38-1	75	82	51	37	77	87	56	50	77	86	55	47	77	84	54	52	56	62	23	30
HST42-1	90	97	61	77	81	90	47	57	84	92	50	61	84	92	50	55	96	99	87	94
HST42-2	90	96	61	77	81	90	47	57	84	92	50	61	84	92	50	55	96	99	88	94
HST42-3	88	96	57	77	79	90	43	56	82	92	46	60	82	92	46	54	97	99	88	94
HST42-4	87	96	55	76	77	90	41	56	81	92	44	60	81	92	44	54	98	99	88	93
HST42-5	86	96	53	76	76	89	39	56	80	91	42	60	80	91	42	54	98	99	88	93
HST42-6	86	96	54	76	77	89	40	56	80	91	43	60	80	91	43	54	98	99	88	93
HST42-7	86	96	53	76	76	89	39	56	79	91	42	60	80	91	42	54	98	99	88	93
HST42-8	85	95	51	76	75	88	38	56	78	91	41	60	79	91	41	54	98	99	87	93
HST43-1	94	97	75	84	85	91	60	87	87	93	63	93	86	93	62	84	92	99	81	69
HST43-2	94	97	80	80	86	92	65	59	88	94	68	63	87	93	67	57	89	98	75	98
HST43-3	93	97	72	78	84	91	58	57	87	93	61	61	86	92	60	56	93	99	83	96
LCT01-1	97	97	76	73	96	97	72	99	97	98	75	93	98	98	76	97	91	94	60	60
LCT01-2	97	98	75	73	96	98	70	100	97	98	73	93	97	98	74	97	92	95	61	60
LCT02-1	98	97	72	67	97	97	72	92	98	98	75	86	97	98	77	95	88	93	53	55
LCT02-4	98	96	70	68	96	96	70	92	97	96	73	86	97	97	75	95	89	93	53	55
LCT13-1	92	92	64	42	96	95	72	57	96	95	71	53	97	96	74	59	82	87	43	34
LCT14-1	92	92	64	43	96	96	71	58	96	95	71	54	97	95	73	60	80	84	42	35
LCT14-6	86	86	59	32	93	92	67	43	92	91	66	40	94	92	68	44	74	77	37	26
LCT39-1	94	93	63	48	98	97	70	65	97	96	70	61	98	97	72	67	81	86	42	39
LCT49-1	68	62	44	15	79	72	53	21	77	69	51	20	81	70	53	22	58	50	27	13
LCT61-1	88	86	39	43	93	91	45	58	93	90	44	54	95	90	46	60	79	79	35	35
LCT70-1	75	79	53	18	85	86	62	25	83	85	61	23	86	86	63	25	63	70	31	15
LST01-1	99	99	82	94	97	99	74	78	98	99	78	84	98	98	77	76	90	96	62	77
LST03-1	94	98	88	88	89	95	74	65	90	96	77	69	89	95	75	63	87	98	73	93
LST03-2	94	98	86	86	88	95	72	63	90	96	75	68	89	95	73	61	88	98	76	95
LST03-3	94	98	85	86	88	95	71	63	90	96	74	68	89	95	73	61	89	98	76	95
LST03-4	93	98	79	86	87	93	65	63	89	94	68	67	89	94	68	61	90	98	77	95
LST03-5	92	98	76	83	86	93	61	61	88	94	65	65	87	94	65	59	92	99	84	99
LST03-6	92	98	74	82	85	93	60	60	87	94	64	65	87	94	64	59	93	99	84	99
LST03-7	91	97	69	82	84	91	55	60	87	93	59	65	87	93	59	58	93	99	85	100
LST03-8	90	96	68	81	83	91	53	59	85	93	57	64	85	92	57	58	94	99	89	99
LST03-9	89	97	67	81	82	92	52	59	85	93	56	63	85	93	56	57	95	99	89	99
LST07-1	91	98	82	90	86	94	68	66	88	95	71	70	87	94	71	64	86	97	71	91
LST07-2	91	98	80	88	86	94	65	65	87	95	69	69	87	95	69	63	86	98	73	93
LST07-3	90	98	77	87	85	94	62	64	87	96	66	68	86	95	66	62	87	98	75	94
LST07-4	90	98	74	86	84	94	60	63	86	95	64	68	85	95	64	61	87	98	76	95
LST07-5	89	98	72	85	83	93	58	63	85	95	61	67	85	94	62	61	88	98	77	96

Table H4. $U(4)O_2 - c_k, E_{sum}, G$ and R_{e2} (Cont'd)

U(4)O ₂ applications and experiments similarities – c _k , E _{sum} , G and R _{e2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}
LST16-1	95	99	82	99	91	97	72	73	93	98	76	78	92	97	75	70	86	96	62	83
LST16-2	95	99	81	97	91	97	70	71	93	98	74	76	92	97	73	69	87	96	64	85
LST16-3	95	99	79	93	90	96	66	68	92	97	70	73	91	96	70	66	88	97	68	88
LST16-4	95	99	78	91	90	96	64	67	91	97	68	72	91	96	68	65	89	98	69	90
LST16-5	94	99	77	90	89	96	63	66	91	97	67	71	90	96	66	64	90	98	71	91
LST16-6	94	99	76	89	88	95	61	65	90	96	65	70	90	96	65	63	90	98	72	92
LST16-7	93	98	74	88	88	95	60	65	90	96	63	69	89	95	63	63	90	98	73	93
LST17-1	95	98	78	99	91	97	69	73	92	97	72	78	92	96	72	70	86	96	62	83
LST17-2	95	98	78	97	91	96	67	71	92	97	71	76	91	96	71	69	86	96	64	85
LST17-3	95	98	77	93	90	95	64	68	91	96	68	73	91	96	68	66	88	97	68	88
LST17-4	94	99	77	91	89	96	63	67	91	97	67	72	90	96	67	65	88	98	68	89
LST17-5	94	98	76	90	89	95	62	66	91	96	66	71	90	95	66	64	89	98	70	91
LST17-6	94	98	75	89	88	95	61	66	90	96	64	70	90	95	64	64	89	98	71	92
LST20-1	93	98	74	85	87	94	60	62	89	96	63	67	88	95	63	60	91	99	79	97
LST20-2	92	98	72	84	86	93	58	62	88	95	61	66	88	94	61	60	92	99	81	98
LST20-3	91	98	69	83	84	93	55	61	87	94	58	65	87	94	58	59	93	99	84	99
LST20-4	90	98	66	82	83	93	52	60	86	94	56	64	86	94	56	58	93	99	85	100
LST21-1	92	98	71	85	86	94	57	62	88	96	60	67	88	95	60	60	92	99	79	96
LST21-2	92	98	69	84	85	93	55	62	88	95	58	66	87	94	58	60	92	99	81	97
LST21-3	91	98	67	83	84	93	52	61	86	94	56	65	86	94	56	59	93	99	84	99
LST21-4	90	98	65	82	83	93	51	60	85	94	54	65	86	94	54	58	94	99	85	100

Figure H33. U(3)O₂ mass indices

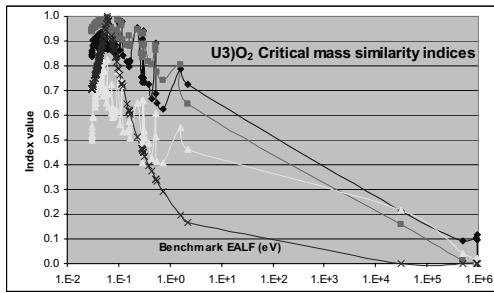


Figure H37. U(3)O₂ cylinder, enlarged

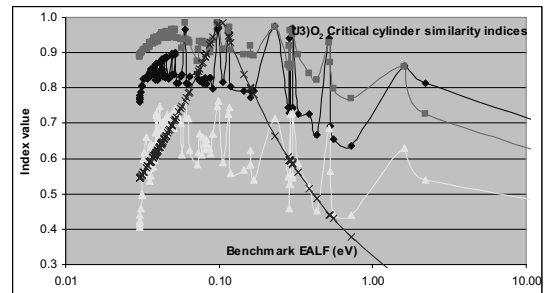


Figure H34. U(3)O₂ mass enlarged

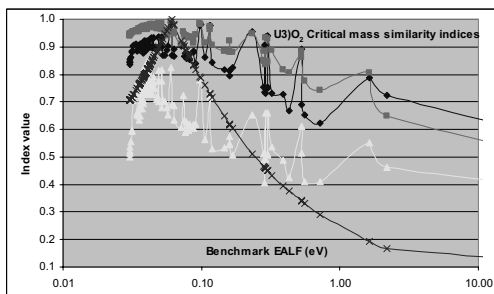


Figure H38. U(3)O₂ slab, enlarged

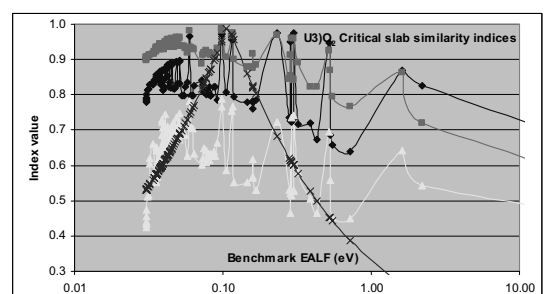


Figure H35. U(3)O₂ volume indices

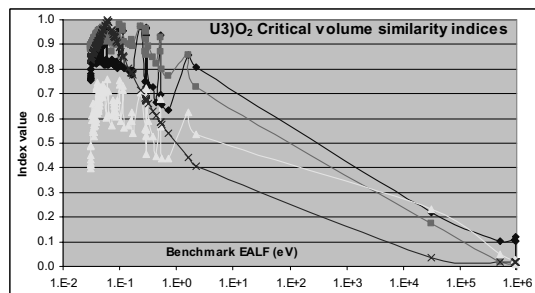


Figure H39. U(3)O₂ concentration

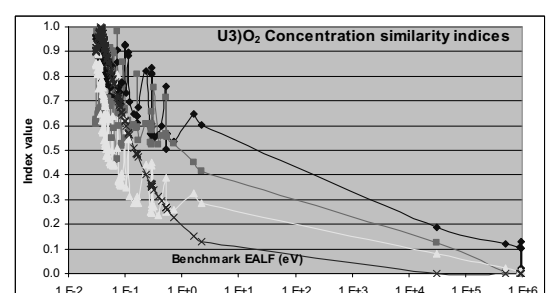


Figure H36. U(3)O₂ volume, enlarged

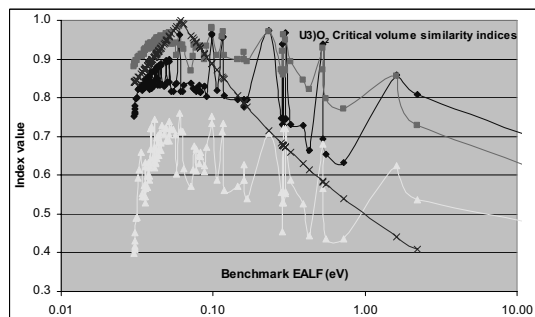


Figure H40. U(3)O₂ conc. Enlarged

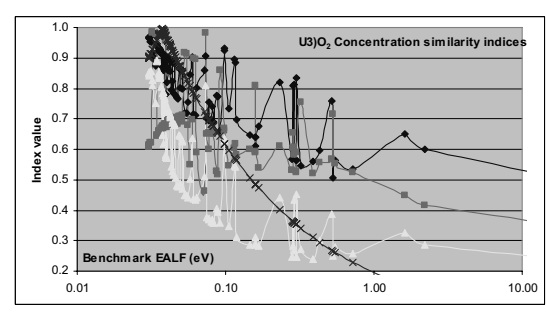


Table H5. $U(3)O_2 - c_k, E_{sum}, G$ and R_{e2}

U(3)O ₂ applicat ions and experiments similarities – c _k , E _{sum} , G and R _{e2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentrati on			
	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}
HMF01-1	10	0	1	0	10	1	2	2	11	1	2	0	11	1	2	0	10	0	1	0
HMF04-1	21	16	22	0	22	17	23	4	22	18	24	0	22	18	25	0	19	12	8	0
HMF08-1	10	1	2	0	11	1	3	2	11	1	3	0	11	1	2	0	11	0	1	0
HMF15-1	11	0	1	0	12	1	1	2	12	1	1	0	13	1	1	0	13	0	0	0
HMF18-1	10	1	2	0	11	1	3	2	11	1	3	0	11	1	2	0	11	0	1	0
HMF20-1	9	1	4	0	10	2	5	2	11	2	5	0	11	2	5	0	12	0	2	0
HMF65-1	11	0	1	0	12	1	1	2	12	1	1	0	13	1	1	0	13	0	0	0
HCT11-1	62	74	41	29	63	77	44	61	64	77	44	38	64	77	45	39	53	53	26	23
HCT11-2	65	78	41	33	65	80	44	65	66	80	44	43	66	79	45	44	56	55	28	26
HCT11-3	67	81	42	38	67	82	44	69	67	82	45	49	67	82	46	50	60	56	30	29
HMT11-1	84	91	53	72	81	91	56	96	80	91	56	93	79	90	55	96	70	58	31	56
HMT11-3	88	94	59	89	82	93	61	94	82	93	61	87	81	93	61	84	76	60	37	70
HMT11-5	89	95	63	98	83	93	62	89	83	93	62	79	83	93	63	77	80	59	44	77
HMT11-7	90	94	65	97	84	91	60	87	84	91	61	75	84	92	63	73	84	55	50	81
HMT11-35	82	88	51	60	79	89	54	88	79	89	54	78	78	88	53	80	68	54	28	47
HMT11-37	86	91	56	76	82	91	59	99	82	91	59	99	81	91	59	99	73	55	35	60
HMT11-39	88	91	60	83	83	90	61	97	83	90	62	93	82	91	63	90	77	52	39	65
HMT11-41	90	91	61	92	84	87	57	92	84	88	58	84	84	89	60	82	86	46	51	72
HMT11-43	88	93	62	84	83	91	62	97	83	91	63	92	82	91	64	90	78	53	40	66
HST01-1	85	93	61	86	81	93	65	95	81	93	64	90	80	91	63	87	69	65	36	68
HST01-2	75	85	51	47	75	87	56	77	74	87	55	60	73	84	53	62	57	53	25	37
HST01-3	86	94	62	87	82	93	65	95	81	93	65	89	80	92	63	86	70	65	36	68
HST01-4	75	84	51	45	75	87	55	76	74	86	55	59	73	84	53	60	57	53	25	35
HST01-5	90	97	76	84	83	94	70	81	83	94	70	65	82	94	70	63	79	68	54	93
HST01-6	89	97	75	86	83	94	71	82	83	94	71	66	82	94	71	64	78	68	52	92
HST01-7	86	94	63	89	82	93	67	94	81	93	66	87	80	92	64	85	69	65	37	69
HST01-8	86	94	62	86	82	93	66	95	81	93	65	90	80	92	63	87	69	65	36	67
HST01-9	75	85	51	45	75	87	56	76	74	87	55	58	73	84	53	60	56	52	25	35
HST01-10	89	97	75	87	83	94	73	82	83	94	73	67	82	94	72	65	78	68	51	90
HST09-1	69	86	51	34	70	87	57	66	69	87	56	44	68	87	56	45	51	71	25	27
HST09-2	73	89	54	43	73	89	59	75	73	89	59	56	72	89	58	58	55	75	27	34
HST09-3	80	92	57	62	78	92	63	89	77	92	62	80	76	92	62	82	61	81	31	48
HST09-4	84	94	62	82	80	93	67	98	80	93	67	94	78	93	66	92	66	86	36	64
HST10-1	87	96	71	93	82	94	72	85	81	94	72	72	80	94	71	70	72	92	45	84
HST10-2	87	96	70	95	82	94	72	86	81	94	72	73	80	94	71	71	72	91	45	83
HST10-3	87	95	69	100	82	94	71	88	81	94	72	77	80	93	71	75	71	90	44	78
HST10-4	87	95	69	98	82	93	71	89	81	94	71	79	80	93	70	76	71	89	44	77
HST11-1	89	97	78	81	83	93	72	79	82	93	72	62	81	93	71	61	78	96	58	97
HST11-1	89	97	78	80	83	93	72	79	82	93	72	62	81	93	71	60	78	96	58	98
HST12-1	91	96	73	73	82	91	61	75	83	91	62	56	83	91	62	55	90	98	81	93
HST25-1	90	96	74	82	83	93	64	80	83	93	64	63	82	93	65	61	82	67	57	96
HST27-1	86	94	64	90	82	94	68	93	82	93	67	85	81	92	65	83	70	65	38	71
HST28-1	89	97	71	88	83	94	70	83	83	94	71	68	82	94	70	66	77	68	48	89
HST28-9	82	88	53	65	79	90	57	91	79	89	57	84	78	88	55	86	65	60	29	51
HST29-1	81	88	55	62	79	90	59	89	79	89	58	80	78	88	57	82	64	59	29	49
HST30-1	89	97	72	89	83	94	72	83	83	94	72	68	82	94	71	67	77	68	48	88

Table H5. $U(3)O_2 - c_k, E_{sum}, G$ and R_{e2} (Cont'd)

U(3)O ₂ applications and experiments similarities – c _k , E _{sum} , G and R _{e2} in %																				
ICSBEPI Id	Mass				Volume				Cylinder				Slab				Concentration			
	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}
HST30-4	81	88	55	62	79	90	59	89	79	89	58	80	78	88	57	82	64	59	29	48
HST33-11A	73	83	49	46	73	86	53	77	73	86	53	59	72	84	52	61	60	58	27	36
HST33-11B	73	85	49	46	73	87	53	77	73	86	53	60	73	85	52	61	61	60	28	36
HST35-1	91	96	74	78	84	92	63	78	84	93	64	60	84	93	64	59	87	67	65	100
HST35-5	90	97	70	90	84	94	69	84	84	94	69	69	83	94	68	68	80	70	49	87
HST35-7	87	93	60	87	83	93	63	95	83	93	63	89	82	92	61	86	74	66	37	68
HST36-1	89	96	68	96	83	94	70	86	83	94	70	74	82	93	69	72	76	68	44	82
HST37-1	91	96	74	79	84	93	63	79	84	93	64	61	84	93	64	60	86	67	62	99
HST37-3	90	97	73	85	84	94	67	81	84	94	67	66	83	94	67	64	82	69	53	92
HST37-6	90	96	68	92	84	94	69	85	84	94	68	71	83	94	67	69	80	69	47	86
HST38-1	73	82	49	40	73	85	53	71	73	84	52	51	72	82	51	53	56	52	24	31
HST42-1	88	95	60	72	80	90	49	75	81	90	50	55	82	91	51	54	95	62	85	91
HST42-2	88	95	59	72	80	90	49	75	80	90	50	55	81	91	51	54	95	62	85	91
HST42-3	86	95	55	71	78	89	45	74	79	90	46	55	80	91	47	53	96	61	85	91
HST42-4	85	95	54	71	77	89	43	74	78	90	44	55	79	91	45	53	96	61	85	90
HST42-5	84	94	52	71	76	88	41	74	77	89	42	55	79	90	43	53	97	61	85	90
HST42-6	85	94	52	71	76	89	42	74	77	89	43	55	79	90	44	53	97	61	85	90
HST42-7	84	94	51	71	76	88	41	74	77	89	42	55	78	90	43	53	97	61	85	90
HST42-8	84	94	50	70	75	88	40	74	76	89	41	54	78	90	42	53	97	61	84	90
HST43-1	91	96	73	91	82	91	61	93	83	91	62	85	83	91	62	83	90	98	81	71
HST43-2	91	96	77	74	83	91	66	76	83	91	66	57	83	92	66	56	88	98	75	95
HST43-3	90	95	71	73	82	90	59	75	83	91	60	56	83	91	60	55	92	98	83	93
LCT01-1	98	98	79	79	97	98	75	100	97	98	76	98	97	98	79	96	92	67	63	62
LCT01-2	98	99	78	79	96	98	74	99	97	98	75	98	97	99	77	95	93	66	64	62
LCT02-1	98	97	73	73	96	97	73	96	96	97	75	94	96	97	77	97	88	62	54	57
LCT02-4	98	96	72	73	96	96	71	97	96	96	73	95	96	97	75	97	90	60	55	57
LCT13-1	94	93	66	45	97	95	72	76	97	95	73	58	97	96	74	60	83	59	45	35
LCT14-1	94	93	66	46	96	96	72	77	97	96	73	59	97	96	73	61	81	61	44	36
LCT14-6	89	88	61	34	94	93	68	66	94	93	69	44	95	93	69	45	76	57	39	27
LCT39-1	96	95	65	51	97	97	71	81	98	97	71	66	97	97	72	68	82	61	44	40
LCT49-1	72	65	46	17	81	73	54	46	81	73	54	22	83	72	54	22	60	42	29	13
LCT61-1	91	88	41	46	94	92	45	77	94	92	46	60	95	91	47	61	81	66	36	36
LCT70-1	79	80	55	19	86	86	62	50	86	86	63	25	87	86	64	26	65	45	33	15
LST01-1	99	99	82	99	96	98	76	88	96	98	77	76	96	98	78	74	90	70	64	79
LST03-1	92	98	85	82	87	94	75	80	87	95	75	63	87	94	74	62	87	68	73	96
LST03-2	92	98	83	80	87	94	73	79	87	94	73	62	87	94	73	60	88	68	76	98
LST03-3	92	97	83	80	87	94	72	79	87	94	72	62	87	94	72	60	89	67	76	98
LST03-4	92	97	78	80	86	93	67	79	86	93	67	61	87	93	69	60	90	67	77	98
LST03-5	91	97	74	77	85	92	63	77	85	93	64	59	86	93	65	58	92	66	84	98
LST03-6	91	97	73	76	85	92	62	77	85	93	63	59	86	93	64	57	93	66	84	97
LST03-7	90	96	68	76	84	91	57	77	84	91	58	59	85	92	60	57	93	65	85	97
LST03-8	89	95	66	75	82	91	55	77	83	91	56	58	84	92	58	56	94	64	89	96
LST03-9	88	96	65	75	82	91	54	76	83	92	55	58	84	92	57	56	94	65	89	96
LST07-1	90	97	81	83	85	94	70	81	85	94	70	64	85	94	71	63	86	69	71	94
LST07-2	89	97	78	82	84	94	67	80	85	94	68	63	85	94	69	62	86	69	73	96
LST07-3	89	97	75	81	84	94	64	79	84	94	65	62	84	94	66	61	87	68	75	97
LST07-4	88	97	73	80	83	94	62	79	83	94	63	62	84	94	65	60	87	68	77	98
LST07-5	88	97	70	79	82	93	60	79	82	93	61	61	83	94	62	60	87	68	77	99

Table H5. $U(3)O_2 - c_k, E_{sum}, G$ and R_{e2} (Cont'd)

U(3)O ₂ applications and experiments similarities – c _k , E _{sum} , G and R _{e2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}
LST16-1	94	98	82	92	90	97	74	85	90	97	74	71	90	96	75	69	86	71	63	85
LST16-2	94	98	81	90	90	96	72	84	90	96	73	69	90	96	73	67	87	71	65	88
LST16-3	93	98	79	86	89	96	68	82	89	96	69	66	89	96	70	65	88	71	68	91
LST16-4	93	98	77	85	88	95	66	81	89	95	67	65	89	95	68	64	89	70	69	92
LST16-5	93	98	76	84	88	95	65	81	88	96	66	65	88	96	67	63	90	70	71	94
LST16-6	92	98	74	83	87	95	63	80	88	95	64	64	88	95	65	62	90	70	72	95
LST16-7	92	98	73	82	87	95	62	80	87	95	63	63	88	95	64	62	90	69	73	96
LST17-1	93	98	78	92	89	96	70	85	90	96	71	71	89	96	72	69	86	71	63	85
LST17-2	93	98	78	90	89	96	69	84	89	96	70	69	89	96	71	68	86	71	64	87
LST17-3	93	98	77	86	88	95	66	82	89	95	67	66	89	95	68	65	88	70	68	91
LST17-4	93	98	76	85	88	95	65	81	88	96	66	66	88	96	67	64	88	70	69	92
LST17-5	93	98	75	84	88	95	64	81	88	95	65	65	88	95	66	63	89	69	71	94
LST17-6	92	97	74	83	87	94	63	80	87	95	64	64	88	95	65	62	89	69	72	94
LST20-1	91	97	73	79	86	94	62	78	86	94	63	61	87	94	64	59	91	68	79	100
LST20-2	91	97	71	78	85	93	60	78	85	93	61	60	86	94	62	58	92	67	81	99
LST20-3	90	97	67	77	84	92	57	77	84	93	57	59	85	93	59	58	93	66	84	98
LST20-4	89	97	65	76	83	92	54	77	84	93	55	59	84	93	57	57	93	66	85	97
LST21-1	91	97	69	79	85	94	59	78	86	94	59	61	86	94	61	59	91	68	79	99
LST21-2	91	97	68	78	85	93	57	78	85	93	58	60	86	94	59	59	92	67	81	99
LST21-3	90	97	65	77	83	93	54	77	84	93	55	59	85	93	57	58	93	66	83	98
LST21-4	89	97	63	76	83	93	53	77	83	93	54	59	84	93	55	57	93	66	85	97

UNH applications and uranium benchmarks

Figure H41. U(100)NH mass indices

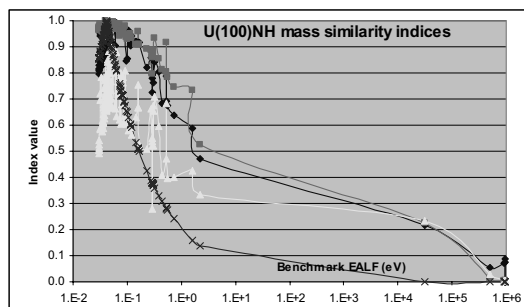


Figure H45. U(100)NH cylinder

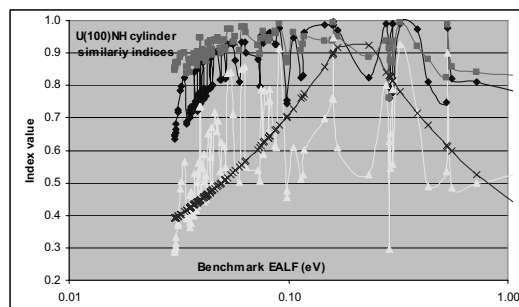


Figure H42. U(100)NH mass, enlarged

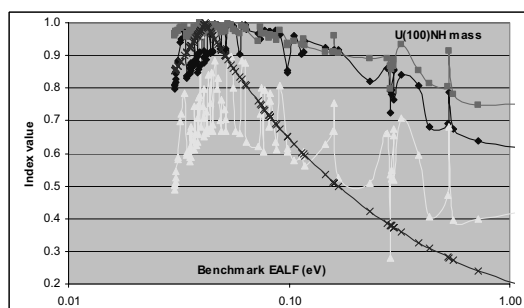


Figure H46. U(100)NH slab

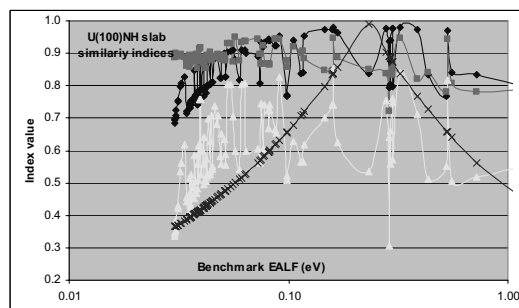


Figure H43. U(100)NH volume indices

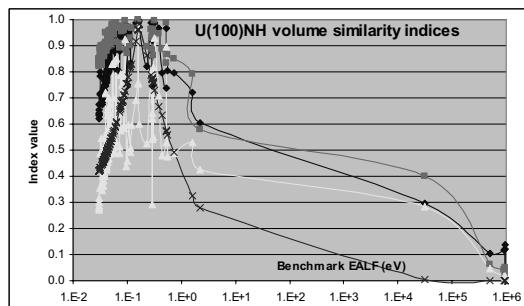


Figure H47. U(100)NH concentration

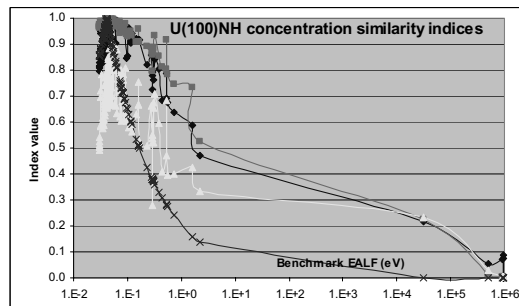


Figure H44. U(100)NH volume, enlarged

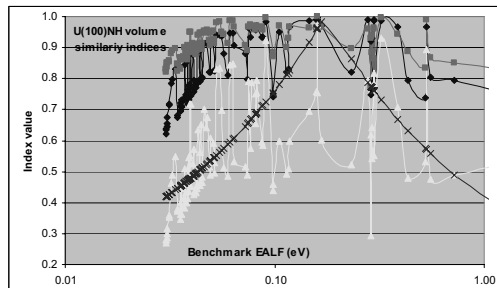


Figure H48. U(100)NH concentration

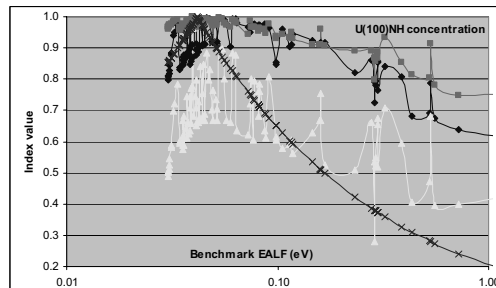


Table H6. U(100)NH – c_k , E_{sum} , G and R_{e2}

U(100)NH applications and experiments similarities – c_k , E_{sum} , G and R_{e2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}
HMF01-1	7	0	0	0	12	4	1	0	12	5	2	0	13	5	2	0	10	0	0	0
HMF04-1	22	23	23	0	30	40	28	0	30	41	29	0	32	43	30	0	19	14	8	0
HMF08-1	7	0	0	0	12	4	1	0	12	5	2	0	13	5	2	0	10	0	0	0
HMF15-1	9	0	0	0	14	5	1	0	14	6	2	0	16	6	2	0	12	0	0	0
HMF18-1	7	0	0	0	12	4	1	0	12	5	2	0	13	5	2	0	10	0	0	0
HMF20-1	5	1	3	0	10	6	4	0	11	7	5	0	13	7	5	0	11	0	1	0
HMF65-1	9	0	0	0	14	5	1	0	14	6	2	0	16	6	2	0	12	0	0	0
HCT11-1	64	75	40	24	80	85	49	49	81	84	50	52	83	78	52	56	52	62	22	21
HCT11-2	67	78	40	27	80	87	48	56	82	86	49	60	84	81	51	64	56	68	25	23
HCT11-3	68	81	41	31	79	89	48	63	81	88	49	68	83	84	51	73	59	73	27	27
HMT11-1	94	93	56	59	97	97	60	83	96	95	60	77	95	88	62	72	70	80	29	51
HMT11-3	97	97	61	73	93	97	57	67	93	97	59	62	92	92	61	58	77	88	36	63
HMT11-5	98	98	63	81	91	97	53	61	90	96	55	57	90	94	60	53	82	92	43	69
HMT11-7	98	97	67	85	88	94	51	58	88	95	53	54	88	95	60	50	86	95	49	73
HMT11-35	92	91	52	50	97	97	60	98	97	95	61	92	96	89	62	86	68	76	26	43
HMT11-37	96	94	58	63	95	97	60	78	95	96	61	73	94	92	63	68	74	85	33	54
HMT11-39	97	95	61	69	93	96	59	71	93	96	61	67	92	94	66	62	79	88	37	59
HMT11-41	97	94	62	76	88	91	51	65	88	93	54	60	89	94	60	56	88	93	50	65
HMT11-43	98	96	63	69	93	97	60	71	93	97	62	66	92	94	66	62	79	89	38	59
HST01-1	97	96	76	71	97	96	76	69	96	94	75	64	94	86	72	60	70	84	34	61
HST01-2	86	89	66	39	99	96	79	79	99	94	80	84	98	84	75	90	56	64	22	33
HST01-3	97	96	76	72	97	97	75	68	96	95	75	64	94	87	72	59	70	85	34	61
HST01-4	85	88	65	37	99	96	78	76	99	93	79	81	98	83	75	87	56	63	22	32
HST01-5	99	99	84	98	90	94	63	50	89	93	65	47	88	89	70	43	81	96	54	84
HST01-6	99	99	85	97	91	95	65	51	90	94	67	47	88	89	71	44	80	95	51	83
HST01-7	98	97	79	73	97	97	79	67	96	95	78	63	93	87	74	58	70	85	35	63
HST01-8	97	96	78	71	97	97	79	69	96	95	79	64	94	87	74	60	69	84	34	61
HST01-9	86	89	67	37	99	96	82	76	99	94	82	81	98	84	76	87	56	63	22	32
HST01-10	100	99	88	95	91	95	70	52	90	94	72	48	89	89	74	45	79	95	50	81
HST09-1	79	92	68	28	97	99	89	57	98	99	90	61	97	94	82	66	50	74	22	24
HST09-2	84	94	71	36	99	100	93	73	99	99	93	78	98	95	84	84	55	78	24	31
HST09-3	92	96	76	51	100	100	97	96	100	99	95	90	98	95	86	84	61	83	29	44
HST09-4	97	98	81	68	98	100	93	73	98	99	91	68	95	94	83	63	67	87	34	58
HST10-1	99	100	90	89	94	98	83	55	93	97	84	52	90	93	80	48	73	93	43	76
HST10-2	99	99	90	87	94	98	83	56	93	98	84	53	91	93	80	49	73	93	43	75
HST10-3	99	99	88	83	95	99	84	59	93	98	85	55	91	93	81	52	73	91	42	71
HST10-4	99	99	88	81	95	99	85	60	94	98	86	56	91	94	81	53	72	91	42	69
HST11-1	100	100	96	98	90	95	72	48	89	95	74	45	87	92	76	42	80	97	57	88
HST11-1	100	100	96	97	90	95	72	48	89	95	73	45	87	92	76	42	80	97	57	88
HST12-1	95	99	72	88	80	89	49	43	80	90	51	40	81	90	56	38	93	99	81	97
HST25-1	98	99	74	99	88	91	53	48	87	91	54	45	87	89	60	42	84	97	57	87
HST27-1	98	97	80	75	96	97	79	66	95	94	79	61	93	87	74	57	70	86	36	64
HST28-1	99	99	80	94	91	95	64	52	90	94	66	49	89	89	68	45	78	94	47	80
HST28-9	92	91	63	53	99	96	69	92	99	94	70	86	97	85	70	80	65	73	26	46
HST29-1	91	91	67	51	99	96	76	96	99	94	76	90	97	84	74	83	64	72	26	44
HST30-1	99	99	83	93	92	96	67	53	91	95	69	49	89	90	71	46	78	94	47	80

Table H6. U(100)NH – c_k , E_{sum} , G and R_{e2} (Cont'd)

U(100)NH applications and experiments similarities – c_k , E_{sum} , G and R_{e2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}
HST30-4	92	91	67	51	99	96	75	96	99	94	76	90	97	85	74	84	64	72	26	44
HST33-11A	80	86	55	38	93	94	64	77	94	92	65	82	94	83	66	88	59	69	24	32
HST33-11B	79	87	54	38	92	93	62	78	93	91	63	83	94	84	64	89	60	73	26	33
HST35-1	97	99	74	95	85	90	51	46	84	90	53	43	85	88	58	40	89	98	65	90
HST35-5	98	99	77	92	91	95	61	53	90	94	62	50	89	89	65	47	81	94	48	79
HST35-7	96	95	68	72	96	96	66	68	95	94	66	64	94	87	67	59	74	85	35	61
HST36-1	99	98	80	86	94	95	70	57	93	93	71	53	91	87	70	50	76	92	43	74
HST37-1	98	99	74	96	86	91	51	47	85	90	53	44	85	89	58	41	88	98	62	89
HST37-3	98	99	76	97	89	95	56	51	88	94	58	47	88	90	63	44	84	96	52	83
HST37-6	98	99	73	90	91	95	59	54	91	94	61	51	90	89	64	47	81	93	46	77
HST38-1	81	85	60	33	97	95	71	67	97	92	72	71	97	82	71	77	55	61	21	28
HST42-1	88	98	59	87	72	86	36	43	72	87	37	40	76	89	43	37	98	100	89	99
HST42-2	88	97	58	87	71	86	35	43	72	87	37	40	75	89	42	37	98	100	89	99
HST42-3	84	97	54	86	67	85	32	42	68	87	33	39	72	90	38	37	99	100	93	100
HST42-4	83	97	53	86	66	85	30	42	67	87	31	39	71	90	37	37	100	100	95	100
HST42-5	81	97	50	86	64	83	28	42	65	85	30	39	70	89	35	37	100	100	97	100
HST42-6	82	97	51	86	64	84	29	42	65	86	30	39	70	89	35	37	100	100	96	100
HST42-7	81	97	50	85	63	83	28	42	65	85	29	39	69	89	35	37	100	100	97	100
HST42-8	80	96	49	85	62	82	27	42	63	85	29	39	68	89	34	36	100	100	98	100
HST43-1	95	99	72	75	80	89	49	65	80	90	51	61	81	90	56	57	93	99	81	64
HST43-2	97	99	78	90	83	90	55	44	82	90	57	41	83	89	62	38	90	99	75	95
HST43-3	94	98	70	88	78	88	46	43	78	89	48	40	80	89	54	38	94	100	83	97
LCT01-1	85	93	61	65	75	87	46	76	75	87	48	71	77	86	52	66	86	92	51	56
LCT01-2	85	94	61	65	74	88	44	75	75	89	46	70	77	88	51	65	86	92	52	56
LCT02-1	91	95	60	60	83	93	51	82	83	93	53	76	84	91	57	71	84	91	44	51
LCT02-4	90	93	59	60	82	90	49	81	82	91	51	76	84	90	56	71	85	91	44	52
LCT13-1	76	87	52	37	77	86	55	76	78	87	56	81	80	86	57	87	74	84	34	32
LCT14-1	78	87	52	38	78	88	54	77	79	88	55	83	80	83	56	89	72	81	32	32
LCT14-6	69	80	47	28	74	83	53	57	75	82	54	61	77	78	55	66	64	73	27	24
LCT39-1	82	89	51	42	82	90	52	86	83	89	53	92	84	85	54	99	73	83	33	36
LCT49-1	47	53	33	14	60	58	42	28	62	57	43	30	65	51	44	32	45	45	18	12
LCT61-1	73	80	28	38	75	78	29	78	76	76	30	83	79	72	31	89	71	75	27	33
LCT70-1	59	73	43	16	72	79	53	33	74	79	54	35	76	76	56	37	53	67	22	14
LST01-1	90	97	66	83	81	91	49	59	81	91	50	55	82	88	54	51	84	94	52	71
LST03-1	91	98	80	99	79	90	57	49	79	89	59	45	79	87	64	42	85	97	66	86
LST03-2	91	98	78	97	78	90	55	48	78	90	57	44	78	88	62	41	87	98	69	88
LST03-3	91	98	77	97	78	90	55	47	77	90	56	44	78	89	61	41	87	98	69	89
LST03-4	90	97	71	96	77	86	48	47	76	86	50	44	78	85	56	41	89	98	70	89
LST03-5	88	97	68	93	73	86	45	46	73	87	47	43	75	87	52	40	91	99	78	92
LST03-6	87	97	67	93	72	87	44	45	73	87	46	42	75	87	52	40	92	99	79	93
LST03-7	86	96	62	92	71	83	40	45	71	84	42	42	74	86	47	39	93	99	79	93
LST03-8	84	96	60	91	68	82	38	45	69	84	40	42	72	86	46	39	94	99	84	94
LST03-9	83	97	59	91	67	85	37	45	68	86	39	42	71	88	44	39	94	99	85	94
LST07-1	89	97	73	99	77	88	50	49	77	87	52	46	78	85	58	43	84	97	64	85
LST07-2	88	97	71	99	76	88	48	49	76	88	50	45	77	87	56	42	85	97	66	86
LST07-3	87	98	68	98	75	89	45	48	75	89	47	45	76	88	53	42	86	98	68	88
LST07-4	86	98	66	97	73	89	44	47	73	89	45	44	75	88	51	41	86	98	70	89
LST07-5	85	97	64	96	72	87	41	47	72	87	43	44	74	87	48	41	87	98	71	89

Table H6. U(100)NH – c_k , E_{sum} , G and R_{e2} (Cont'd)

U(100)NH applications and experiments similarities – c_k , E_{sum} , G and R_{e2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}
LST16-1	92	98	70	90	83	93	53	55	82	92	55	51	83	88	59	47	83	95	54	77
LST16-2	92	98	70	92	82	92	52	53	82	92	53	50	82	88	58	46	84	96	56	79
LST16-3	91	98	69	96	80	91	48	51	80	91	50	48	81	89	55	45	86	97	60	82
LST16-4	91	98	68	97	79	90	46	50	79	90	48	47	80	88	54	44	87	97	62	83
LST16-5	91	98	68	99	79	91	45	50	79	91	47	46	80	89	53	43	88	97	63	85
LST16-6	90	98	66	100	77	90	44	49	78	90	45	46	79	88	51	43	88	98	65	85
LST16-7	89	98	65	99	77	89	43	49	77	89	44	46	79	88	50	42	89	98	66	86
LST17-1	91	97	67	90	82	91	50	55	82	91	51	51	83	88	56	48	83	95	53	77
LST17-2	92	97	67	92	82	91	49	53	82	90	51	50	83	88	56	46	84	95	55	79
LST17-3	91	97	67	96	80	89	47	51	80	89	48	48	81	88	54	44	86	97	60	82
LST17-4	91	98	67	97	80	91	45	50	80	91	47	47	81	90	53	44	87	97	60	83
LST17-5	91	98	67	99	79	89	45	50	79	89	46	46	80	88	52	43	87	97	63	85
LST17-6	90	97	66	100	78	88	43	49	78	88	45	46	80	88	50	43	88	98	64	85
LST20-1	89	98	66	95	75	89	43	47	75	90	45	44	77	89	50	41	90	98	72	90
LST20-2	88	97	64	94	74	87	41	46	74	88	43	43	76	88	48	40	91	99	75	91
LST20-3	86	97	61	93	71	86	38	46	72	87	40	43	74	88	45	40	92	99	78	92
LST20-4	85	97	59	92	70	86	36	45	70	87	38	42	73	89	43	39	93	99	80	93
LST21-1	88	98	63	96	74	89	40	47	75	89	42	44	77	90	47	41	90	99	72	90
LST21-2	87	97	61	94	73	86	38	46	73	87	40	43	76	88	45	40	91	99	75	91
LST21-3	86	97	59	93	71	86	36	46	71	87	38	43	74	89	43	40	92	99	78	92
LST21-4	84	98	57	92	69	87	35	45	70	88	36	42	73	90	42	39	93	99	80	93

Figure H49. U(20)NH mass indices

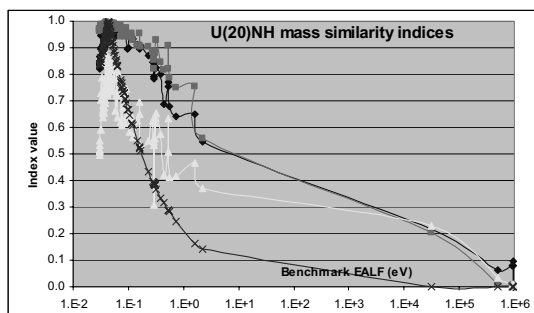


Figure H53. U(20)NH cylinder

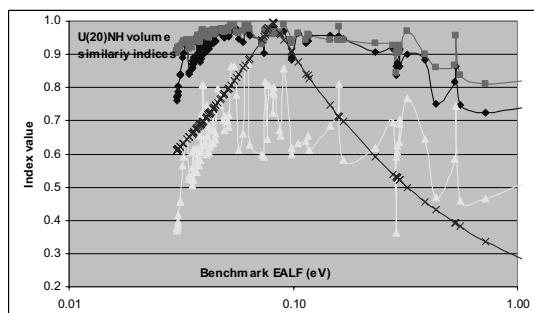


Figure H50. U(20)NH mass, enlarged

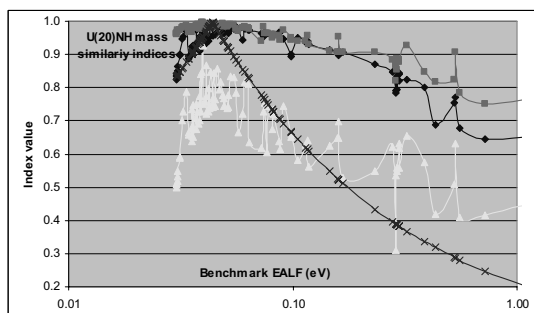


Figure H54. U(20)NH slab

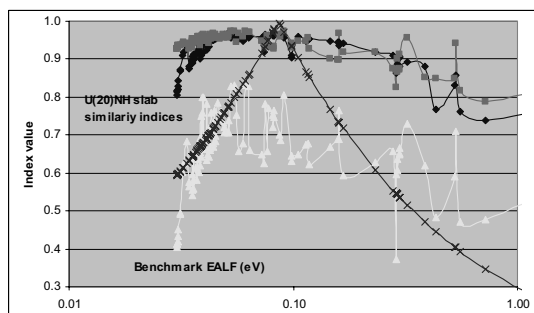


Figure H51. U(20)NH volume indices

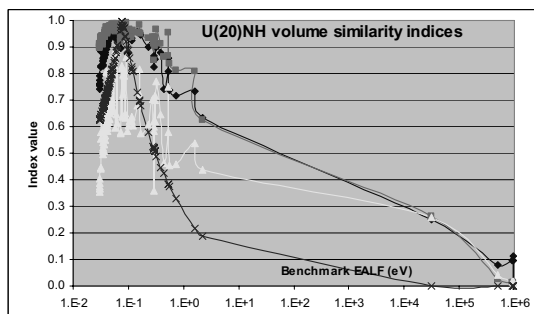


Figure H55. U(20)NH concentration

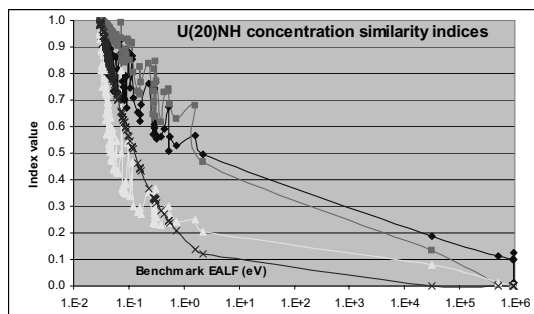


Figure H52. U(20)NH volume, enlarged

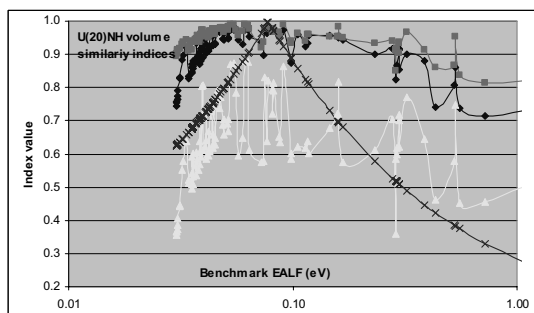


Figure H56. U(20)NH concentration

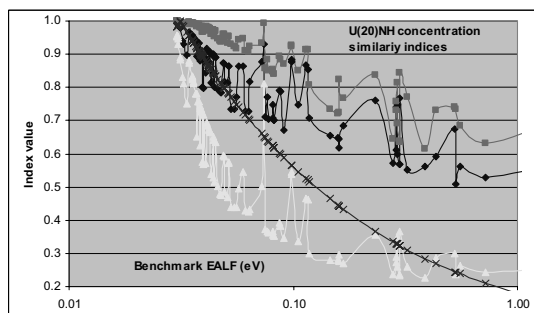


Table H7. U(20)NH – c_k , E_{sum} , G and R_{e2}

U(20)NH applications and experiments similarities – c_k , E_{sum} , G and R_{e2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}
HMF01-1	8	0	1	0	9	1	2	0	10	1	1	0	11	1	1	0	10	0	0	0
HMF04-1	22	20	23	0	25	26	26	0	25	27	27	0	26	28	28	0	19	14	8	0
HMF08-1	8	0	1	0	9	1	2	0	10	1	2	0	11	1	1	0	10	0	0	0
HMF15-1	10	0	1	0	11	1	1	0	12	1	1	0	13	2	1	0	12	0	0	0
HMF18-1	8	0	1	0	9	1	2	0	10	1	2	0	11	1	1	0	10	0	0	0
HMF20-1	6	1	3	0	8	3	4	0	8	3	4	0	10	3	4	0	11	0	1	0
HMF65-1	10	0	1	0	11	1	1	0	12	1	1	0	13	2	1	0	12	0	0	0
HCT11-1	64	75	41	25	72	81	46	33	73	81	47	34	74	79	48	35	53	63	24	21
HCT11-2	68	79	41	28	74	84	45	37	75	84	46	38	76	82	47	39	56	68	26	24
HCT11-3	69	82	42	32	74	86	46	42	75	86	47	43	77	85	48	45	59	73	29	27
HMT11-1	93	93	56	61	96	96	60	81	96	96	61	83	95	93	62	85	71	81	30	52
HMT11-3	96	96	61	75	96	98	64	100	96	98	64	97	96	96	66	95	77	88	36	64
HMT11-5	97	98	64	83	96	98	61	91	96	98	63	89	96	97	66	86	82	92	43	70
HMT11-7	97	97	66	87	94	96	59	86	95	96	61	84	95	97	66	82	86	94	50	74
HMT11-35	91	91	53	51	94	95	57	68	95	95	58	70	94	92	59	72	68	77	27	43
HMT11-37	95	94	58	64	96	96	62	86	96	96	63	88	96	95	65	90	75	85	34	55
HMT11-39	97	94	62	70	96	95	63	94	96	96	66	96	96	69	99	99	79	88	38	60
HMT11-41	96	94	62	78	94	92	58	96	94	93	60	94	96	95	65	92	88	93	50	66
HMT11-43	97	96	64	71	96	97	65	94	96	97	67	97	96	96	70	99	79	89	39	60
HST01-1	96	96	72	73	98	97	79	97	97	96	78	99	96	93	75	98	70	84	35	62
HST01-2	85	88	62	40	92	94	71	53	92	93	69	54	91	88	66	55	57	65	24	34
HST01-3	96	96	72	74	98	98	79	98	98	97	79	100	96	93	75	97	71	85	35	62
HST01-4	84	88	62	38	91	94	70	51	91	92	69	52	91	87	65	54	57	64	24	32
HST01-5	99	99	85	99	96	97	73	74	96	97	74	73	96	95	76	71	81	96	54	85
HST01-6	99	99	84	99	97	98	74	76	97	97	75	74	96	96	76	72	80	95	52	84
HST01-7	96	96	74	75	98	98	82	100	98	97	81	98	96	93	77	95	71	85	36	64
HST01-8	96	96	74	73	98	98	81	97	98	97	80	99	96	93	77	98	70	84	35	62
HST01-9	84	88	63	38	92	94	72	51	92	93	71	52	91	88	67	54	57	64	23	32
HST01-10	99	99	86	97	97	98	79	77	97	97	80	75	96	96	79	73	79	95	50	82
HST09-1	77	91	63	29	86	95	75	38	86	96	74	39	86	94	71	40	51	73	24	24
HST09-2	82	93	66	37	90	97	77	49	90	97	77	50	89	96	73	51	55	77	26	31
HST09-3	90	95	70	52	95	98	82	70	95	98	81	71	94	97	77	73	62	82	30	44
HST09-4	95	97	75	69	97	99	86	92	97	99	86	94	96	97	81	97	67	87	35	59
HST10-1	98	99	83	91	97	99	87	83	97	99	86	81	96	97	83	78	74	93	44	77
HST10-2	98	99	83	89	97	99	87	84	97	99	87	82	96	97	83	80	73	93	44	76
HST10-3	98	98	82	85	97	99	88	89	97	99	87	87	96	97	83	84	73	91	43	72
HST10-4	97	98	81	83	97	99	88	90	97	99	87	88	96	97	83	86	73	91	42	70
HST11-1	99	100	93	95	96	97	81	72	96	97	81	70	95	96	80	68	80	97	57	89
HST11-1	99	100	93	95	96	97	81	71	96	97	81	70	95	96	80	68	80	97	57	89
HST12-1	95	98	73	86	90	94	58	65	90	94	59	63	92	94	63	61	93	99	81	99
HST25-1	98	98	76	96	95	96	62	72	95	96	64	71	95	95	67	69	84	97	57	88
HST27-1	97	97	75	77	98	98	83	98	98	97	82	96	97	93	78	93	71	86	37	65
HST28-1	98	99	79	96	97	98	74	78	97	97	75	76	96	95	74	74	79	94	48	82
HST28-9	91	91	63	55	96	95	68	73	96	94	68	75	95	90	67	77	65	73	28	46
HST29-1	91	91	65	52	95	95	72	70	96	94	72	71	95	90	69	74	65	72	28	44
HST30-1	98	99	82	96	97	98	77	79	97	98	78	77	96	96	76	75	78	94	47	81

Table H7. U(20)NH – c_k , E_{sum} , G and R_{e2} (Cont'd)

U(20)NH applications and experiments similarities – c_k , E_{sum} , G and R_{e2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}
HST30-4	91	91	65	52	95	95	72	70	95	94	72	71	95	90	69	73	65	73	28	44
HST33-11A	79	86	55	39	86	91	60	52	87	90	60	53	87	87	61	54	60	69	26	33
HST33-11B	79	87	53	39	86	91	58	52	86	91	59	53	87	87	60	55	61	73	27	33
HST35-1	97	99	75	92	93	95	60	69	94	95	62	68	95	94	66	66	89	98	65	92
HST35-5	98	99	77	94	96	98	70	80	96	97	72	78	96	96	72	76	82	94	49	80
HST35-7	96	95	67	74	97	97	72	98	97	96	73	100	97	93	72	97	75	85	36	62
HST36-1	98	98	78	88	98	97	78	85	98	97	78	83	97	94	75	81	77	92	44	75
HST37-1	98	99	75	94	94	95	60	70	94	95	62	69	95	95	66	67	88	98	62	91
HST37-3	98	99	77	99	96	98	66	76	96	97	67	74	96	96	70	72	84	96	53	84
HST37-6	98	98	74	92	97	98	69	81	97	97	70	79	97	96	71	77	81	93	47	78
HST38-1	80	85	58	34	88	91	64	45	88	90	64	46	88	85	62	47	56	62	23	28
HST42-1	90	97	59	85	83	92	45	64	84	92	46	62	87	93	50	60	98	100	88	100
HST42-2	90	97	59	85	83	92	44	64	84	92	45	62	87	93	49	60	98	100	89	100
HST42-3	87	97	55	84	79	91	41	63	80	92	42	62	84	94	45	60	99	100	93	99
HST42-4	85	97	53	84	77	91	39	63	79	92	40	61	83	94	43	60	99	100	95	99
HST42-5	84	96	51	83	76	90	37	63	77	91	38	61	82	93	41	60	99	100	95	98
HST42-6	84	97	52	84	76	90	37	63	78	91	39	61	82	93	42	60	99	100	95	99
HST42-7	83	96	51	83	75	90	37	63	77	91	38	61	81	93	41	59	100	100	96	98
HST42-8	82	96	50	83	74	89	36	63	76	90	37	61	80	93	40	59	100	100	95	98
HST43-1	95	98	73	77	90	94	58	98	90	94	59	95	92	94	63	93	93	99	81	65
HST43-2	97	99	79	88	92	94	64	66	92	94	65	64	93	94	68	63	90	99	75	97
HST43-3	95	98	70	86	89	93	55	64	89	93	57	63	91	94	60	61	94	99	83	99
LCT01-1	90	94	66	67	88	93	60	89	89	93	62	91	91	93	64	93	88	92	54	56
LCT01-2	89	95	65	67	87	94	58	89	88	94	60	91	90	94	63	94	88	93	54	57
LCT02-1	94	96	64	61	93	96	64	82	94	96	65	84	95	96	68	86	85	91	46	52
LCT02-4	94	94	63	62	92	94	62	82	93	94	64	84	95	95	67	87	87	91	47	52
LCT13-1	82	88	56	38	85	90	62	51	86	91	63	52	88	91	65	54	77	84	37	32
LCT14-1	83	89	56	39	87	92	62	52	87	92	63	53	89	90	64	54	75	81	35	33
LCT14-6	75	82	51	29	81	87	58	38	82	87	58	39	83	85	59	40	68	74	30	24
LCT39-1	87	91	55	43	90	93	61	58	91	93	62	59	92	92	63	61	76	84	36	37
LCT49-1	55	56	37	14	63	62	44	19	65	62	44	19	67	59	44	20	50	47	20	12
LCT61-1	79	82	31	39	82	85	36	52	84	85	36	53	86	83	37	55	74	76	29	33
LCT70-1	65	75	46	16	73	81	54	22	75	81	55	22	76	80	55	23	56	68	25	14
LST01-1	94	98	72	85	93	97	65	88	94	97	66	86	95	96	68	83	86	95	54	72
LST03-1	96	99	87	97	93	96	73	73	94	96	75	71	95	95	78	69	88	98	69	88
LST03-2	96	99	85	95	92	96	71	71	93	96	72	69	94	95	76	67	90	98	73	90
LST03-3	96	99	84	94	92	96	70	71	92	96	72	69	94	96	75	67	90	98	73	90
LST03-4	95	98	78	94	91	94	64	71	92	94	65	69	93	94	69	67	91	98	74	90
LST03-5	93	98	75	91	88	94	60	68	89	94	61	67	91	94	65	65	94	99	81	93
LST03-6	92	98	73	90	87	94	59	68	88	94	60	66	91	94	64	64	95	99	82	94
LST03-7	91	97	68	90	86	92	54	68	87	92	56	66	90	93	60	64	95	99	83	94
LST03-8	89	97	67	89	84	91	52	67	85	92	53	65	88	93	57	63	96	100	87	96
LST03-9	89	98	66	89	83	92	51	66	84	93	53	65	87	94	56	63	97	100	88	96
LST07-1	94	98	80	98	91	95	67	74	92	95	68	72	93	94	72	70	88	97	67	86
LST07-2	93	98	78	97	90	95	64	73	91	95	66	71	93	95	70	69	88	98	69	88
LST07-3	93	99	75	95	89	96	61	72	90	96	62	70	92	95	66	68	89	98	72	89
LST07-4	92	99	73	94	88	95	59	71	89	96	61	69	91	95	64	67	90	98	73	90
LST07-5	91	98	70	94	87	94	57	70	88	95	58	69	90	95	62	67	90	98	74	91

Table H7. U(20)NH – c_k , E_{sum} , G and R_{e2} (Cont'd)

U(20)NH applications and experiments similarities – c_k , E_{sum} , G and R_{e2} in %																				
ICSBE Id	Mass				Volume				Cylinder				Slab				Concentration			
	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}
LST16-1	97	99	78	92	95	98	70	81	96	98	72	80	97	97	74	77	86	95	58	78
LST16-2	97	99	78	94	95	98	69	79	95	98	70	78	96	97	73	76	87	96	60	80
LST16-3	96	99	76	98	93	97	65	76	94	97	66	75	96	96	70	73	89	97	64	83
LST16-4	96	99	75	100	93	97	63	75	93	97	64	74	95	96	68	71	90	98	65	85
LST16-5	95	99	75	99	92	97	62	74	93	97	63	73	95	97	67	70	91	98	67	86
LST16-6	95	99	73	98	91	96	60	73	92	96	61	72	94	96	65	70	91	98	69	87
LST16-7	94	99	72	97	91	96	58	73	92	96	60	71	94	96	63	69	92	98	70	87
LST17-1	96	99	74	92	95	97	67	82	95	97	68	80	96	96	71	78	86	95	57	78
LST17-2	96	98	74	94	94	97	66	80	95	97	67	78	96	96	71	76	87	96	59	80
LST17-3	96	98	74	98	93	96	63	76	94	96	64	75	95	96	68	73	89	97	63	83
LST17-4	96	99	74	100	93	97	62	75	94	97	63	74	95	97	67	72	90	97	64	85
LST17-5	96	99	74	99	92	96	61	74	93	96	62	73	95	96	66	70	90	98	66	86
LST17-6	95	98	73	98	92	95	59	74	92	95	61	72	94	95	64	70	91	98	68	86
LST20-1	94	99	73	93	89	96	59	70	90	96	60	68	93	96	64	66	93	99	76	91
LST20-2	93	98	71	92	88	94	56	69	89	94	58	67	92	95	61	66	94	99	78	92
LST20-3	91	98	68	91	86	94	53	68	87	94	54	67	90	95	58	65	95	99	82	94
LST20-4	90	98	65	90	85	94	51	68	86	94	52	66	89	95	56	64	96	99	83	94
LST21-1	93	99	69	93	89	95	55	70	90	96	56	68	92	96	60	66	93	99	76	91
LST21-2	92	98	68	92	88	94	53	69	89	94	55	68	91	95	58	66	94	99	78	92
LST21-3	91	98	65	91	86	94	51	68	87	94	52	67	90	95	56	65	95	99	81	93
LST21-4	90	98	64	90	85	94	49	68	86	95	51	66	89	95	54	64	96	99	83	94

Figure H57. U(5)NH mass indices

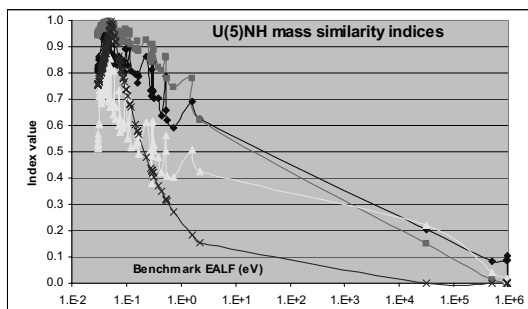


Figure H61. U(5)NH cylinder

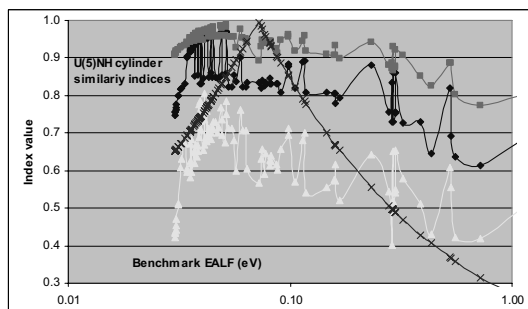


Figure H58. U(5)NH mass, enlarged

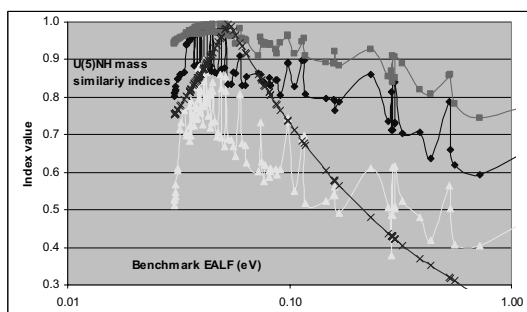


Figure H62. U(5)NH slab

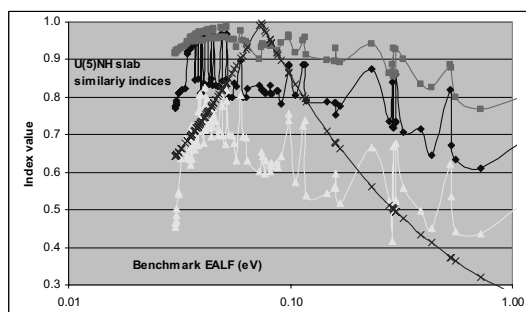


Figure H59. U(5)NH volume indices

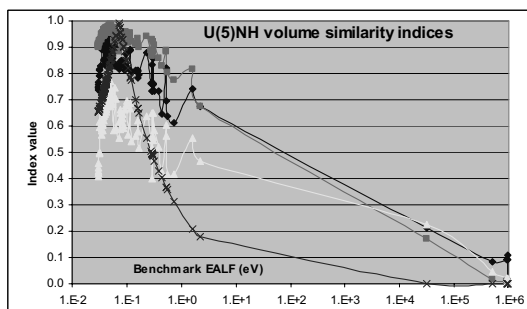


Figure H63. U(5)NH concentration

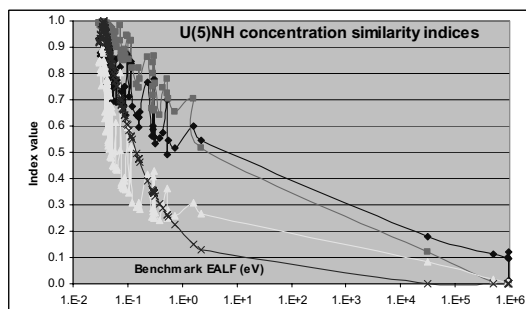


Figure H60. U(5)NH volume, enlarged

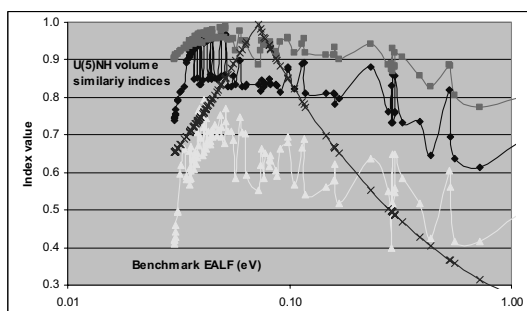


Figure H64. U(5)NH concentration

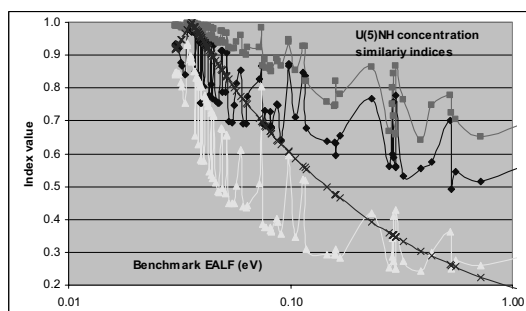


Table H8. U(5)NH – c_k , E_{sum} , G and R_{e2}

U(5)NH applications and experiments similarities – c_k , E_{sum} , G and R_{e2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}
HMF01-1	9	0	1	0	9	1	2	0	9	1	2	0	10	1	1	0	10	0	1	0
HMF04-1	20	15	22	0	21	17	23	0	21	17	23	0	21	16	24	0	18	12	8	0
HMF08-1	9	0	2	0	9	1	2	0	9	1	2	0	10	1	2	0	10	0	1	0
HMF15-1	11	0	1	0	11	1	1	0	11	1	1	0	12	1	1	0	12	0	0	0
HMF18-1	9	0	2	0	9	1	2	0	9	1	2	0	10	1	2	0	10	0	1	0
HMF20-1	8	1	4	0	8	2	4	0	9	2	4	0	10	1	5	0	11	0	2	0
HMF65-1	11	0	1	0	11	1	1	0	11	1	1	0	12	1	1	0	12	0	0	0
HCT11-1	59	74	40	27	61	77	42	31	61	77	42	31	61	77	44	32	52	65	26	22
HCT11-2	62	78	41	31	64	80	42	36	64	80	42	36	63	80	44	36	54	70	28	26
HCT11-3	64	81	42	35	65	83	42	41	65	83	43	41	65	83	45	41	57	75	30	29
HMT11-1	81	91	52	67	81	92	54	77	81	92	54	78	79	91	54	79	68	82	31	55
HMT11-3	84	94	58	83	83	94	59	96	83	94	59	96	81	94	60	98	73	89	37	68
HMT11-5	85	95	63	91	83	94	59	95	83	94	61	95	82	94	63	93	78	92	44	75
HMT11-7	86	94	64	96	84	92	59	90	84	93	60	90	83	93	63	88	81	94	50	79
HMT11-35	79	88	49	57	80	90	52	65	79	90	52	65	78	89	52	66	66	78	28	46
HMT11-37	83	92	55	71	82	92	57	82	82	92	57	82	80	92	57	84	71	85	35	58
HMT11-39	84	92	59	78	83	91	59	90	83	91	60	90	82	92	61	91	75	88	39	64
HMT11-41	86	91	60	86	83	89	55	99	84	89	57	100	83	90	60	99	83	92	51	71
HMT11-43	85	93	61	78	83	92	61	90	83	92	62	91	82	92	63	92	75	89	40	64
HST01-1	83	94	60	81	83	94	63	93	83	94	63	93	81	93	62	95	68	85	36	66
HST01-2	73	86	51	44	76	89	55	50	76	88	54	51	74	86	53	51	56	67	25	36
HST01-3	83	94	60	81	84	95	63	94	83	94	63	94	81	94	62	95	69	86	37	67
HST01-4	73	85	50	42	76	88	55	49	75	88	54	49	73	86	52	50	56	66	25	35
HST01-5	87	97	75	90	85	95	71	78	85	96	71	78	83	96	72	77	78	96	55	91
HST01-6	87	97	73	91	85	96	71	79	85	96	72	79	83	96	72	78	77	95	52	90
HST01-7	84	95	62	83	84	95	65	96	83	95	65	96	81	94	63	97	68	86	38	68
HST01-8	83	94	61	81	84	95	65	93	83	94	64	93	81	94	63	94	68	85	36	66
HST01-9	73	85	51	42	76	89	56	49	76	88	55	49	73	86	53	50	56	66	25	35
HST01-10	87	97	74	93	85	96	73	81	85	96	73	80	83	96	73	79	76	95	51	88
HST09-1	66	86	50	32	70	89	56	37	69	89	56	37	67	88	54	37	49	72	25	26
HST09-2	70	89	52	41	73	91	58	47	73	91	58	47	71	90	56	48	53	76	27	33
HST09-3	76	92	56	58	78	93	62	67	78	93	62	67	75	93	60	68	59	82	31	47
HST09-4	80	94	61	77	81	95	66	88	81	95	66	89	78	95	64	90	64	87	36	63
HST10-1	83	96	69	99	83	95	71	86	82	96	71	86	80	95	70	85	70	92	45	83
HST10-2	83	96	69	99	83	95	71	88	82	96	71	88	80	95	70	86	70	92	45	81
HST10-3	83	96	68	94	83	95	71	93	82	95	71	92	80	95	69	91	69	91	44	77
HST10-4	83	95	67	92	83	95	70	94	82	95	71	94	80	95	69	93	69	90	44	75
HST11-1	85	97	76	86	83	95	73	75	83	95	73	74	81	95	72	73	75	96	58	95
HST11-1	85	97	76	86	83	95	73	74	83	95	73	74	81	95	72	73	75	96	58	96
HST12-1	86	96	73	78	82	92	62	68	82	93	63	67	82	93	66	66	87	98	81	95
HST25-1	87	97	73	87	85	95	64	76	85	95	66	75	84	95	68	74	80	97	58	94
HST27-1	84	95	63	85	85	95	66	98	84	95	66	98	82	94	64	99	69	87	38	69
HST28-1	86	97	69	94	85	96	70	82	85	96	70	81	83	96	70	80	75	94	49	87
HST28-9	80	89	53	61	81	91	56	70	81	91	56	70	79	90	54	71	64	76	29	50
HST29-1	79	89	54	58	81	91	58	67	81	91	57	67	79	90	56	68	63	75	29	48
HST30-1	86	97	71	95	85	96	71	82	85	96	71	82	83	96	71	81	75	94	48	87

Table H8. U(5)NH – c_k , E_{sum} , G and R_{e2} (Cont'd)

U(5)NH applications and experiments similarities – c_k , E_{sum} , G and R_{e2} in %																				
ICSBE Id	Mass				Volume				Cylinder				Slab				Concentration			
	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}
HST30-4	79	89	54	58	81	91	58	67	80	91	57	67	78	90	56	68	63	75	29	47
HST33-11A	71	84	49	43	73	87	52	49	73	87	52	49	72	86	51	50	59	71	27	35
HST33-11B	71	85	49	43	73	88	51	50	73	87	51	50	72	87	51	51	60	75	29	35
HST35-1	88	97	75	84	85	94	64	73	85	94	65	72	85	95	67	71	85	98	66	98
HST35-5	88	97	69	96	86	96	69	83	86	96	70	83	84	96	70	82	79	94	49	85
HST35-7	85	94	59	81	85	94	62	94	85	94	61	94	83	94	60	95	73	87	38	67
HST36-1	87	96	67	98	86	96	69	89	85	96	68	89	84	95	68	87	75	92	45	80
HST37-1	89	97	74	85	85	94	64	73	85	95	65	73	85	95	67	72	84	98	63	97
HST37-3	88	97	72	91	86	96	68	79	86	96	68	79	85	96	70	78	81	96	54	90
HST37-6	88	97	67	98	86	96	68	85	86	96	68	85	85	96	68	84	79	94	48	84
HST38-1	71	82	48	37	73	86	52	43	73	85	51	43	72	84	50	43	55	64	24	30
HST42-1	85	95	61	77	79	92	50	66	80	92	51	66	81	93	55	65	92	99	84	93
HST42-2	85	95	61	77	79	91	50	66	80	92	51	66	81	93	54	65	92	99	85	93
HST42-3	83	95	57	76	77	91	46	66	78	92	47	66	79	92	50	65	93	99	85	92
HST42-4	82	95	55	76	76	91	44	66	77	92	45	65	78	92	49	65	93	99	85	92
HST42-5	81	95	53	76	75	90	42	65	76	91	44	65	78	92	47	64	93	99	85	92
HST42-6	82	95	53	76	75	91	43	66	76	91	44	65	78	92	47	64	93	99	85	92
HST42-7	81	95	53	75	75	90	42	65	76	91	43	65	78	92	46	64	93	99	85	92
HST42-8	80	94	51	75	74	90	41	65	75	91	42	65	77	92	45	64	93	99	84	92
HST43-1	86	96	73	85	82	92	62	98	82	93	63	98	82	93	66	100	87	98	81	70
HST43-2	87	96	76	79	83	93	66	69	83	93	67	69	82	94	69	68	84	98	75	97
HST43-3	86	96	71	78	81	92	60	67	82	93	61	67	82	93	64	66	88	99	82	95
LCT01-1	89	96	75	74	88	96	70	85	88	96	71	85	89	96	76	86	87	94	60	60
LCT01-2	89	96	74	74	88	96	68	85	88	96	70	85	88	96	74	87	87	95	60	61
LCT02-1	90	96	70	68	89	96	69	78	89	96	70	79	89	96	74	80	84	93	52	56
LCT02-4	90	95	69	68	89	94	67	79	89	94	68	79	89	95	72	80	85	93	52	56
LCT13-1	84	91	62	42	86	92	65	49	86	92	65	49	86	93	68	50	78	87	43	35
LCT14-1	84	91	61	43	86	93	65	50	86	93	65	50	86	93	67	50	76	84	41	35
LCT14-6	79	86	56	32	82	89	60	37	82	89	61	37	82	89	62	37	70	78	36	26
LCT39-1	86	93	61	48	88	94	64	55	88	94	64	55	88	94	67	56	77	86	42	39
LCT49-1	62	62	42	16	67	67	47	18	67	67	47	18	68	67	48	18	55	52	27	13
LCT61-1	81	87	38	43	83	89	40	50	83	89	40	50	84	89	42	51	76	80	34	35
LCT70-1	69	78	51	18	74	81	55	21	74	82	56	21	74	82	57	21	60	70	31	15
LST01-1	91	98	81	94	90	98	75	92	90	98	76	92	90	98	81	90	85	96	61	78
LST03-1	98	99	90	88	96	97	79	76	96	97	80	76	96	97	82	75	93	98	77	94
LST03-2	98	99	88	86	95	97	77	74	96	97	78	74	96	97	81	73	94	99	80	96
LST03-3	98	99	88	85	95	97	76	74	96	97	78	74	96	97	80	73	94	99	80	96
LST03-4	98	98	83	85	95	95	71	74	95	96	72	74	96	96	76	73	95	99	81	97
LST03-5	96	98	79	82	93	95	67	71	93	95	68	71	94	96	72	70	97	99	88	100
LST03-6	96	98	78	82	92	95	66	71	93	95	67	71	94	96	72	70	97	99	89	99
LST03-7	96	97	73	81	91	94	61	71	92	94	63	70	93	95	67	69	98	99	89	99
LST03-8	94	96	71	80	90	93	59	70	91	94	61	69	92	94	65	68	99	100	93	98
LST03-9	94	97	70	80	89	94	58	69	90	94	60	69	92	95	64	68	99	100	94	98

Table H8. U(5)NH – c_k , E_{sum} , G and R_{e2} (Cont'd)

U(5)NH applications and experiments similarities – c_k , E_{sum} , G and R_{e2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}
LST16-1	98	100	86	98	97	99	77	85	97	99	78	85	97	99	82	84	91	97	66	84
LST16-2	98	100	86	96	97	99	75	83	97	99	77	83	97	99	81	82	91	97	68	86
LST16-3	98	99	84	92	96	98	71	80	96	98	73	80	96	98	77	78	93	98	72	89
LST16-4	98	99	82	91	95	97	70	79	96	98	71	78	96	98	75	77	94	98	73	91
LST16-5	98	99	81	89	95	98	68	77	95	98	70	77	96	98	74	76	94	99	75	92
LST16-6	98	99	79	88	95	97	67	77	95	97	68	76	96	98	72	75	95	99	77	93
LST16-7	98	99	78	88	95	97	65	76	95	97	67	76	96	97	71	75	95	99	77	94
LST17-1	98	99	82	98	97	98	74	85	97	98	75	85	97	98	79	84	91	97	65	84
LST17-2	98	99	82	96	96	98	72	83	96	98	74	83	96	98	78	82	91	97	67	85
LST17-3	98	99	82	92	96	97	70	80	96	97	71	80	96	98	75	78	93	98	72	89
LST17-4	98	99	80	91	95	98	68	79	96	98	70	78	96	98	74	77	93	98	72	91
LST17-5	98	99	79	89	95	97	67	78	95	97	69	77	96	97	73	76	94	99	75	92
LST17-6	98	99	78	89	95	97	66	77	95	97	68	77	96	97	72	76	94	99	76	93
LST20-1	97	99	78	84	94	96	66	73	94	97	67	73	95	97	71	72	96	99	83	98
LST20-2	97	98	75	83	93	95	63	72	94	96	65	72	95	96	69	71	97	99	85	99
LST20-3	96	98	72	82	92	95	61	71	93	95	62	71	94	96	66	70	98	100	88	100
LST20-4	95	98	70	81	91	95	58	71	92	95	60	70	93	96	64	69	98	100	90	99
LST21-1	97	98	74	84	93	96	62	73	94	97	64	73	95	97	68	72	97	99	83	97
LST21-2	96	98	72	83	93	95	61	72	93	96	62	72	94	96	66	71	97	100	85	99
LST21-3	96	98	70	82	92	95	58	71	92	95	60	71	94	96	64	70	98	100	88	100
LST21-4	95	98	68	82	91	95	57	71	92	95	58	71	93	96	62	70	98	100	90	99

Figure H65. U(4)NH mass indices

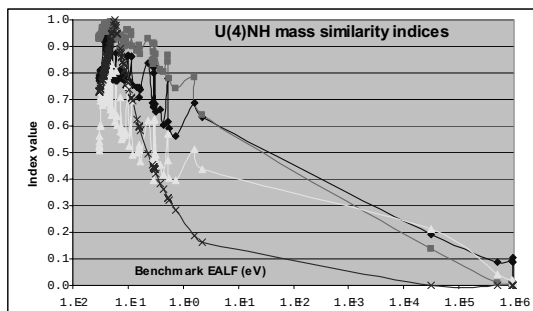


Figure H69. U(4)NH cylinder

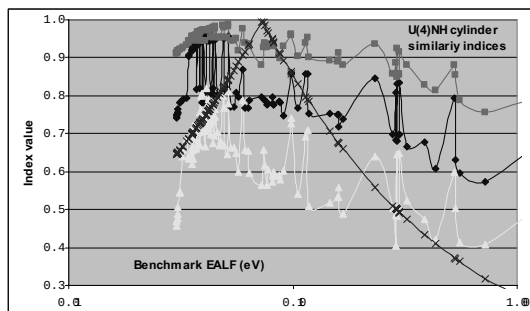


Figure H66. U(4)NH mass, enlarged

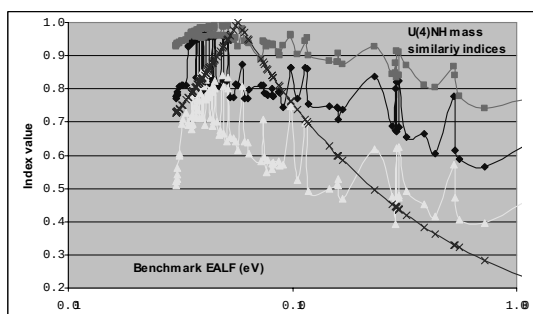


Figure H70. U(4)NH slab

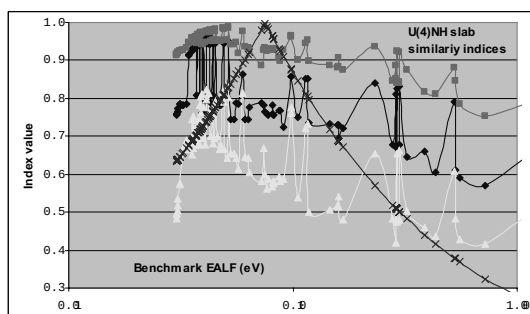


Figure H67. U(4)NH volume indices

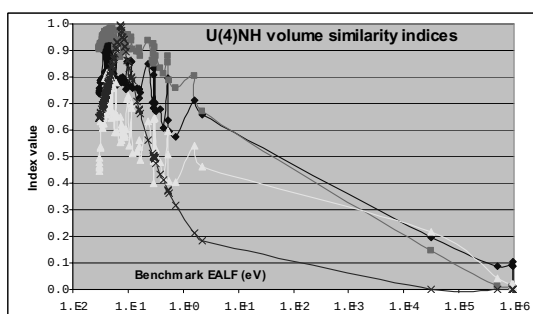


Figure H71. U(4)NH concentration

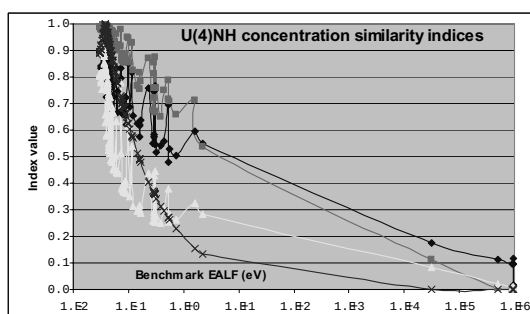


Figure H68. U(4)NH volume, enlarged

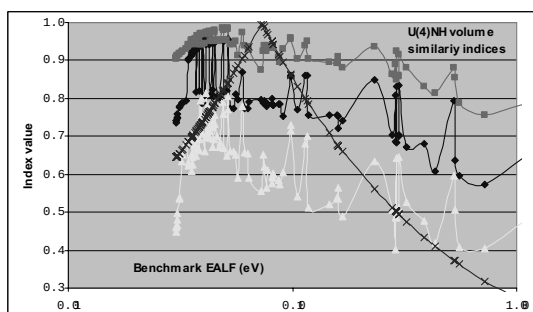


Figure H72. U(4)NH concentration

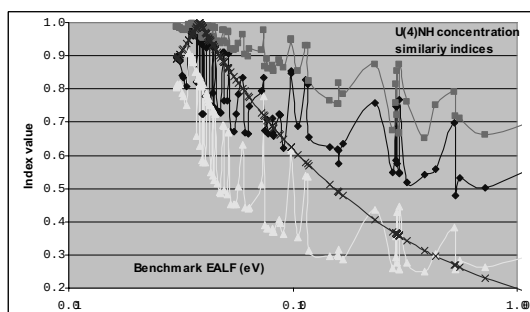


Table H9. U(4)NH – c_k , E_{sum} , G and R_{en}

U(4)NH applications and experiments similarities – c_k , E_{sum} , G and R_{e2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}
HMF01-1	9	0	1	0	9	1	1	0	9	1	1	0	9	1	1	0	10	0	1	0
HMF04-1	19	14	21	0	20	15	22	0	20	15	22	0	20	14	22	0	18	11	8	0
HMF08-1	9	1	2	0	9	1	2	0	9	1	2	0	9	1	2	0	10	0	1	0
HMF15-1	11	0	1	0	11	1	1	0	11	1	1	0	11	1	1	0	12	0	1	0
HMF18-1	9	1	2	0	9	1	2	0	9	1	2	0	9	1	2	0	10	0	1	0
HMF20-1	9	1	4	0	9	1	4	0	9	1	4	0	9	1	4	0	11	0	2	0
HMF65-1	11	0	1	0	11	1	1	0	11	1	1	0	11	1	1	0	12	0	1	0
HCT11-1	56	74	40	28	57	76	40	32	57	76	41	32	57	75	42	32	50	66	26	23
HCT11-2	59	78	41	32	60	79	41	36	60	79	41	36	59	79	43	37	53	71	28	26
HCT11-3	60	80	42	36	61	81	42	41	61	81	42	41	61	81	44	42	56	75	30	30
HMT11-1	75	90	49	70	76	90	51	79	75	90	51	78	74	90	50	80	66	82	31	57
HMT11-3	78	93	55	86	78	93	56	97	78	93	56	97	76	93	56	99	71	89	38	70
HMT11-5	80	94	60	95	79	93	59	93	79	93	60	94	77	93	61	92	75	92	44	77
HMT11-7	81	93	61	100	80	91	59	89	80	92	60	89	79	92	61	87	78	94	51	82
HMT11-35	74	87	47	59	74	88	49	66	74	88	49	66	72	88	48	67	64	78	29	48
HMT11-37	77	90	53	74	77	90	54	83	77	90	54	83	75	90	54	85	69	85	35	60
HMT11-39	79	90	57	81	78	90	57	91	78	90	58	91	77	90	58	92	72	88	40	66
HMT11-41	81	89	58	89	80	88	56	99	80	88	56	100	79	89	58	98	80	92	51	73
HMT11-43	79	91	58	81	79	91	58	92	78	91	59	91	77	91	59	93	72	89	41	66
HST01-1	78	93	57	83	78	93	59	94	78	93	59	94	75	93	58	96	66	85	37	68
HST01-2	69	84	48	45	70	86	51	51	70	86	50	51	68	85	48	52	55	68	26	37
HST01-3	78	93	57	84	78	94	59	95	78	93	59	95	76	93	58	97	67	86	37	69
HST01-4	68	84	47	44	70	86	50	49	70	85	50	49	68	84	48	50	55	67	26	36
HST01-5	81	96	71	87	81	95	70	77	80	95	70	77	79	95	70	76	75	96	55	94
HST01-6	81	96	70	88	81	95	69	78	80	95	69	78	78	95	70	77	74	95	53	93
HST01-7	78	94	59	86	78	94	61	97	78	94	61	97	76	93	59	98	66	86	38	70
HST01-8	78	93	58	83	78	94	60	94	78	93	60	94	76	93	58	96	66	85	37	68
HST01-9	69	84	48	44	70	86	51	49	70	86	51	49	68	84	48	50	55	67	26	36
HST01-10	81	96	70	90	81	95	70	80	80	95	70	80	78	95	70	78	74	94	51	91
HST09-1	62	84	47	33	64	85	51	37	63	86	50	37	61	85	48	38	48	72	26	27
HST09-2	65	87	49	42	67	88	53	47	67	88	52	47	65	87	50	48	52	76	28	34
HST09-3	71	91	53	60	72	91	56	67	72	91	56	67	69	91	54	68	58	82	31	49
HST09-4	75	93	57	79	75	93	61	90	75	93	60	89	72	93	59	91	62	87	36	65
HST10-1	77	95	65	96	77	94	66	85	77	94	66	85	75	94	65	84	67	92	45	85
HST10-2	77	95	65	98	77	94	66	87	77	94	66	87	75	94	65	85	67	92	45	84
HST10-3	77	94	64	97	77	94	66	91	77	94	66	92	74	94	65	90	67	90	44	79
HST10-4	77	94	64	95	77	94	66	93	77	94	65	93	74	93	64	92	67	90	44	78
HST11-1	79	95	71	83	79	94	71	74	78	94	71	74	76	94	70	73	73	95	58	98
HST11-1	79	95	71	83	79	94	71	73	78	94	71	74	76	94	70	72	73	96	58	99
HST12-1	81	94	71	75	79	92	65	67	79	93	66	67	78	93	67	66	83	98	78	92
HST25-1	82	96	69	84	81	94	66	75	81	95	67	75	79	95	68	73	78	97	58	97
HST27-1	79	94	60	88	79	94	62	99	79	94	62	99	77	93	60	100	67	87	39	72
HST28-1	81	96	66	91	80	95	67	80	80	95	67	81	78	95	67	79	73	94	49	90
HST28-9	75	89	50	63	76	90	52	71	75	89	52	71	73	89	51	72	62	76	30	51
HST29-1	74	88	51	60	76	89	54	68	75	89	53	68	73	88	52	69	62	75	30	49

Table H9. U(4)NH – c_k , E_{sum} , G and R_{en} (Cont'd)

U(4)NH applications and experiments similarities – c_k , E_{sum} , G and R_{e2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}
HST30-1	81	96	67	91	80	95	68	81	80	95	68	81	78	95	68	80	73	94	49	89
HST30-4	74	88	51	60	75	89	54	68	75	89	53	67	73	88	52	69	62	75	30	49
HST33-11A	67	84	46	44	68	85	49	50	68	85	48	50	67	84	47	51	57	72	28	36
HST33-11B	68	85	47	45	69	86	49	50	68	86	49	50	67	85	48	51	58	76	29	36
HST35-1	83	96	71	81	82	94	66	72	82	94	67	72	81	94	68	70	82	98	66	99
HST35-5	82	96	66	93	82	95	67	82	81	95	67	82	80	95	67	81	76	94	50	88
HST35-7	80	93	56	84	80	93	58	95	80	93	57	95	78	93	57	96	71	87	38	69
HST36-1	81	95	64	99	81	95	65	88	81	95	65	88	79	95	64	86	73	92	45	83
HST37-1	83	96	71	82	82	94	66	72	82	95	67	73	81	95	68	71	81	97	63	100
HST37-3	83	96	69	88	82	95	67	78	82	96	68	78	81	95	68	77	79	96	54	93
HST37-6	83	96	64	95	82	95	65	84	82	95	65	84	80	95	64	83	76	94	48	86
HST38-1	66	81	45	38	68	83	48	43	68	83	47	43	66	82	46	44	54	65	25	31
HST42-1	81	94	60	74	78	92	54	66	78	92	55	66	79	92	58	65	88	98	82	90
HST42-2	81	94	60	74	78	92	53	65	78	92	54	66	79	92	57	64	89	98	82	90
HST42-3	79	94	56	73	76	91	50	65	76	92	51	65	77	92	54	64	89	99	81	90
HST42-4	78	93	54	73	75	91	48	65	76	92	49	65	77	92	52	64	89	99	81	89
HST42-5	78	93	52	73	74	91	46	65	75	91	47	65	76	92	50	64	90	99	81	89
HST42-6	78	93	53	73	75	91	47	65	75	91	48	65	76	92	50	64	90	99	81	89
HST42-7	78	93	52	73	74	91	46	65	75	91	47	65	76	92	49	64	90	99	81	89
HST42-8	77	93	51	73	74	90	45	64	74	91	46	65	75	91	48	63	90	99	80	89
HST43-1	81	94	71	88	79	92	65	100	79	93	66	99	78	93	67	99	83	98	78	72
HST43-2	81	95	73	77	80	93	68	68	79	93	69	68	78	93	69	67	81	98	75	94
HST43-3	81	94	70	75	79	92	63	66	79	93	64	67	78	93	66	65	84	98	79	92
LCT01-1	87	96	76	76	86	96	73	86	86	96	74	86	86	96	78	87	85	95	62	62
LCT01-2	86	96	75	76	86	96	72	86	86	96	73	86	86	96	76	88	85	95	62	63
LCT02-1	86	95	71	70	86	95	70	79	86	95	71	79	85	95	73	81	82	93	54	57
LCT02-4	86	94	70	71	86	94	68	80	86	94	69	80	85	94	72	81	83	93	54	58
LCT13-1	82	91	63	44	83	91	64	49	83	92	65	49	83	92	66	50	77	87	45	36
LCT14-1	82	91	62	44	83	92	64	50	83	92	65	50	83	92	66	51	75	85	43	36
LCT14-6	78	87	57	33	80	88	60	37	79	88	60	37	79	88	61	38	70	79	38	27
LCT39-1	84	93	62	50	85	94	64	56	85	94	64	56	84	94	66	57	76	87	44	41
LCT49-1	63	64	44	16	66	67	46	18	66	67	46	18	66	67	47	19	55	54	28	13
LCT61-1	80	88	39	45	81	89	40	50	81	89	40	50	81	89	42	51	75	81	36	37
LCT70-1	69	78	51	19	71	80	54	21	71	80	54	21	71	81	55	22	60	71	32	15
LST01-1	87	98	81	98	87	97	78	91	87	98	79	91	86	98	81	89	83	96	63	80
LST03-1	96	98	86	85	95	97	81	75	95	97	82	75	95	97	82	74	92	98	78	97
LST03-2	96	98	85	83	95	97	80	73	95	97	80	73	94	97	81	72	93	99	81	99
LST03-3	96	98	84	82	95	97	79	73	95	97	80	73	94	97	81	72	94	99	81	99
LST03-4	96	97	81	82	94	96	74	73	95	96	76	73	94	96	78	72	95	99	82	100
LST03-5	95	97	78	79	93	95	71	70	93	95	72	70	93	96	75	69	96	99	88	97
LST03-6	94	97	77	79	92	95	70	70	93	95	71	70	93	96	74	69	97	99	89	96
LST03-7	94	96	72	79	92	94	65	70	92	94	66	70	93	95	70	69	97	99	89	96
LST03-8	93	96	70	78	90	94	63	69	91	94	64	69	92	94	68	68	98	99	91	95
LST03-9	93	96	69	77	90	94	62	69	90	95	63	69	91	95	67	68	98	99	91	95
LST07-1	98	98	85	86	97	97	78	76	97	97	79	76	96	98	81	75	94	99	77	95
LST07-2	98	98	83	85	96	97	76	75	96	97	77	75	96	98	80	74	95	99	79	97
LST07-3	97	98	81	83	96	97	74	74	96	97	75	74	96	98	78	73	96	99	81	98
LST07-4	97	98	79	82	96	97	71	73	96	97	73	73	96	97	76	72	96	99	83	99

Table H9. U(4)NH – c_k , E_{sum} , G and R_{en} (Cont'd)

U(4)NH applications and experiments similarities – c_k , E_{sum} , G and R_{e2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}
LST07-5	97	98	76	82	95	97	69	72	96	97	70	73	96	97	74	71	97	99	84	100
LST16-1	96	99	83	95	96	99	80	84	96	99	81	84	95	99	83	83	91	97	67	86
LST16-2	96	99	84	93	95	98	79	82	95	99	80	82	95	99	82	81	91	98	69	88
LST16-3	96	99	82	89	95	98	75	79	95	98	77	79	95	98	79	78	93	98	72	92
LST16-4	96	99	81	88	95	98	74	78	95	98	75	78	95	98	78	76	93	99	74	93
LST16-5	96	99	80	86	94	98	72	76	95	98	74	77	94	98	77	75	94	99	75	95
LST16-6	96	98	78	85	94	97	71	76	95	98	72	76	95	98	75	74	94	99	77	96
LST16-7	96	98	77	85	94	97	70	75	94	97	71	75	94	97	74	74	95	99	78	97
LST17-1	96	99	80	95	95	98	77	84	95	98	78	84	95	98	80	83	91	97	67	86
LST17-2	96	99	81	93	95	98	76	82	95	98	77	82	95	98	79	81	91	98	69	88
LST17-3	96	98	80	89	95	97	73	79	95	98	74	79	95	98	77	78	93	98	72	92
LST17-4	96	99	79	88	94	98	72	78	95	98	73	78	94	98	76	76	93	98	73	93
LST17-5	96	98	78	86	94	97	71	76	94	97	72	77	94	97	75	75	93	99	75	95
LST17-6	96	98	77	86	94	97	70	76	95	97	71	76	94	97	75	75	94	99	76	96
LST20-1	95	98	77	81	94	96	70	72	94	97	71	72	94	97	74	71	96	99	83	99
LST20-2	95	97	75	80	93	96	68	71	93	96	69	71	94	96	72	70	96	99	85	98
LST20-3	94	97	72	79	92	95	65	70	93	96	66	70	93	96	69	69	97	99	88	97
LST20-4	94	97	69	79	92	95	62	70	92	95	63	70	93	96	67	69	98	100	90	96
LST21-1	95	98	73	81	93	96	66	72	94	97	68	72	94	97	71	71	96	99	83	100
LST21-2	95	97	72	80	93	96	65	71	93	96	66	71	93	96	69	70	96	99	85	98
LST21-3	94	97	69	79	92	95	62	70	92	96	64	70	93	96	67	69	97	100	88	97
LST21-4	94	97	68	79	91	95	61	70	92	96	62	70	93	96	65	69	98	100	90	96

Figure H73. U(3)NH mass indices

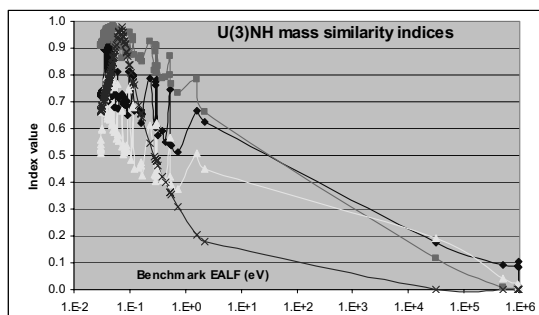


Figure H77. U(3)NH cylinder

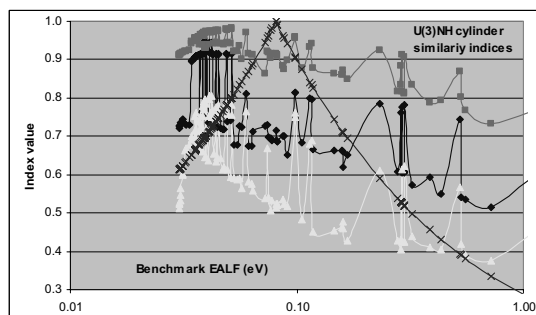


Figure H74. U(3)NH mass, enlarged

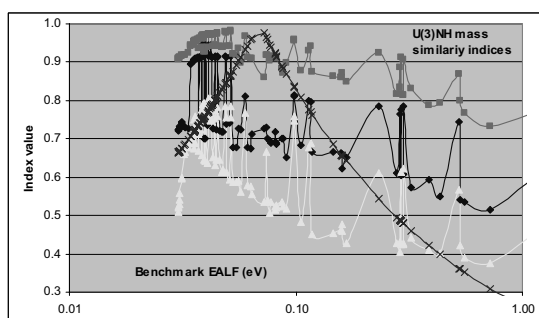


Figure H78. U(3)NH slab

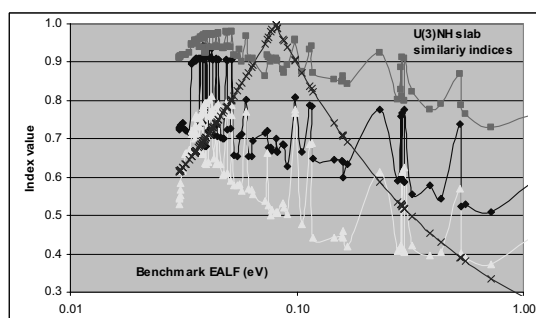


Figure H75. U(3)NH volume indices

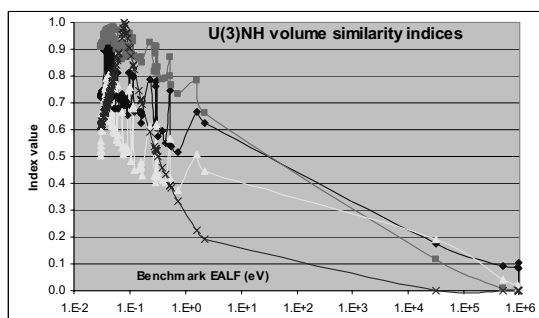


Figure H79. U(3)NH concentration

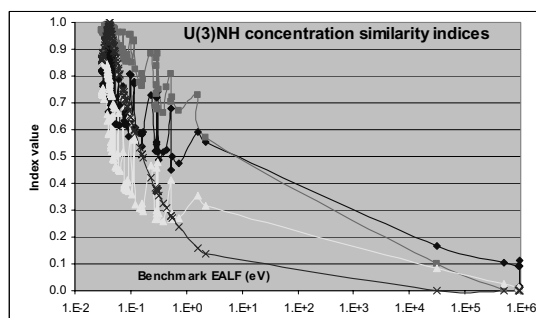


Figure H76. U(3)NH volume, enlarged

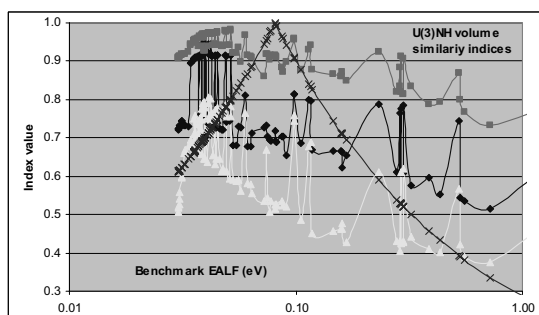


Figure H80. U(3)NH concentration

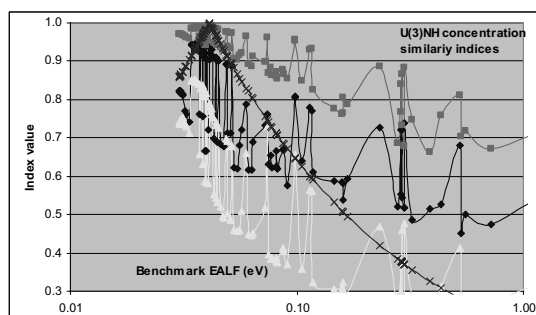


Table H10. U(3)NH – c_k , E_{sum} , G and R_{e2}

U(3)NH applications and experiments similarities – c_k , E_{sum} , G and R_{e2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}
HMF01-1	9	0	1	0	9	0	1	0	9	0	1	0	9	0	1	0	9	0	1	0
HMF04-1	18	12	19	0	18	12	19	0	18	12	19	0	17	11	18	0	16	10	8	0
HMF08-1	9	1	2	0	9	1	2	0	9	1	2	0	9	1	2	0	9	0	1	0
HMF15-1	10	0	1	0	10	0	1	0	10	0	1	0	11	0	1	0	11	0	1	0
HMF18-1	9	1	2	0	9	1	2	0	9	1	2	0	9	1	2	0	9	0	1	0
HMF20-1	9	1	4	0	9	1	4	0	9	1	4	0	10	1	4	0	11	1	2	0
HMF65-1	10	0	1	0	10	0	1	0	10	0	1	0	11	0	1	0	11	0	1	0
HCT11-1	51	73	38	31	51	73	38	34	51	73	38	33	51	73	37	33	48	67	27	24
HCT11-2	54	77	39	35	54	77	39	38	54	77	39	38	53	76	39	38	50	72	29	27
HCT11-3	55	79	40	40	55	79	40	43	55	79	40	43	55	79	40	43	53	76	31	31
HMT11-1	67	88	45	76	67	88	45	83	67	88	45	83	65	87	44	82	61	83	32	59
HMT11-3	69	90	51	94	70	90	51	98	69	91	51	98	68	90	50	98	66	88	39	73
HMT11-5	71	91	56	96	71	91	56	89	71	91	56	89	70	91	56	89	69	91	45	80
HMT11-7	72	90	56	91	73	90	56	84	72	90	56	84	71	90	57	85	72	92	51	85
HMT11-35	65	85	43	64	65	85	43	70	65	85	43	69	64	84	42	69	59	79	30	50
HMT11-37	68	88	48	81	69	88	48	88	68	88	48	88	67	87	48	87	64	85	36	62
HMT11-39	70	87	52	88	70	87	52	96	70	87	52	96	68	87	52	96	67	87	40	68
HMT11-41	73	86	53	98	73	86	53	94	73	86	54	94	72	86	54	95	73	90	52	76
HMT11-43	70	88	54	89	70	88	54	96	70	88	54	96	69	88	53	96	67	88	41	69
HST01-1	69	91	52	92	69	91	52	99	69	91	52	99	67	90	51	99	62	86	38	71
HST01-2	61	82	43	50	61	82	43	54	61	82	43	54	59	80	41	54	52	69	27	38
HST01-3	69	91	52	92	69	91	53	100	69	91	52	100	67	91	51	100	63	86	38	71
HST01-4	61	81	42	48	61	81	43	52	61	81	42	52	59	80	41	52	52	68	27	37
HST01-5	73	94	65	79	73	94	65	73	73	94	65	73	71	94	65	73	70	95	55	98
HST01-6	72	94	65	81	73	94	65	74	72	94	65	74	71	94	64	75	69	94	53	96
HST01-7	69	92	53	94	69	92	54	98	69	92	53	98	67	91	52	98	62	86	39	73
HST01-8	69	91	53	91	69	91	53	99	69	91	52	99	67	91	51	99	62	85	38	71
HST01-9	61	81	43	48	61	81	43	52	61	81	43	52	59	80	41	52	52	68	27	37
HST01-10	72	94	65	82	72	94	65	76	72	94	64	76	70	94	63	76	68	94	52	94
HST09-1	54	80	42	36	54	80	42	39	54	80	42	39	52	79	40	39	45	70	27	28
HST09-2	57	83	44	46	58	83	44	50	57	83	44	50	55	82	42	50	49	75	29	36
HST09-3	62	87	48	66	62	87	48	71	62	87	48	71	60	86	46	71	54	81	32	51
HST09-4	65	90	52	87	65	90	52	94	65	90	52	94	63	89	50	94	58	85	37	67
HST10-1	68	92	59	88	68	92	59	81	68	92	59	81	66	92	58	81	62	91	46	88
HST10-2	68	92	59	89	68	92	59	82	68	92	59	82	66	92	58	83	62	91	46	87
HST10-3	68	91	58	94	68	91	58	87	68	92	58	87	65	91	57	87	62	89	45	82
HST10-4	68	91	58	96	68	91	58	88	68	91	58	88	65	91	57	89	62	89	45	81
HST11-1	70	93	64	76	70	93	65	70	70	93	64	70	68	93	63	70	67	94	58	98
HST11-1	70	93	65	76	70	93	65	70	70	93	65	70	68	93	64	70	67	94	59	98
HST12-1	73	92	67	69	73	92	67	63	73	92	67	63	72	92	66	63	76	96	73	89
HST25-1	74	94	64	77	74	94	64	71	74	94	64	71	72	94	64	71	72	96	58	99
HST27-1	70	92	54	96	70	92	54	96	70	92	54	96	68	91	53	96	63	87	40	74
HST28-1	72	94	61	83	72	94	61	76	72	94	61	76	70	94	61	77	68	93	49	93

Table H10. U(3)NH – c_k , E_{sum} , G and R_{e2} (Cont'd)

U(3)NH applications and experiments similarities – c_k , E_{sum} , G and R_{e2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}
HST30-4	66	86	46	66	66	86	46	71	66	86	46	71	64	85	44	71	58	76	31	51
HST33-11A	61	82	42	49	61	82	43	53	60	82	42	53	59	81	41	52	54	73	29	38
HST33-11B	61	83	43	49	61	83	43	53	61	83	43	53	60	83	42	53	55	77	30	38
HST35-1	75	94	67	74	76	94	67	68	75	94	67	68	74	94	67	68	76	96	66	95
HST35-5	74	94	61	85	74	94	62	78	74	94	61	78	72	94	61	78	71	94	50	91
HST35-7	72	92	51	92	72	92	52	100	72	92	51	100	70	91	51	100	67	87	39	71
HST36-1	73	94	59	90	73	94	59	83	73	94	59	83	71	93	58	84	68	92	46	86
HST37-1	75	94	66	75	76	94	66	69	75	94	66	69	74	94	66	69	76	96	63	97
HST37-3	75	94	63	80	75	94	63	74	75	95	63	74	74	94	63	74	73	95	54	96
HST37-6	74	94	59	86	74	94	59	80	74	94	59	80	73	94	59	80	71	93	49	90
HST38-1	59	79	41	42	60	79	41	46	59	79	41	46	58	77	40	45	51	66	26	33
HST42-1	74	92	60	68	74	92	60	62	74	92	60	62	74	92	62	62	81	97	75	87
HST42-2	74	92	60	67	74	92	60	62	75	92	60	62	74	92	62	62	81	97	75	87
HST42-3	73	91	56	67	73	91	56	62	73	92	56	62	73	92	58	62	82	97	75	87
HST42-4	73	91	54	67	73	91	54	61	73	91	55	62	73	92	57	62	82	97	74	86
HST42-5	72	91	52	67	72	91	52	61	73	91	53	61	73	91	55	62	82	97	74	86
HST42-6	73	91	53	67	73	91	53	61	73	91	53	61	73	91	55	62	82	97	74	86
HST42-7	72	91	52	66	72	91	52	61	73	91	52	61	73	91	54	62	82	97	74	86
HST42-8	72	91	51	66	72	91	51	61	72	91	51	61	73	91	53	61	82	97	74	86
HST43-1	73	92	67	97	73	92	67	95	73	92	67	96	72	92	66	96	76	96	73	75
HST43-2	73	92	68	70	73	92	68	64	73	93	68	65	72	92	67	65	74	96	71	90
HST43-3	73	92	66	68	73	92	66	63	73	92	66	63	72	92	66	63	77	96	74	89
LCT01-1	81	96	76	84	81	96	76	91	81	96	76	91	81	96	78	90	80	95	65	65
LCT01-2	81	96	75	84	81	96	74	91	81	96	75	91	81	96	77	91	81	96	66	65
LCT02-1	80	94	69	77	80	94	69	84	80	94	69	83	79	94	69	83	77	93	56	60
LCT02-4	80	93	68	78	80	93	68	84	80	93	68	84	79	93	69	84	78	93	57	60
LCT13-1	78	91	62	48	78	91	62	52	78	91	62	52	78	91	63	52	74	88	48	37
LCT14-1	78	91	61	49	78	91	61	53	78	91	61	53	77	91	61	53	72	87	46	38
LCT14-6	75	87	57	36	75	87	57	39	74	87	57	39	74	87	57	39	68	81	41	28
LCT39-1	79	92	61	54	79	92	61	59	79	92	61	59	78	92	61	59	73	89	47	42
LCT49-1	63	66	45	18	63	66	45	19	63	66	45	19	63	66	45	19	56	57	32	14
LCT61-1	76	89	41	49	76	89	40	53	76	88	41	53	76	89	42	53	72	84	38	38
LCT70-1	67	79	51	21	67	79	51	22	66	79	51	22	66	79	51	22	59	73	35	16
LST01-1	81	97	77	93	81	97	77	86	81	97	77	86	80	97	77	86	79	96	66	83
LST03-1	92	97	81	77	92	97	81	71	92	97	81	71	91	97	80	71	90	98	78	100
LST03-2	92	97	79	75	92	97	79	70	92	97	80	70	91	97	79	70	91	98	81	98
LST03-3	92	96	79	75	92	96	79	69	92	97	79	69	91	96	79	70	91	98	81	97
LST03-4	92	96	78	75	92	96	78	69	92	96	78	69	91	96	78	69	92	98	82	97
LST03-5	91	95	76	72	91	95	76	67	91	95	76	67	91	95	76	67	93	98	85	94
LST03-6	91	95	75	72	91	95	75	66	91	95	75	66	90	95	76	67	93	98	85	93
LST03-7	90	95	71	72	90	95	71	66	91	95	72	66	90	95	73	66	94	98	85	93
LST03-8	90	94	70	71	90	94	70	65	90	94	70	65	90	94	72	65	94	98	85	91
LST03-9	89	95	69	71	89	95	69	65	90	95	69	65	90	95	71	65	94	99	85	91
LST07-1	94	97	80	78	94	97	80	72	94	98	81	72	94	98	81	73	93	99	78	99
LST07-2	94	97	79	77	94	97	79	71	94	97	80	71	94	97	80	71	94	99	79	100
LST07-3	94	97	78	76	94	97	78	70	94	97	78	70	94	97	79	70	94	99	82	98
LST07-4	94	97	77	75	95	97	77	69	95	97	77	69	94	97	78	70	95	99	83	97
LST07-5	95	97	75	75	95	97	75	69	95	97	75	69	94	97	77	69	96	99	84	97

Table H10. U(3)NH – c_k , E_{sum} , G and R_{e2} (Cont'd)

U(3)NH applications and experiments similarities – c_k , E_{sum} , G and R_{e2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}
LST16-1	92	98	78	86	92	98	78	80	92	98	78	80	91	98	79	80	89	97	68	89
LST16-2	92	98	78	84	92	98	78	78	92	98	79	78	91	98	79	78	89	98	70	92
LST16-3	91	98	78	81	92	98	78	75	92	98	78	75	91	98	79	75	90	98	73	95
LST16-4	92	97	77	80	92	98	77	74	92	98	78	74	91	98	78	74	91	98	74	97
LST16-5	91	97	77	79	91	97	76	73	91	97	77	73	91	97	78	73	91	99	76	98
LST16-6	92	97	76	78	92	97	76	72	92	97	76	72	91	97	77	72	92	99	77	99
LST16-7	92	97	75	77	92	97	75	71	92	97	75	71	91	97	76	72	92	99	78	100
LST17-1	92	98	76	87	92	98	76	80	92	98	76	80	91	98	76	80	89	97	68	89
LST17-2	91	98	76	85	91	98	76	78	91	98	76	78	90	98	77	78	89	98	69	91
LST17-3	91	97	76	81	91	97	76	75	91	97	76	75	91	97	77	75	90	98	73	95
LST17-4	91	97	75	80	91	97	75	74	91	98	76	74	91	97	76	74	90	98	73	97
LST17-5	91	97	75	79	91	97	75	73	91	97	75	73	91	97	76	73	91	98	75	98
LST17-6	92	97	75	78	92	97	75	72	92	97	75	72	91	97	76	72	92	99	76	99
LST20-1	91	96	75	74	91	96	75	68	91	96	75	68	91	96	76	69	93	99	83	96
LST20-2	91	96	74	73	91	96	74	68	91	96	74	68	91	96	75	68	93	99	84	95
LST20-3	91	96	71	72	91	96	71	67	91	96	71	67	91	96	73	67	94	99	85	93
LST20-4	91	95	69	72	91	95	69	66	91	95	69	66	91	96	72	66	95	99	85	93
LST21-1	91	96	73	74	91	96	72	69	91	96	73	69	91	96	74	69	93	99	83	96
LST21-2	91	96	71	73	91	96	71	68	91	96	71	68	91	96	73	68	94	99	84	95
LST21-3	91	96	69	72	91	96	69	67	91	96	69	67	91	96	72	67	94	99	85	94
LST21-4	91	95	68	72	91	95	67	66	91	96	68	66	91	96	70	66	95	99	85	93

PuO₂ applications and plutonium benchmarks

Figure H81. Pu(100/0/0/0)O₂ mass

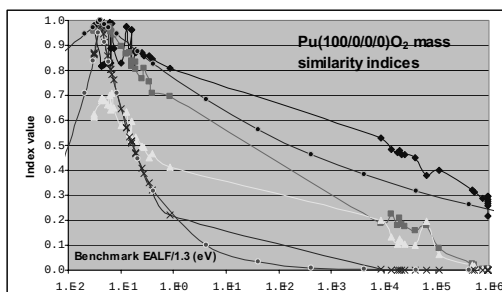


Figure H85. Pu(100/0/0/0)O₂ cylinder

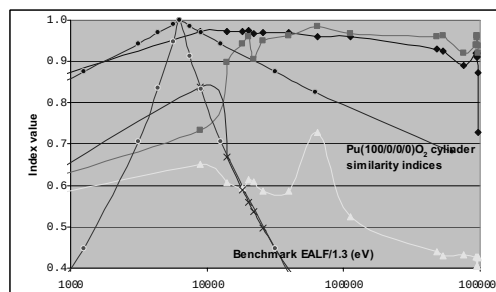


Figure H82. Pu(100/0/0/0)O₂ mass, enl.

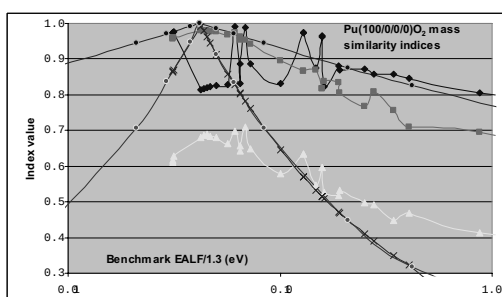


Figure H86. Pu(100/0/0/0)O₂ slab

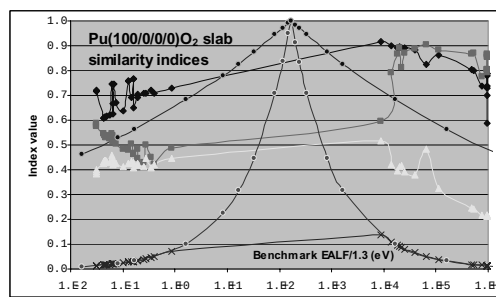


Figure H83. Pu(100/0/0/0)O₂ volume

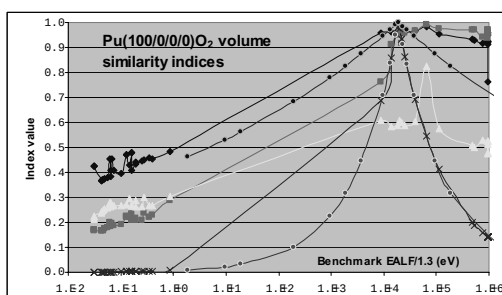


Figure H87. Pu(100/0/0/0)O₂ slab

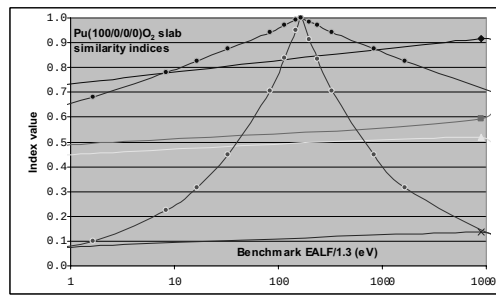


Figure H84. Pu(100/0/0/0)O₂ volume, enl.

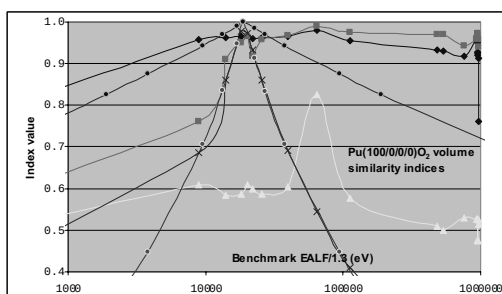


Figure H88. Pu(100/0/0/0)O₂ concentration

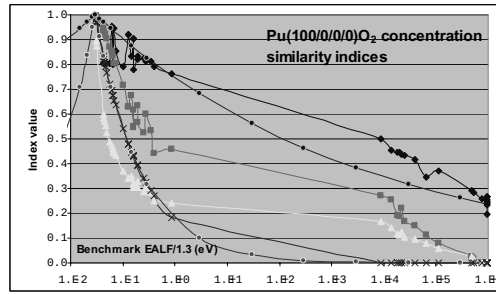


Table H11. Pu(100/0/0/0)O₂ – c_k, E_{sum}, G and R_{e2}

Pu(100/0/0/0)O ₂ applications and experiments similarities – c _k , E _{sum} , G and R _{a2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}
PMF01-1	27	0	0	0	95	96	53	14	91	94	43	8	73	81	21	1	24	0	0	0
PMF02-1	21	0	0	0	76	94	51	14	73	92	42	8	59	79	21	1	19	0	0	0
PMF03-1	28	0	0	0	92	97	48	14	91	96	40	8	78	86	22	1	26	0	0	0
PMF03-2	31	2	2	0	93	97	50	19	93	96	43	11	80	87	24	2	28	2	2	0
PMF03-3	30	0	0	0	93	97	48	14	92	96	40	8	79	87	22	1	27	0	0	0
PMF03-4	32	3	2	0	93	97	51	20	93	96	44	11	80	87	25	2	29	2	2	0
PMF03-5	29	0	0	0	93	97	48	14	92	96	40	8	79	86	22	1	27	0	0	0
PMF05-1	29	0	0	0	92	94	53	16	89	92	43	9	74	78	22	1	26	0	0	0
PMF11-1	38	18	19	0	98	99	82	54	96	99	73	31	83	90	48	5	35	11	8	0
PMF16-1	53	19	20	0	96	76	61	69	97	73	65	84	92	59	52	14	50	27	17	0
PMF22-1	27	0	0	0	96	96	53	14	92	94	43	8	74	81	21	1	25	0	0	0
PMF29-1	26	0	0	0	91	96	52	14	87	94	43	8	70	80	21	1	23	0	0	0
PMF37-1	40	9	6	0	96	98	58	41	96	97	52	24	86	88	32	4	37	8	6	0
PMF37-5	45	16	10	0	97	97	60	69	97	96	59	40	88	89	38	6	42	15	9	0
PMF37-7	46	17	10	0	96	96	59	86	97	95	59	50	89	87	39	8	43	17	10	0
PMF37-10	48	21	12	0	97	96	61	97	97	96	61	56	90	89	41	9	45	19	11	0
PMF37-12	47	18	11	0	96	95	59	98	97	94	59	59	89	86	40	10	44	19	12	0
PMF37-15	48	22	13	0	96	91	59	86	97	90	61	67	90	79	42	11	46	25	14	0
PMF37-16	46	18	11	0	96	92	60	93	97	91	61	54	89	81	42	9	44	22	13	0
PST09-1	98	96	63	87	43	17	22	0	50	27	28	0	72	57	40	1	99	99	88	96
PST09-2	97	96	62	87	42	17	22	0	50	27	27	0	72	58	39	1	99	100	89	97
PST09-3	97	96	61	86	42	17	21	0	50	27	26	0	72	59	38	1	99	100	89	97
PST14-1	97	87	63	57	47	22	27	0	55	30	32	0	76	48	42	3	92	63	34	48
PST14-2	97	87	63	57	47	22	27	0	55	30	33	0	76	48	43	3	92	63	34	48
PST15-1	96	82	60	52	48	23	27	0	56	30	32	1	77	46	43	3	90	55	31	43
PST15-2	96	82	60	52	48	23	27	0	56	30	32	1	77	46	43	3	90	55	31	43
PST22-1	82	84	53	51	41	21	27	0	47	28	32	1	65	46	41	3	78	62	32	43
PST22-2	83	90	58	64	39	19	27	0	46	27	32	0	64	48	41	2	79	72	37	54
PST22-3	83	95	64	80	38	18	26	0	45	27	33	0	63	51	42	2	80	83	45	68
PST22-4	83	97	66	86	38	18	26	0	44	27	33	0	62	52	43	2	80	87	49	72
PST22-5	82	98	68	91	37	17	25	0	44	26	32	0	62	54	44	2	81	90	53	77
PST22-6	82	98	68	94	37	17	25	0	43	26	32	0	61	53	44	2	81	92	55	79
PST22-7	82	98	69	96	37	17	24	0	43	26	31	0	61	54	44	2	81	93	57	81
PST22-8	82	98	69	98	37	17	24	0	43	26	31	0	61	54	43	2	81	94	59	82
PST22-9	82	98	68	99	37	16	24	0	43	26	30	0	61	55	43	2	81	95	60	83
PST25-1	99	97	70	83	45	20	28	0	53	29	35	0	74	55	46	2	96	85	48	69
PST25-7	89	96	66	80	41	19	28	0	48	28	35	0	67	54	44	2	86	85	46	67
PST25-14	88	87	55	53	43	22	29	0	50	30	34	0	69	51	43	3	83	68	35	45
PST25-21	88	83	52	47	44	22	29	0	51	29	34	1	70	48	43	3	83	63	33	39
PST25-28	86	81	49	39	45	24	30	0	52	31	35	1	71	50	44	4	81	60	31	33
PST25-34	86	75	45	35	46	22	27	0	53	29	32	1	72	45	41	5	81	53	28	29
PST25-39	81	69	41	22	49	29	30	1	55	35	36	1	73	49	45	7	76	46	24	18
PST26-1	99	95	71	78	46	20	27	0	53	28	34	0	75	52	43	2	95	80	44	66
PST26-4	89	94	65	76	41	19	27	0	48	27	33	0	67	51	43	2	85	80	43	64
PST26-9	87	81	53	47	43	21	26	0	50	28	32	1	69	44	42	3	82	57	30	39
PST26-15	87	77	50	41	45	21	26	0	52	27	32	1	71	43	41	4	82	53	29	34
PST26-17	84	71	47	32	46	23	27	0	52	29	32	1	71	42	42	5	79	44	25	27

Figure H89. Pu(95/5/0/0)O₂ mass

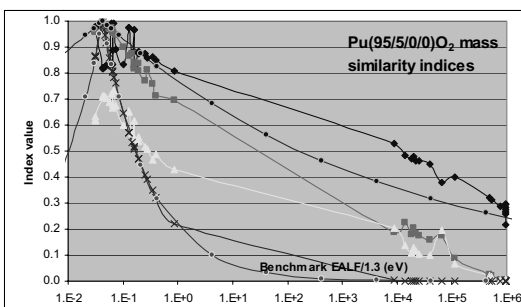


Figure H93. Pu(95/5/0/0)O₂ cylinder

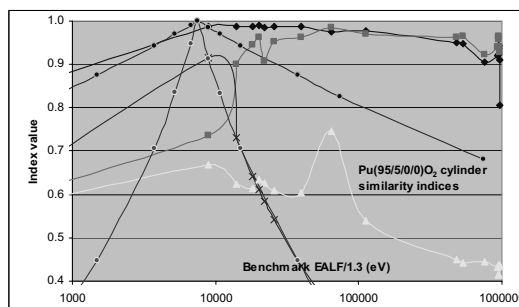


Figure H90. Pu(95/5/0/0)O₂ mass, enl.

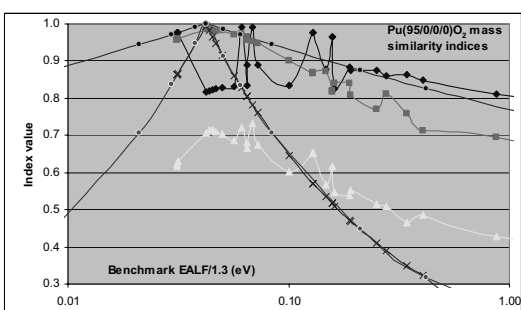


Figure H94. Pu(95/5/0/0)O₂ slab

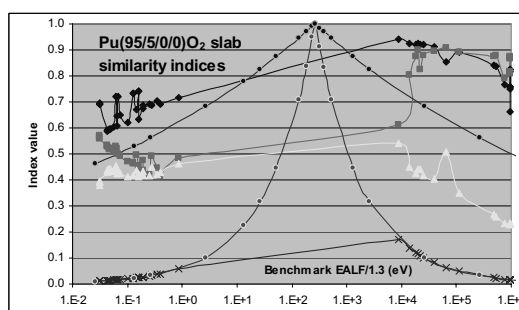


Figure H91. Pu(95/5/0/0)O₂ volume

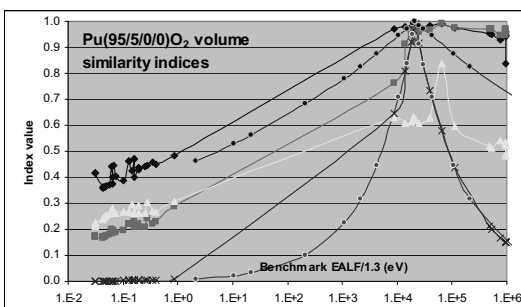


Figure H95. Pu(95/5/0/0)O₂ slab – Enl.

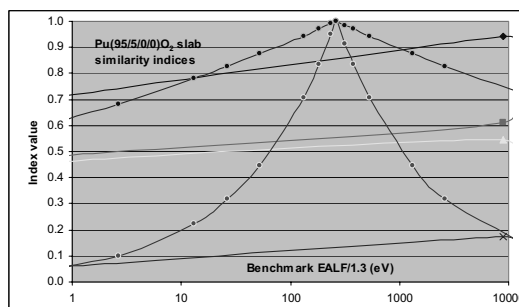


Figure H92. Pu(95/5/0/0)O₂ volume, enl.

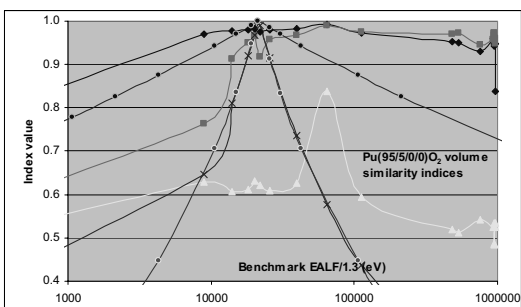


Figure H96. Pu(95/5/0/0)O₂ concentration

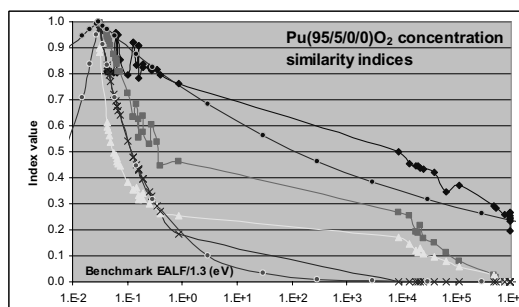


Table H12. Pu(95/5/0/0)O₂ – c_k, E_{sum}, G and R_{e2}

Pu(95/5/0/0)O ₂ applications and experiments similarities – c _k , E _{sum} , G and R _{e2} in %																				
ICSBEF Id	Mass				Volume				Cylinder				Slab				Concentration			
	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}
PMF01-1	27	0	0	0	96	96	53	15	92	94	44	9	76	82	23	2	24	0	0	0
PMF02-1	22	0	0	0	84	95	53	15	81	93	44	9	66	81	23	2	20	0	0	0
PMF03-1	28	0	0	0	94	97	48	15	94	96	41	9	82	87	24	2	26	0	0	0
PMF03-2	31	2	2	0	95	97	51	20	95	96	44	12	84	88	26	2	28	2	2	0
PMF03-3	30	0	0	0	95	97	48	15	94	96	41	9	82	87	24	2	27	0	0	0
PMF03-4	32	3	2	0	95	97	52	21	95	96	45	12	84	88	27	2	29	2	2	0
PMF03-5	29	0	0	0	95	97	49	15	94	96	42	9	82	87	24	2	27	0	0	0
PMF05-1	29	0	0	0	93	94	54	17	91	92	44	10	77	79	24	2	26	0	0	0
PMF11-1	38	18	19	0	99	99	84	58	98	99	75	34	85	91	51	6	35	11	8	0
PMF16-1	53	19	20	0	97	76	63	65	99	74	67	91	94	61	54	17	50	27	17	0
PMF22-1	27	0	0	0	96	96	53	15	92	94	43	9	76	82	23	2	25	0	0	0
PMF29-1	26	0	0	0	95	96	53	15	91	94	44	9	75	82	23	2	23	0	0	0
PMF37-1	40	9	7	0	97	98	59	44	98	97	54	26	89	89	35	5	37	8	6	0
PMF37-5	45	16	10	0	98	97	63	74	99	96	61	43	91	89	40	8	42	15	10	0
PMF37-7	46	17	10	0	98	96	61	92	99	95	61	54	92	88	42	10	44	17	11	0
PMF37-10	48	21	13	0	98	97	63	97	99	96	63	61	92	90	44	11	45	19	11	0
PMF37-12	47	18	11	0	98	95	61	92	99	94	61	64	92	88	42	12	44	19	12	0
PMF37-15	48	22	14	0	98	91	61	81	99	90	63	73	93	81	45	14	46	25	15	0
PMF37-16	46	18	12	0	98	92	62	99	99	91	63	58	92	83	44	11	44	22	13	0
PST09-1	98	96	63	87	42	17	23	0	49	27	28	0	70	56	40	1	99	99	88	97
PST09-2	98	96	62	86	42	17	22	0	49	27	27	0	69	56	39	1	99	100	90	97
PST09-3	98	96	62	86	41	17	21	0	49	27	27	0	69	57	38	1	99	100	90	97
PST14-1	98	87	65	57	46	22	27	0	53	30	32	0	73	46	42	2	92	63	36	48
PST14-2	98	87	65	57	46	22	27	0	53	30	32	0	73	47	42	2	92	63	35	48
PST15-1	97	82	62	52	47	23	26	0	54	30	32	0	74	45	42	2	91	56	32	43
PST15-2	97	82	62	52	47	23	26	0	54	30	32	0	74	45	42	2	91	55	32	43
PST22-1	83	84	55	51	40	21	27	0	46	28	32	0	63	45	41	2	78	62	33	43
PST22-2	83	90	60	65	39	19	27	0	45	27	32	0	62	47	41	2	79	72	38	54
PST22-3	83	96	67	81	38	18	26	0	44	27	33	0	61	50	42	2	80	84	46	68
PST22-4	83	97	69	86	37	18	26	0	43	27	33	0	60	51	43	1	81	87	50	72
PST22-5	83	98	70	92	37	17	25	0	43	26	32	0	60	52	44	1	81	91	54	77
PST22-6	82	98	71	95	36	17	25	0	43	26	32	0	59	52	44	1	81	92	56	79
PST22-7	82	98	71	97	36	17	24	0	42	26	31	0	59	52	44	1	81	93	58	81
PST22-8	82	98	71	98	36	17	24	0	42	26	31	0	59	53	44	1	81	94	60	82
PST22-9	82	98	71	100	36	17	24	0	42	26	30	0	59	53	43	1	81	95	61	84
PST25-1	99	98	72	83	44	20	28	0	52	29	35	0	72	53	46	2	96	86	49	70
PST25-7	89	97	68	81	40	19	28	0	47	28	35	0	65	52	45	2	86	85	47	68
PST25-14	88	87	57	53	42	22	30	0	49	30	35	0	67	50	44	2	83	68	36	45
PST25-21	88	84	54	47	44	22	29	0	50	29	34	1	69	48	43	3	84	64	34	40
PST25-28	86	81	51	39	45	24	30	0	51	31	36	1	69	49	45	3	81	61	32	33
PST25-34	86	76	47	35	46	22	27	0	52	29	32	1	70	45	42	4	82	54	29	29
PST25-39	81	70	43	22	48	29	31	1	55	35	37	1	72	48	46	6	76	46	25	18
PST26-1	99	95	73	78	45	20	26	0	52	28	33	0	72	50	43	2	95	81	45	66
PST26-4	89	95	67	76	40	19	26	0	47	27	33	0	65	49	43	2	85	81	44	64
PST26-9	87	81	55	47	43	21	26	0	49	28	32	1	67	44	42	3	82	57	32	39
PST26-15	88	77	52	41	44	21	26	0	51	27	32	1	69	42	42	3	83	53	30	34
PST26-17	85	71	49	32	45	23	27	0	52	29	33	1	69	41	43	4	80	45	26	27

Figure H97. Pu(80/10/10/0)O₂ mass

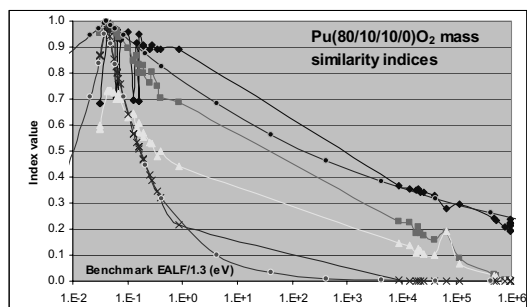


Figure H101. Pu(80/10/10/0)O₂ cylinder

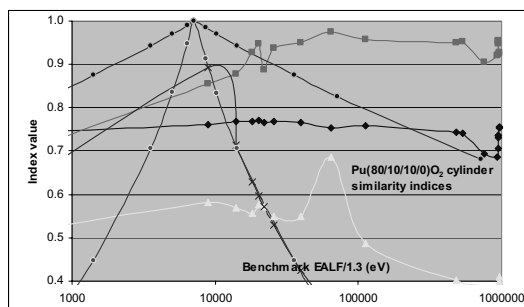


Figure H98. Pu(80/10/10/0)O₂ mass, enl.

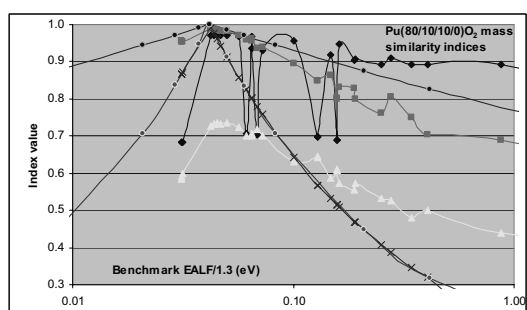


Figure H102. Pu(80/10/10/0)O₂ slab

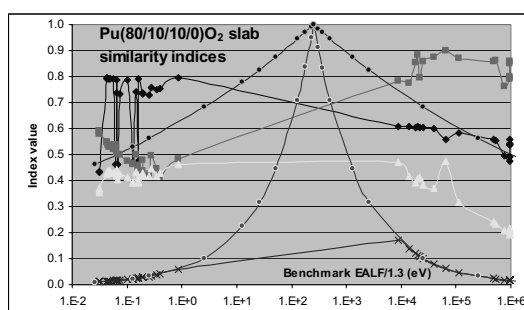


Figure H99. Pu(80/10/10/0)O₂ volume

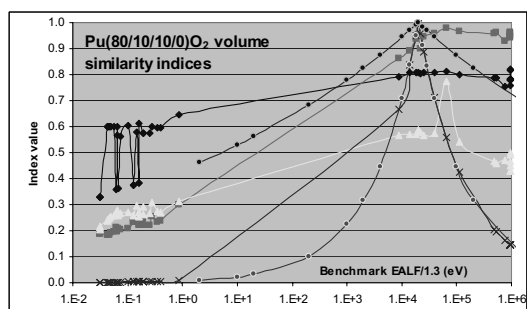


Figure H103. Pu(80/10/10/0)O₂ slab, enl.

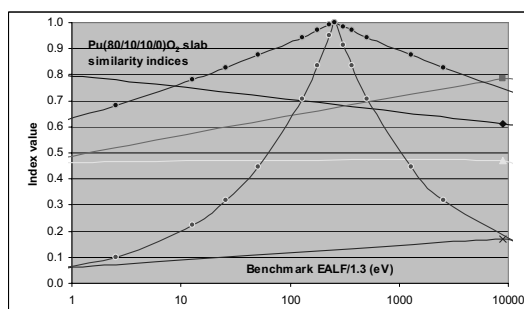


Figure H100. Pu(80/10/10/0)O₂ volume

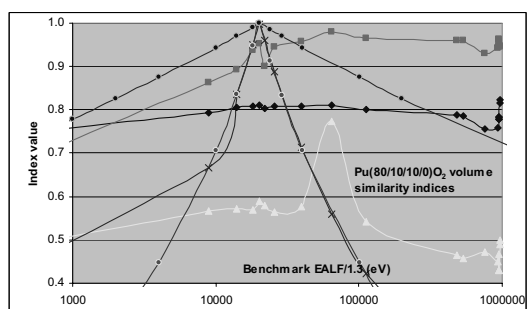


Figure H104. Pu(80/10/10/0)O₂ concentr.

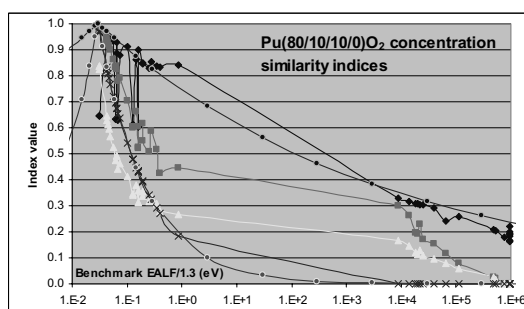


Table H13. Pu(80/10/10/0)O₂ – c_k, E_{sum}, G and R_{e2}

Pu(80/10/10/0)O ₂ applications and experiments similarities – c _k , E _{sum} , G and R _{a2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}
PMF01-1	20	0	0	0	78	94	47	15	71	92	38	9	49	79	20	2	17	0	0	0
PMF02-1	24	0	0	0	82	95	50	14	75	93	41	9	56	80	22	2	22	0	0	0
PMF03-1	21	0	0	0	78	96	43	14	73	95	37	9	54	85	21	2	18	0	0	0
PMF03-2	23	2	2	0	79	96	46	19	74	95	39	12	55	86	23	2	20	2	2	0
PMF03-3	22	0	0	0	78	96	43	14	74	95	37	9	54	86	21	2	19	0	0	0
PMF03-4	24	3	2	0	79	96	47	20	74	95	40	12	56	86	24	2	21	2	2	0
PMF03-5	22	0	0	0	78	96	43	14	74	95	37	9	54	86	21	2	19	0	0	0
PMF05-1	21	0	0	0	76	93	47	16	69	91	39	10	50	76	21	2	18	0	0	0
PMF11-1	28	19	19	0	81	98	77	56	75	98	69	33	56	90	47	6	24	12	8	0
PMF16-1	37	23	15	0	79	86	57	67	76	85	58	89	61	78	47	17	33	30	17	0
PMF22-1	19	0	0	0	76	94	45	15	69	92	37	9	48	79	19	2	16	0	0	0
PMF29-1	23	0	0	0	82	95	49	14	75	93	40	9	54	80	21	2	20	0	0	0
PMF37-1	30	9	7	0	80	97	54	42	76	96	49	25	59	87	32	5	26	8	6	0
PMF37-5	33	16	10	0	81	96	58	71	77	95	55	42	60	88	37	8	29	15	10	0
PMF37-7	34	17	10	0	81	95	57	89	77	94	55	53	60	86	38	10	30	17	11	0
PMF37-10	35	21	13	0	81	95	59	100	77	95	58	60	61	88	41	11	31	19	11	0
PMF37-12	35	18	11	0	81	94	57	95	77	93	56	63	61	85	39	12	31	20	12	0
PMF37-15	36	23	14	0	81	89	57	84	77	88	57	71	61	77	42	14	32	26	15	0
PMF37-16	34	18	12	0	80	90	58	96	77	89	57	57	60	80	41	11	30	23	13	0
PST09-1	68	95	60	87	33	19	22	0	36	29	27	0	43	58	37	1	65	98	83	97
PST09-2	68	95	59	87	33	19	21	0	36	29	26	0	43	59	36	1	65	99	84	97
PST09-3	68	96	58	87	33	19	20	0	36	29	25	0	43	59	35	1	65	99	84	97
PST14-1	70	85	65	57	37	23	26	0	41	31	31	0	47	46	39	2	61	60	35	48
PST14-2	70	85	64	57	38	24	26	0	41	31	31	0	47	47	39	2	61	60	34	48
PST15-1	69	80	61	52	38	24	25	0	41	31	31	0	48	45	39	2	60	53	31	43
PST15-2	69	80	61	52	38	24	25	0	41	31	31	0	48	45	39	2	60	52	31	43
PST22-1	95	83	57	51	61	22	27	0	67	29	32	0	79	46	41	3	90	60	36	43
PST22-2	96	90	63	64	60	21	27	0	66	29	32	0	79	48	41	2	91	71	41	54
PST22-3	97	96	70	80	60	20	26	0	66	28	33	0	79	51	42	2	93	83	49	68
PST22-4	97	97	72	86	60	19	26	0	66	28	33	0	79	52	43	1	93	86	53	72
PST22-5	97	98	73	91	60	19	25	0	66	28	32	0	79	54	44	1	94	90	57	77
PST22-6	97	98	73	94	60	18	25	0	66	28	32	0	79	53	44	1	94	92	60	79
PST22-7	97	99	74	96	60	18	25	0	66	28	31	0	79	54	44	1	95	93	61	81
PST22-8	97	99	73	98	60	18	24	0	66	28	31	0	79	55	43	1	95	94	63	82
PST22-9	97	99	73	99	60	18	24	0	66	28	30	0	79	55	42	1	95	95	65	83
PST25-1	71	96	70	83	36	21	27	0	39	30	34	0	46	54	43	2	63	83	47	69
PST25-7	93	96	71	80	56	21	28	0	62	30	35	0	74	53	44	2	89	84	49	67
PST25-14	92	86	59	53	58	24	30	0	63	31	35	0	74	50	43	2	86	66	38	45
PST25-21	90	83	55	47	58	23	29	0	63	31	34	1	73	48	43	3	85	62	36	39
PST25-28	91	80	53	39	60	25	31	0	65	33	36	1	76	50	45	3	85	59	33	33
PST25-34	89	75	48	35	60	23	27	0	65	30	33	1	75	45	42	4	84	52	31	29
PST25-39	89	69	44	22	65	30	31	1	70	36	37	1	80	49	46	6	84	45	27	18
PST26-1	70	94	72	78	36	21	26	0	40	30	32	0	46	50	40	2	63	78	44	66
PST26-4	93	94	70	76	56	20	27	0	62	29	33	0	73	50	42	2	88	79	46	64
PST26-9	91	80	57	47	58	22	26	0	63	29	32	1	74	44	41	3	85	55	34	39
PST26-15	89	76	53	41	57	22	27	0	63	29	32	1	73	42	41	3	83	51	32	34
PST26-17	89	70	50	32	60	24	27	0	65	30	33	1	75	41	43	4	83	43	28	27

Figure H105. Pu(90/10/0/0)O₂ mass

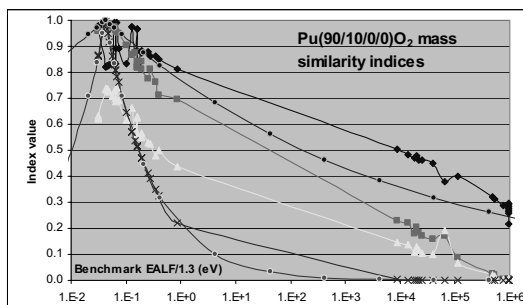


Figure H109. Pu(90/10/0/0)O₂ cylinder

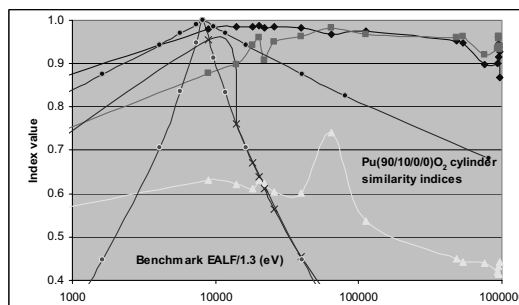


Figure H106. Pu(90/10/0/0)O₂ mass, enl.

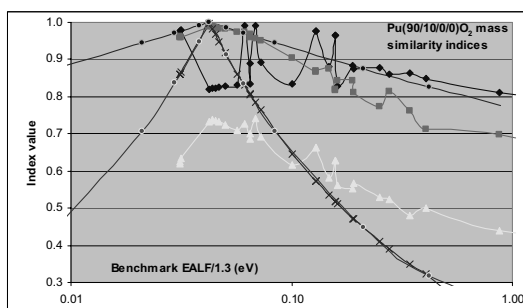


Figure H110. Pu(90/10/0/0)O₂ slab

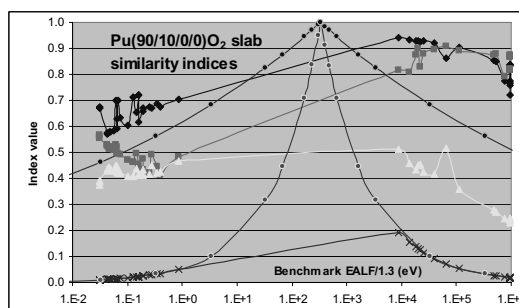


Figure H107. Pu(90/10/0/0)O₂ volume

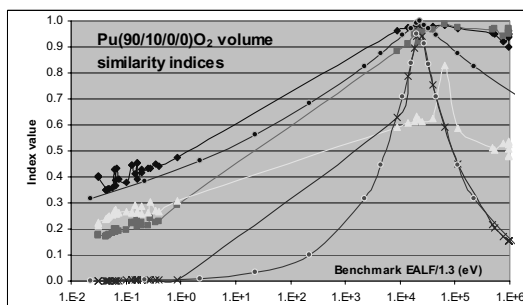


Figure H111. Pu(90/10/0/0)O₂ slab, enl.

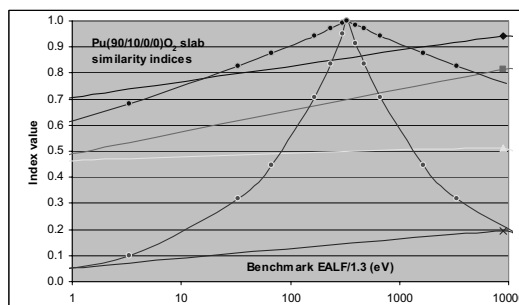


Figure H108. Pu(90/10/0/0)O₂ volume

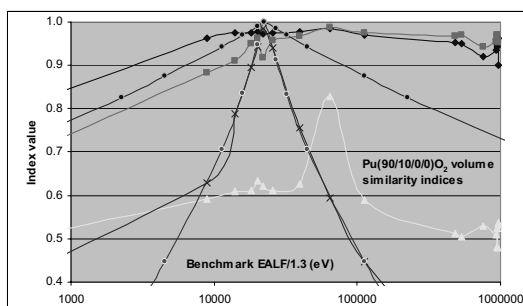


Figure H112. Pu(90/10/0/0)O₂ concentr.

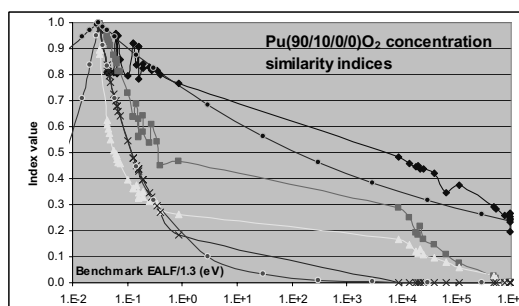


Table H14. Pu(90/10/0/0)O₂ – c_k, E_{sum}, G and R_{e2}

Pu(90/10/0/0)O ₂ applications and experiments similarities – c _k , E _{sum} , G and R _{a2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}
PMF01-1	27	0	0	0	95	96	52	15	91	94	43	9	77	82	24	2	24	0	0	0
PMF02-1	22	0	0	0	90	95	53	15	87	93	44	9	72	82	24	2	20	0	0	0
PMF03-1	28	0	0	0	94	97	48	15	94	96	41	9	83	87	25	2	26	0	0	0
PMF03-2	31	2	2	0	95	97	51	21	95	96	44	12	85	88	27	3	29	2	2	0
PMF03-3	29	0	0	0	95	97	48	15	94	96	41	9	84	87	25	2	27	0	0	0
PMF03-4	32	3	2	0	95	97	51	22	95	96	45	13	86	88	28	3	29	2	2	0
PMF03-5	29	0	0	0	95	97	48	15	94	96	42	9	84	87	25	2	27	0	0	0
PMF05-1	29	0	0	0	92	94	53	17	90	92	44	10	77	79	24	2	26	0	0	0
PMF11-1	38	17	19	0	98	99	83	59	97	98	74	36	86	91	52	7	35	11	8	0
PMF16-1	51	23	15	0	96	88	59	63	98	88	63	95	94	82	51	19	48	29	17	0
PMF22-1	27	0	0	0	94	95	51	16	90	94	42	9	76	82	23	2	25	0	0	0
PMF29-1	26	0	0	0	96	96	54	15	93	94	44	9	78	82	24	2	23	0	0	0
PMF37-1	40	9	7	0	97	97	59	45	98	97	54	27	90	89	36	5	37	8	6	0
PMF37-5	45	16	10	0	98	97	63	76	98	96	60	45	92	89	41	9	42	15	10	0
PMF37-7	46	17	11	0	98	96	61	94	98	95	60	56	93	88	43	11	44	17	11	0
PMF37-10	48	20	13	0	98	96	63	94	99	96	63	64	93	90	45	13	45	19	11	0
PMF37-12	47	18	11	0	98	95	61	90	98	94	61	67	93	88	43	14	44	19	12	0
PMF37-15	48	22	14	0	97	91	61	79	98	90	62	76	93	81	46	15	46	25	15	0
PMF37-16	46	18	12	0	97	92	62	98	98	91	62	61	93	83	45	12	44	22	13	0
PST09-1	98	96	63	87	40	18	23	0	47	27	28	0	68	56	39	1	99	99	88	97
PST09-2	98	96	62	86	40	18	22	0	47	28	27	0	67	56	39	1	99	100	90	98
PST09-3	98	96	62	86	40	18	21	0	47	28	26	0	67	57	38	1	99	100	90	98
PST14-1	98	87	66	57	45	22	26	0	52	30	32	0	71	46	41	2	92	64	36	48
PST14-2	98	87	66	57	45	22	26	0	52	30	32	0	71	46	41	2	92	64	36	48
PST15-1	97	82	63	52	45	23	26	0	53	30	32	0	72	45	41	2	91	56	33	44
PST15-2	97	82	63	52	46	23	26	0	53	30	32	0	72	45	41	2	91	56	33	44
PST22-1	83	84	56	51	39	21	26	0	45	28	32	0	62	45	41	2	78	63	34	43
PST22-2	84	90	62	65	38	20	27	0	44	28	32	0	60	47	41	2	80	73	40	54
PST22-3	83	96	69	81	36	19	26	0	42	27	33	0	59	50	42	1	81	84	48	68
PST22-4	83	97	71	86	36	18	26	0	42	27	33	0	59	51	43	1	81	88	51	72
PST22-5	83	98	73	92	36	18	25	0	42	27	32	0	58	52	44	1	81	91	55	77
PST22-6	83	98	73	95	35	17	25	0	41	26	31	0	58	51	44	1	81	93	58	80
PST22-7	82	99	74	97	35	17	24	0	41	26	31	0	58	52	44	1	81	94	59	81
PST22-8	82	99	74	98	35	17	24	0	41	26	31	0	57	53	43	1	81	94	61	83
PST22-9	82	99	73	100	35	17	24	0	41	26	30	0	57	53	43	1	81	95	62	84
PST25-1	99	98	73	83	43	20	27	0	50	29	35	0	70	53	45	1	96	86	50	70
PST25-7	89	97	70	81	39	20	27	0	45	29	35	0	63	52	45	1	86	85	49	68
PST25-14	88	88	58	54	41	22	29	0	48	30	35	0	65	49	44	2	84	69	37	45
PST25-21	88	84	55	47	43	22	29	0	49	30	34	0	67	48	43	2	84	64	35	40
PST25-28	86	81	52	39	44	24	30	0	50	32	36	1	67	49	45	3	82	61	33	33
PST25-34	86	76	48	35	45	23	27	0	51	29	33	1	69	45	42	3	82	54	30	29
PST25-39	81	70	44	22	48	29	31	1	54	35	37	1	70	48	46	5	77	47	26	18
PST26-1	99	96	74	78	43	20	26	0	50	28	33	0	70	50	42	1	95	81	46	66
PST26-4	89	95	69	76	39	19	26	0	46	27	33	0	63	49	42	1	86	81	46	64
PST26-9	88	81	57	47	42	21	26	0	48	28	31	0	66	43	41	2	83	58	33	40
PST26-15	88	77	53	41	43	21	26	0	50	28	32	1	67	42	42	3	83	54	31	35
PST26-17	85	71	50	32	44	23	27	0	50	29	32	1	68	41	43	3	80	45	27	27

Figure H113. Pu(80/15/5/0)O₂ mass

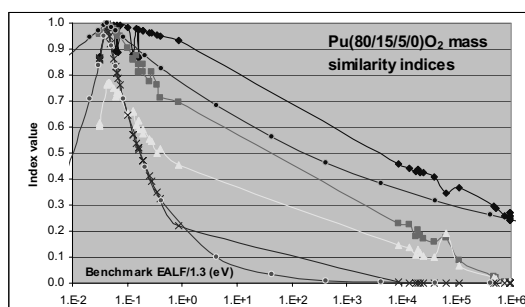


Figure H117. Pu(80/15/5/0)O₂ cylinder

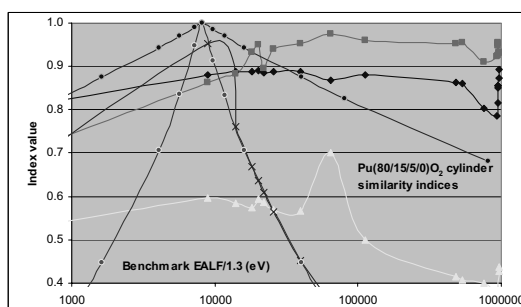


Figure H114. Pu(80/15/5/0)O₂ mass, enl.

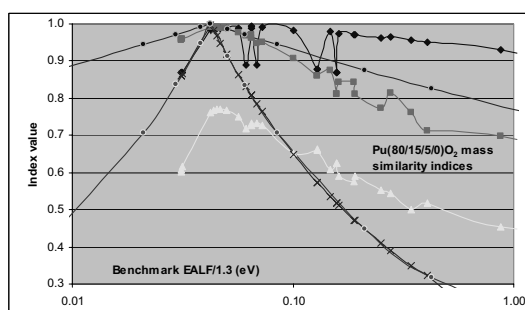


Figure H118. Pu(80/15/5/0)O₂ slab

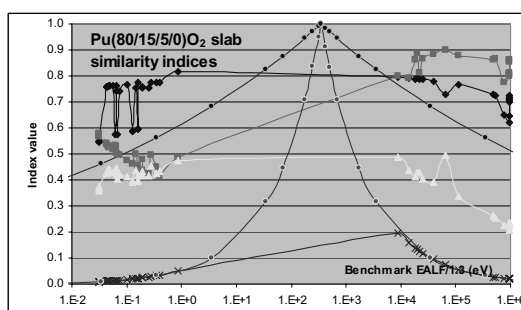


Figure H115. Pu(80/15/5/0)O₂ volume

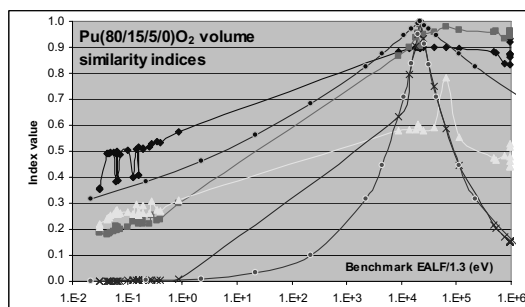


Figure H119. Pu(80/15/5/0)O₂ slab, enl.

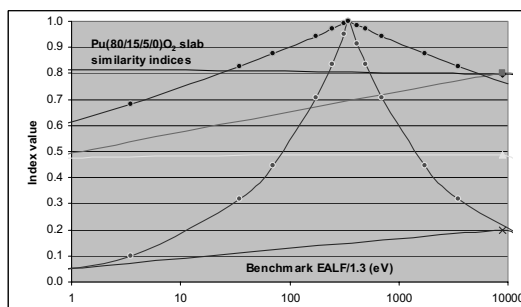


Figure H116. Pu(80/15/5/0)O₂ volume

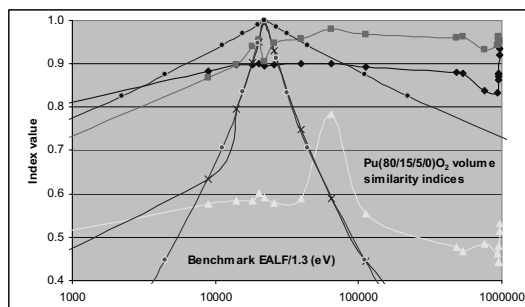


Figure H120. Pu(80/15/5/0)O₂ concentr

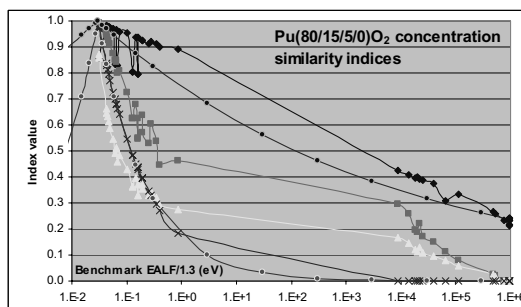


Table H15. Pu(80/15/5/0)O₂ – c_k, E_{sum}, G and R_{e2}

Pu(80/15/5/0)O ₂ applications and experiments similarities – c _k , E _{slim} , G and R _{e2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}
PMF01-1	24	0	0	0	86	95	48	15	82	93	40	9	64	80	22	2	22	0	0	0
PMF02-1	25	0	0	0	93	95	53	15	89	93	44	9	72	81	24	2	23	0	0	0
PMF03-1	26	0	0	0	87	96	44	15	85	95	38	9	71	85	23	2	23	0	0	0
PMF03-2	29	2	2	0	88	96	47	20	86	95	41	12	73	87	25	3	26	2	2	0
PMF03-3	27	0	0	0	88	96	44	15	86	95	38	9	72	86	23	2	24	0	0	0
PMF03-4	30	3	2	0	88	96	48	21	86	95	42	13	73	86	26	3	27	2	2	0
PMF03-5	27	0	0	0	88	96	44	15	86	95	38	9	72	86	23	2	24	0	0	0
PMF05-1	26	0	0	0	84	93	48	17	80	91	40	10	65	78	22	2	23	0	0	0
PMF11-1	35	17	19	0	90	98	78	59	87	98	70	36	73	90	49	7	31	11	8	0
PMF16-1	46	23	15	0	88	87	58	63	88	86	60	95	80	80	49	20	43	29	17	0
PMF22-1	24	0	0	0	83	94	46	15	79	92	38	9	62	80	21	2	21	0	0	0
PMF29-1	26	0	0	0	92	95	52	15	87	93	43	9	70	81	24	2	23	0	0	0
PMF37-1	37	9	7	0	89	97	55	44	88	96	50	27	77	88	34	6	33	8	6	0
PMF37-5	41	16	10	0	90	96	59	75	89	95	57	45	78	88	39	9	37	15	10	0
PMF37-7	42	17	11	0	90	95	58	93	89	94	57	56	79	87	40	12	39	17	11	0
PMF37-10	44	20	13	0	90	96	60	95	89	95	59	64	79	89	43	13	40	19	11	0
PMF37-12	43	18	11	0	90	94	58	90	89	93	57	67	79	86	41	14	40	19	12	0
PMF37-15	44	22	14	0	90	90	58	80	89	88	58	76	79	79	44	16	41	26	15	0
PMF37-16	42	18	12	0	89	91	59	99	89	89	59	61	79	81	43	13	39	22	13	0
PST09-1	87	96	62	87	36	19	22	0	41	29	27	0	55	57	38	1	86	99	86	97
PST09-2	87	96	61	86	36	19	22	0	41	29	27	0	55	57	37	1	86	99	87	98
PST09-3	87	96	60	86	36	19	21	0	41	29	26	0	55	58	36	1	86	99	87	98
PST14-1	88	86	66	57	40	23	26	0	45	31	31	0	59	46	39	2	81	63	36	48
PST14-2	88	86	66	57	40	23	26	0	45	31	31	0	59	46	39	2	81	62	36	48
PST15-1	87	81	63	52	41	24	26	0	46	31	31	0	59	45	40	2	79	55	33	44
PST15-2	87	81	63	52	41	24	26	0	46	31	31	0	59	44	39	2	79	55	33	44
PST22-1	97	84	59	51	52	22	27	0	59	29	32	0	78	46	41	2	94	62	37	43
PST22-2	98	91	65	65	51	21	27	0	58	29	32	0	77	47	41	2	95	72	43	54
PST22-3	99	96	73	81	50	20	26	0	57	28	33	0	76	50	42	1	97	84	51	68
PST22-4	99	98	75	86	50	19	26	0	57	28	33	0	76	52	43	1	97	88	54	73
PST22-5	99	99	77	92	49	19	25	0	57	28	32	0	76	53	44	1	98	91	59	77
PST22-6	99	99	77	95	49	18	25	0	57	27	31	0	76	52	44	1	98	93	61	80
PST22-7	99	99	77	97	49	18	24	0	57	28	31	0	76	53	44	1	98	94	63	81
PST22-8	99	99	77	98	49	18	24	0	57	28	31	0	76	54	43	1	98	94	65	83
PST22-9	99	99	76	100	49	18	24	0	57	28	30	0	76	54	42	1	98	95	66	84
PST25-1	89	97	72	83	39	21	27	0	44	30	34	0	58	53	44	1	83	85	49	70
PST25-7	99	97	73	81	49	21	28	0	56	30	35	0	74	53	44	1	96	85	51	68
PST25-14	98	88	61	54	51	23	30	0	58	31	35	0	76	50	44	2	94	68	40	45
PST25-21	97	84	58	47	51	23	29	0	58	31	34	0	76	48	44	2	93	64	37	40
PST25-28	96	81	55	39	53	25	31	0	60	33	36	1	78	49	45	3	92	60	35	33
PST25-34	96	76	50	35	54	23	28	0	60	30	33	1	78	45	42	3	91	54	32	29
PST25-39	93	70	45	22	58	30	31	1	65	36	37	1	82	49	47	5	89	46	28	18
PST26-1	89	95	73	79	39	21	26	0	44	29	32	0	58	50	41	1	83	80	46	66
PST26-4	99	95	73	76	49	20	26	0	56	29	33	0	74	50	42	1	96	81	48	64
PST26-9	97	81	59	47	51	22	26	0	58	29	32	0	75	44	42	2	92	57	35	40
PST26-15	96	77	55	41	52	22	26	0	58	29	32	1	76	42	42	3	91	53	33	35
PST26-17	95	71	52	32	53	24	27	0	60	30	33	1	77	41	43	3	90	44	29	27

Figure H121. Pu(71/17/11/1)O₂ mass

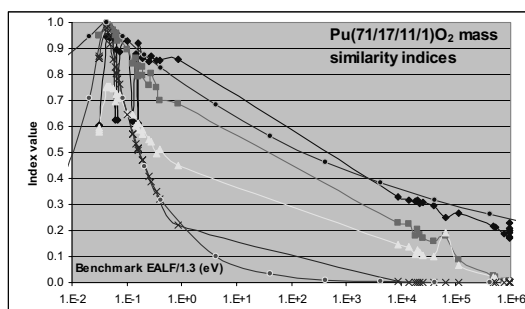


Figure H125. Pu(71/17/11/1)O₂ cylinder

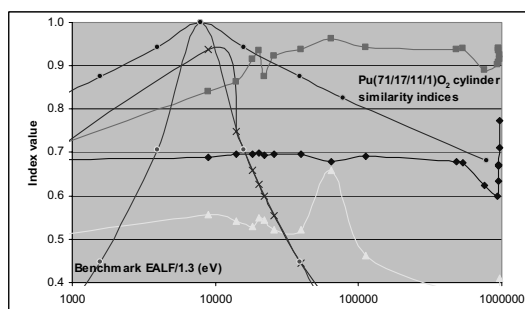


Figure H122. Pu(71/17/11/1)O₂ mass, enl.

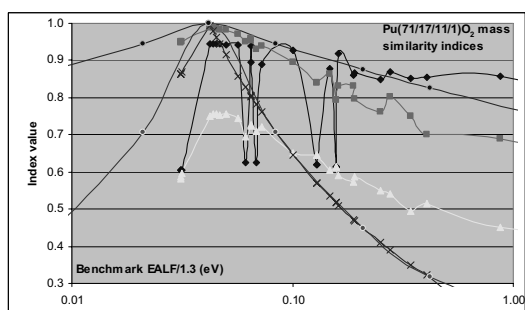


Figure H126. Pu(71/17/11/1)O₂ slab

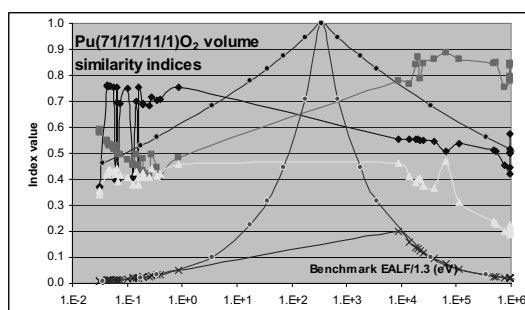


Figure H123. Pu(71/17/11/1)O₂ volume

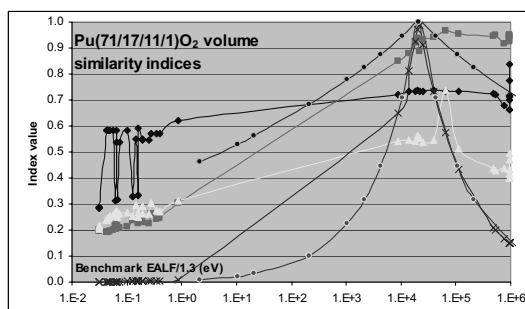


Figure H127. Pu(71/17/11/1)O₂ concentr.

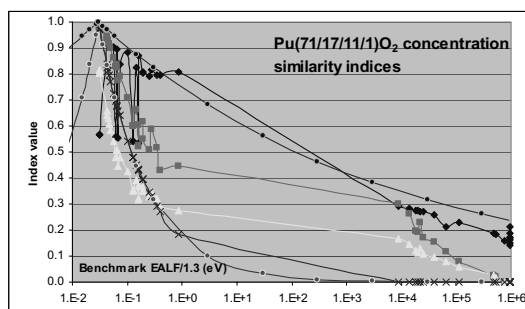


Figure H124. Pu(71/17/11/1)O₂ volume

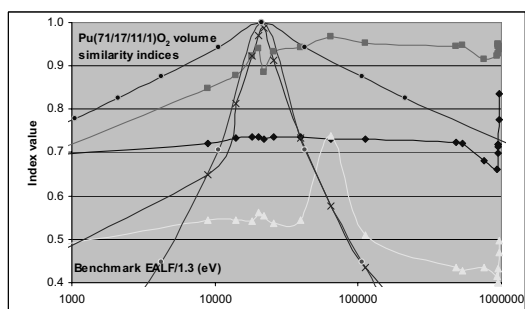


Figure H128. Pu(71/17/11/1)O₂ concentr.

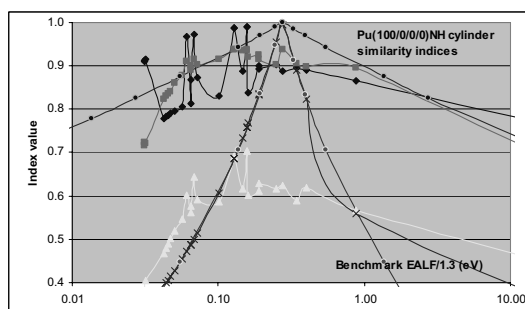


Table H16. Pu(71/17/11/1)O₂ - c_k, E_{sum}, G and R_{e2}

Pu(71/17/11/1)O ₂ applications and experiments similarities – c _k , E _{sum} , G and R _{e2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}
PMF01-1	18	0	0	0	70	93	43	15	63	91	36	9	45	78	20	2	15	0	0	0
PMF02-1	23	0	0	0	84	95	50	15	77	92	41	9	57	80	23	2	21	0	0	0
PMF03-1	19	0	0	0	71	94	40	15	67	93	34	9	50	84	21	2	16	0	0	0
PMF03-2	21	2	2	0	72	95	43	20	68	94	37	12	51	85	23	3	18	2	2	0
PMF03-3	20	0	0	0	72	95	40	15	67	94	34	9	50	85	21	2	17	0	0	0
PMF03-4	22	3	2	0	72	95	44	21	68	94	38	13	51	85	24	3	19	2	2	0
PMF03-5	20	0	0	0	72	95	40	15	67	94	34	9	50	84	21	2	17	0	0	0
PMF05-1	19	0	0	0	68	91	44	17	62	89	36	10	45	75	20	2	16	0	0	0
PMF11-1	25	18	19	0	73	97	74	58	68	96	66	35	51	89	47	7	21	12	8	0
PMF16-1	33	23	15	0	72	85	54	65	69	84	56	94	56	78	46	20	29	30	17	0
PMF22-1	17	0	0	0	66	92	42	15	60	90	34	9	42	78	19	2	14	0	0	0
PMF29-1	21	0	0	0	78	94	47	15	71	92	39	9	52	79	22	2	19	0	0	0
PMF37-1	27	9	7	0	73	95	51	44	69	94	46	26	54	86	31	6	23	8	6	0
PMF37-5	30	16	10	0	74	94	55	73	70	94	52	45	55	86	37	9	26	15	10	0
PMF37-7	31	17	11	0	74	93	54	91	70	92	52	55	55	85	38	12	27	17	11	0
PMF37-10	32	21	13	0	74	94	56	97	70	93	55	63	55	87	40	13	28	19	11	0
PMF37-12	31	18	11	0	74	92	54	92	70	91	53	66	55	84	39	14	27	20	12	0
PMF37-15	32	22	14	0	73	88	55	81	70	86	54	75	56	77	41	16	28	26	15	0
PMF37-16	31	18	12	0	73	89	55	99	69	87	54	60	55	79	41	13	27	23	13	0
PST09-1	61	95	60	87	29	20	22	0	31	30	26	0	37	58	36	1	57	98	80	97
PST09-2	60	95	59	86	29	20	21	0	31	30	26	0	37	58	35	1	57	98	82	97
PST09-3	60	95	58	86	29	20	20	0	31	30	25	0	37	59	34	1	57	98	81	98
PST14-1	62	84	65	57	33	24	25	0	35	31	30	0	41	46	38	2	54	60	35	48
PST14-2	62	84	65	57	33	24	25	0	35	31	30	0	41	46	38	2	54	60	35	48
PST15-1	61	79	61	52	33	25	25	0	36	31	30	0	41	44	38	2	53	52	32	44
PST15-2	61	79	61	52	33	25	25	0	36	31	30	0	41	44	38	2	53	52	32	44
PST22-1	92	83	59	51	59	23	27	0	65	30	32	0	75	45	41	2	87	61	37	43
PST22-2	93	89	65	64	58	21	27	0	64	29	32	0	75	47	41	2	88	71	43	54
PST22-3	94	95	72	81	58	20	26	0	64	29	33	0	75	51	42	1	90	83	51	68
PST22-4	94	97	75	86	58	20	26	0	64	29	33	0	75	52	43	1	90	86	54	72
PST22-5	94	98	76	92	58	20	25	0	64	29	32	0	76	53	43	1	91	90	58	77
PST22-6	94	98	75	94	58	19	25	0	64	28	31	0	76	53	44	1	91	92	61	80
PST22-7	95	99	76	96	58	19	24	0	64	29	31	0	76	54	43	1	91	93	63	81
PST22-8	95	99	76	98	58	19	24	0	64	29	30	0	76	55	43	1	92	94	64	83
PST22-9	95	99	75	99	58	19	24	0	64	29	30	0	76	55	42	1	92	94	66	84
PST25-1	63	95	69	83	31	22	26	0	34	31	33	0	40	53	42	1	56	83	48	70
PST25-7	89	96	73	80	54	22	28	0	59	31	34	0	70	53	44	1	85	84	51	68
PST25-14	88	86	60	53	55	24	30	0	60	32	35	0	70	50	43	2	82	66	39	45
PST25-21	86	83	57	47	55	24	29	0	60	31	34	0	69	48	43	2	80	62	37	40
PST25-28	87	80	54	39	57	26	31	0	62	34	36	1	72	49	44	3	82	59	34	33
PST25-34	85	75	50	35	57	24	27	0	62	30	33	1	71	44	41	3	80	52	32	29
PST25-39	86	69	45	22	62	31	31	1	67	37	37	1	76	48	46	5	81	45	27	18
PST26-1	63	93	71	78	32	22	25	0	34	30	32	0	40	50	39	1	55	78	45	66
PST26-4	89	94	72	76	54	21	26	0	59	29	33	0	69	50	42	1	84	79	48	64
PST26-9	87	80	59	47	55	23	26	0	60	29	32	0	69	43	41	2	81	55	35	40
PST26-15	85	76	55	41	55	23	26	0	59	29	32	1	69	42	41	3	79	51	33	34
PST26-17	86	70	51	32	57	24	27	0	62	30	33	1	71	41	42	3	80	43	29	27

PuNH applications and plutonium benchmarks

Figure H129. Pu(100/0/0/0)NH mass

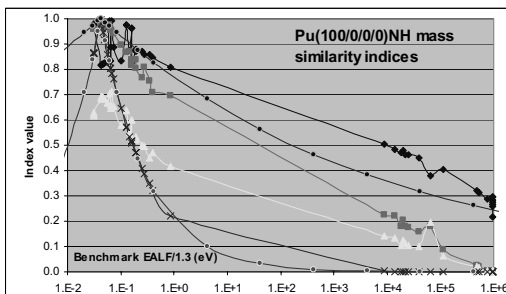


Figure H133. Pu(100/0/0/0)NH cylinder

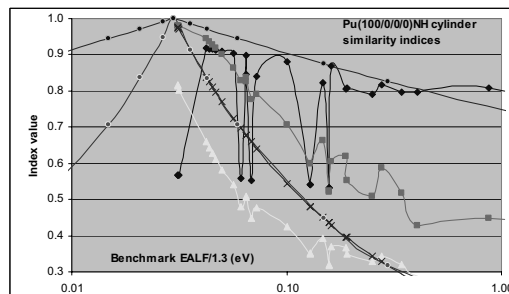


Figure H130. Pu(100/0/0/0)NH mass, enl.

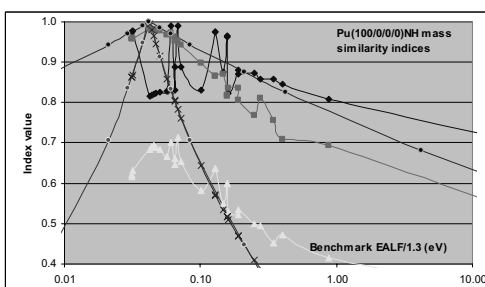


Figure H134. Pu(100/0/0/0)NH slab

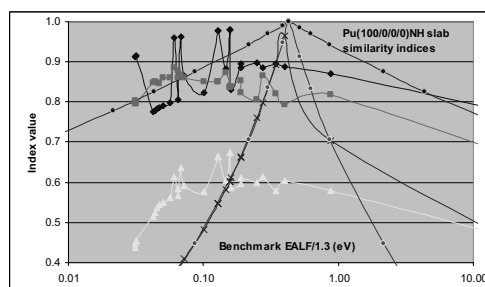


Figure H131. Pu(100/0/0/0)NH volume

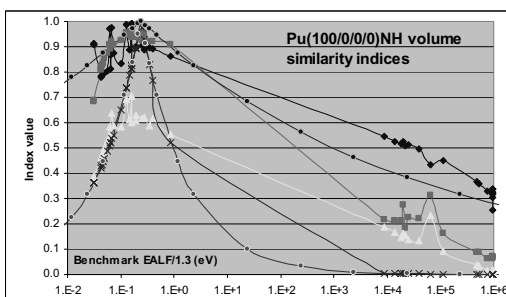


Figure H135. Pu(100/0/0/0)NH concentration

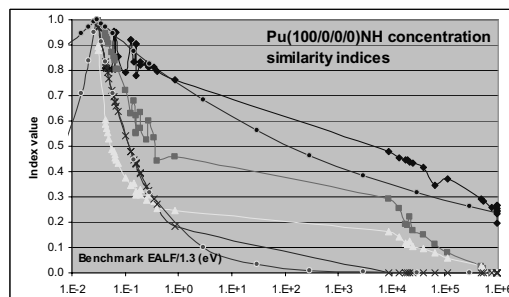


Figure H132. Pu(100/0/0/0)NH volume

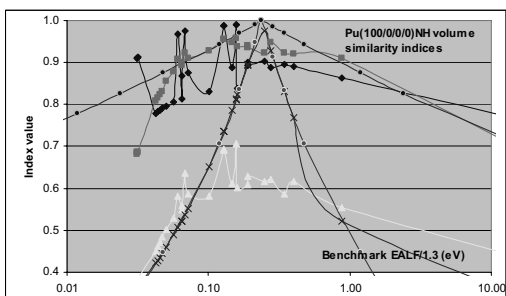


Figure H136. Pu(100/0/0/0)NH concentration

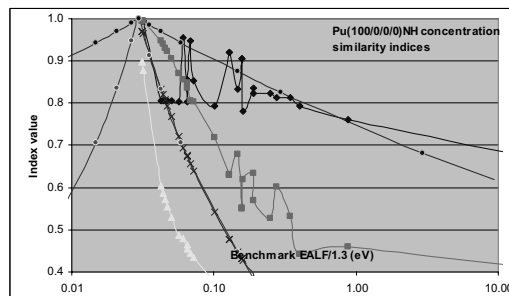


Table H17. Pu(100/0/0/0)NH - c_k , E_{sum} , G and R_{e2}

Pu(100/0/0/0)NH applications and experiments similarities – c_k , E_{sum} , G and R_{e2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}
PMF01-1	27	0	0	0	32	6	2	0	32	7	2	0	35	11	2	0	24	0	0	0
PMF02-1	21	0	0	0	25	6	2	0	26	7	2	0	28	11	2	0	19	0	0	0
PMF03-1	38	18	19	0	43	31	23	0	44	33	24	0	46	37	25	0	35	11	8	0
PMF03-2	26	0	0	0	30	7	2	0	31	7	2	0	33	11	2	0	23	0	0	0
PMF03-3	28	0	0	0	33	7	1	0	33	8	2	0	36	12	2	0	26	0	0	0
PMF03-4	31	2	2	0	36	9	3	0	36	10	3	0	39	15	4	0	28	2	2	0
PMF03-5	30	0	0	0	34	7	1	0	35	8	2	0	37	12	2	0	27	0	0	0
PMF05-1	32	3	2	0	37	9	4	0	37	10	4	0	40	15	5	0	29	2	2	0
PMF11-1	29	0	0	0	34	7	1	0	34	8	2	0	37	12	2	0	27	0	0	0
PMF16-1	29	0	0	0	33	6	2	0	34	7	2	0	36	11	3	0	26	0	0	0
PMF22-1	51	23	14	0	55	21	19	1	56	25	20	1	58	35	23	1	48	29	16	0
PMF29-1	27	0	0	0	32	6	2	0	33	7	2	0	35	11	2	0	25	0	0	0
PMF37-1	40	9	6	0	45	16	9	0	46	17	9	0	49	22	11	0	37	8	6	0
PMF37-5	45	16	10	0	50	22	13	0	50	24	14	0	53	30	15	0	42	15	9	0
PMF37-7	46	17	10	0	51	22	14	0	52	24	14	0	55	31	16	0	43	17	10	0
PMF37-10	48	21	12	0	52	27	16	0	53	29	17	0	56	36	19	0	45	19	11	0
PMF37-12	47	18	11	0	52	21	15	0	53	24	15	0	55	31	17	0	44	19	12	0
PMF37-15	48	22	13	0	53	21	16	0	53	24	17	0	56	31	19	1	46	25	14	0
PMF37-16	46	18	11	0	51	19	15	0	52	21	16	0	54	29	18	0	44	22	13	0
PST09-1	98	96	63	87	91	69	39	36	91	72	41	34	92	79	46	27	99	99	88	97
PST09-2	98	96	62	86	91	68	38	36	91	72	40	34	91	80	45	27	100	100	90	97
PST09-3	98	96	62	86	91	69	37	36	91	72	39	34	91	80	44	27	100	100	90	97
PST14-1	97	87	64	57	99	96	69	74	99	94	69	69	98	85	66	55	92	63	35	48
PST14-2	97	87	64	57	99	96	69	74	99	94	69	69	98	85	66	55	92	63	34	48
PST15-1	96	82	60	52	99	96	71	81	99	94	70	76	98	84	68	60	91	55	31	43
PST15-2	96	82	60	52	99	96	71	81	99	94	70	76	98	84	67	60	91	55	31	43
PST22-1	82	84	53	51	84	94	60	82	84	92	60	77	83	84	59	61	78	62	32	43
PST22-2	83	90	58	65	83	93	58	65	83	91	59	61	82	85	58	48	79	72	37	54
PST22-3	83	95	65	81	81	89	55	52	81	89	56	49	81	86	57	39	80	84	45	68
PST22-4	83	97	67	86	81	88	53	49	81	88	55	46	80	86	56	36	80	87	49	72
PST22-5	83	98	68	92	80	85	50	46	80	86	52	43	79	86	55	34	81	91	53	77
PST22-6	82	98	69	95	79	83	48	44	79	84	50	41	79	85	54	33	81	92	56	79
PST22-7	82	98	69	96	79	82	47	44	79	83	49	41	78	85	54	32	81	93	57	81
PST22-8	82	98	69	98	78	82	46	43	78	83	48	40	78	85	53	32	81	94	59	82
PST22-9	82	98	68	99	78	81	45	42	78	82	47	39	78	85	51	31	81	95	60	83
PST25-1	99	97	70	83	97	91	58	51	97	91	60	47	96	89	61	38	96	85	48	69
PST25-7	89	96	66	80	87	90	56	52	87	90	58	49	86	88	58	39	86	85	46	67
PST25-14	88	87	55	53	89	95	61	79	89	94	62	73	88	87	61	58	83	68	35	45
PST25-21	88	84	52	47	90	94	61	89	90	93	61	83	89	85	60	66	84	63	33	39
PST25-28	86	81	49	39	89	95	62	93	89	94	63	99	89	87	61	80	81	60	31	33
PST25-34	86	76	45	35	90	92	59	83	90	90	59	89	89	82	58	89	81	53	28	29
PST25-39	81	69	42	22	86	91	56	52	87	90	57	56	87	82	58	70	76	46	25	18
PST26-1	99	95	71	78	97	92	64	54	97	92	64	50	96	87	64	40	95	81	45	66
PST26-4	89	94	65	76	87	91	59	55	87	90	59	51	87	86	59	41	85	80	43	64
PST26-9	87	81	54	47	89	94	63	89	89	92	63	83	89	82	61	66	82	57	31	39
PST26-15	87	77	50	41	90	92	62	98	90	90	62	96	90	81	60	76	82	53	29	34
PST26-17	85	71	47	32	89	92	62	77	89	90	62	82	89	79	60	97	79	44	25	27

Figure H137. Pu(95/5/0/0)NH mass

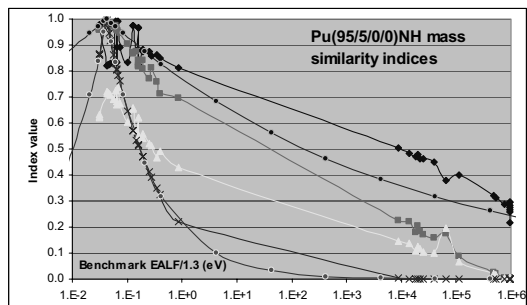


Figure H141. Pu(95/5/0/0)NH cylinder

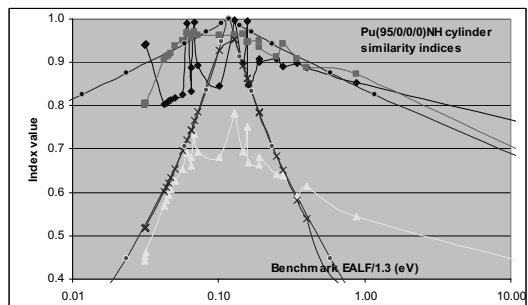


Figure H138. Pu(95/5/0/0)NH mass, enl.

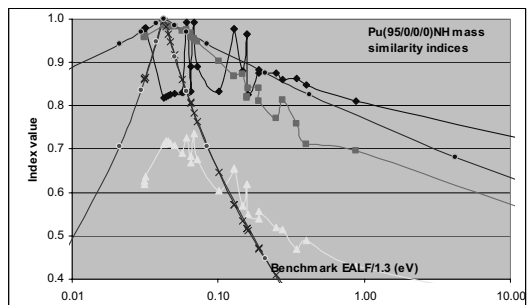


Figure H142. Pu(95/5/0/0)NH slab

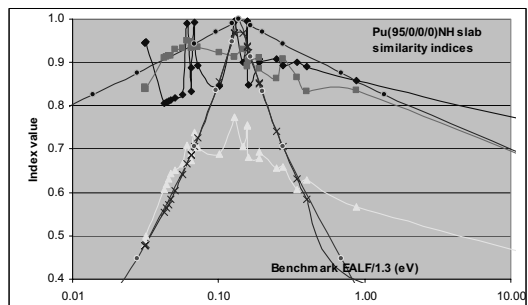


Figure H139. Pu(95/5/0/0)NH volume

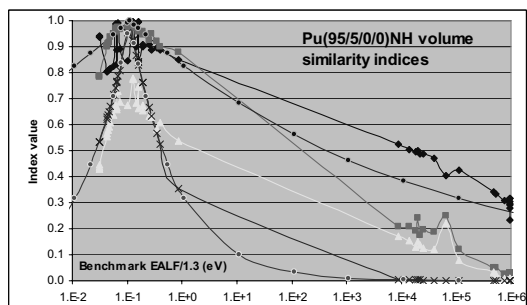


Figure H143. Pu(95/5/0/0)NH concentr.

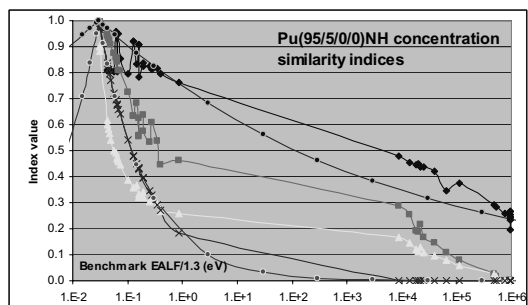


Figure H140. Pu(95/5/0/0)NH volume

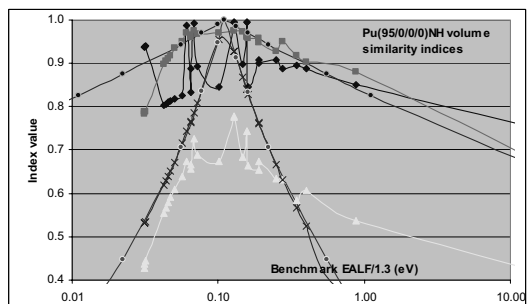


Figure H144. Pu(95/5/0/0)NH concentr.

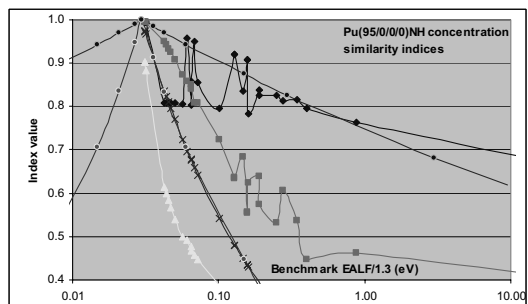


Table H18. Pu(95/5/0/0)NH - c_k , E_{sum} , G and R_{e2}

Pu(95/5/0/0)NH applications and experiments similarities – c _k , E _{slim} , G and R _{e2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}	c _k	E _s	G	R _{e2}
PMF 01-1	27	0	0	0	29	3	1	0	29	3	1	0	30	4	1	0	24	0	0	0
PMF02-1	22	0	0	0	23	3	1	0	24	3	1	0	24	4	1	0	20	0	0	0
PMF03-1	38	17	19	0	40	25	22	0	41	25	22	0	41	26	23	0	35	11	8	0
PMF03-2	26	0	0	0	28	3	1	0	28	3	1	0	29	4	1	0	23	0	0	0
PMF03-3	28	0	0	0	30	3	1	0	30	3	1	0	31	4	1	0	26	0	0	0
PMF03-4	31	2	2	0	33	5	3	0	34	5	3	0	34	6	3	0	29	2	2	0
PMF03-5	30	0	0	0	32	3	1	0	32	3	1	0	32	4	1	0	27	0	0	0
PMF05-1	32	3	2	0	34	5	3	0	34	5	3	0	35	6	4	0	29	2	2	0
PMF11-1	29	0	0	0	32	3	1	0	32	3	1	0	32	4	1	0	27	0	0	0
PMF16-1	29	0	0	0	31	3	1	0	31	3	1	0	31	3	1	0	26	0	0	0
PMF22-1	51	23	15	0	53	21	17	0	53	23	18	0	54	29	20	0	48	29	17	0
PMF29-1	27	0	0	0	30	3	1	0	30	3	1	0	30	4	1	0	25	0	0	0
PMF37-1	40	9	7	0	43	12	8	0	43	12	8	0	44	14	9	0	37	8	6	0
PMF37-5	45	16	10	0	47	19	12	0	47	20	12	0	48	22	13	0	42	15	10	0
PMF37-7	46	17	10	0	49	20	12	0	49	21	13	0	50	23	14	0	44	17	11	0
PMF37-10	48	20	13	0	50	24	15	0	50	25	15	0	51	27	16	0	45	19	11	0
PMF37-12	47	18	11	0	49	19	13	0	50	21	14	0	51	24	15	0	44	19	12	0
PMF37-15	48	22	14	0	50	21	15	0	51	22	16	0	51	25	17	0	46	25	15	0
PMF37-16	46	18	12	0	49	17	14	0	49	19	15	0	50	23	16	0	44	22	13	0
PST09-1	98	96	64	87	94	79	45	53	94	81	46	52	95	84	50	48	99	99	88	97
PST09-2	98	96	63	86	94	78	44	53	94	80	45	52	95	84	49	48	100	100	90	97
PST09-3	98	96	62	86	94	79	43	53	94	81	44	52	95	84	48	48	100	100	90	97
PST14-1	98	87	66	57	100	97	78	93	100	96	78	95	100	91	77	97	92	64	36	48
PST14-2	98	87	65	57	100	97	78	93	100	96	78	95	100	91	77	97	92	63	36	48
PST15-1	97	82	62	52	99	96	74	84	99	95	75	86	99	89	76	94	91	56	32	43
PST15-2	97	82	62	52	99	96	74	84	99	95	75	86	99	89	75	94	91	55	32	43
PST22-1	83	84	55	51	85	96	66	83	85	95	67	85	85	90	68	92	78	62	33	43
PST22-2	83	90	60	65	84	97	68	95	85	96	68	93	85	92	69	86	80	72	39	54
PST22-3	83	96	67	81	83	96	66	76	83	96	66	74	83	93	67	69	80	84	47	68
PST22-4	83	97	69	86	83	95	64	72	83	95	65	70	83	93	67	64	81	87	50	72
PST22-5	83	98	71	92	82	94	61	67	82	94	63	65	82	93	65	60	81	91	54	77
PST22-6	83	98	71	95	81	92	59	65	81	92	61	63	81	92	64	58	81	92	57	80
PST22-7	82	98	72	97	81	91	58	64	81	92	59	62	81	92	63	57	81	93	58	81
PST22-8	82	99	72	98	81	91	57	63	81	91	58	61	81	91	62	56	81	94	60	82
PST22-9	82	99	71	100	80	90	55	62	80	91	57	60	81	91	61	56	81	95	62	84
PST25-1	99	98	72	83	99	97	67	74	99	97	69	72	99	95	71	67	96	86	49	70
PST25-7	89	97	68	81	89	97	67	77	89	96	68	74	89	95	69	69	86	85	48	68
PST25-14	88	87	57	54	90	97	68	87	90	97	69	89	90	93	71	97	84	68	37	45
PST25-21	88	84	54	47	91	96	65	76	91	95	66	79	91	91	68	85	84	64	34	40
PST25-28	86	81	51	39	89	95	63	63	89	94	64	65	89	91	66	71	81	61	32	33
PST25-34	86	76	47	35	90	92	58	57	90	91	59	58	90	87	61	63	82	54	30	29
PST25-39	81	70	43	22	85	88	54	36	85	87	55	37	86	84	57	40	76	46	26	18
PST26-1	99	96	74	78	99	97	73	79	99	97	73	76	99	94	74	71	95	81	46	66
PST26-4	89	95	68	76	89	97	69	81	89	96	69	79	89	94	70	72	85	81	45	64
PST26-9	87	81	56	47	90	95	67	76	90	94	68	78	90	88	69	85	83	57	32	39
PST26-15	88	77	52	41	91	93	63	67	91	91	64	68	91	86	66	74	83	53	30	34
PST26-17	85	71	49	32	89	90	61	52	89	89	61	54	89	83	63	58	80	45	27	27

Figure H145. Pu(80/10/10/0)NH mass

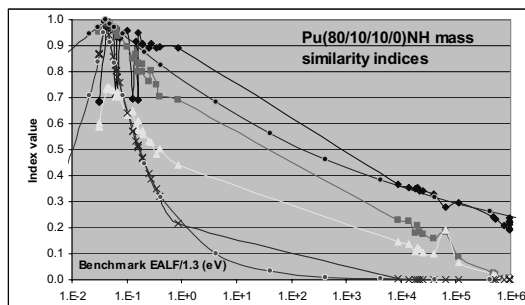


Figure H149. Pu(80/10/10/0)NH cylinder

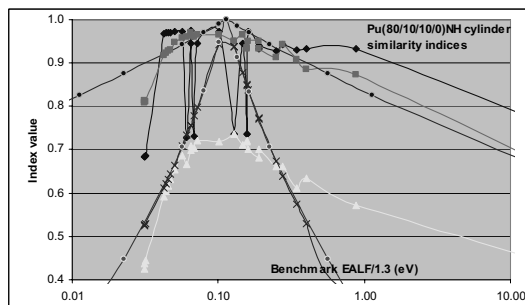


Figure H146. Pu(80/10/10/0)NH mass

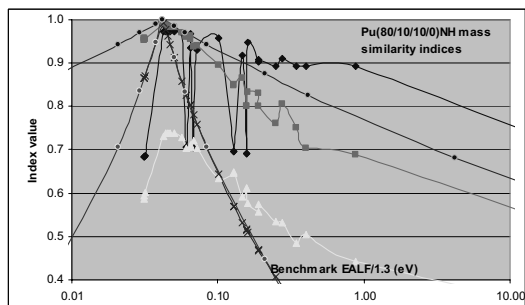


Figure H150. Pu(80/10/10/0)NH slab

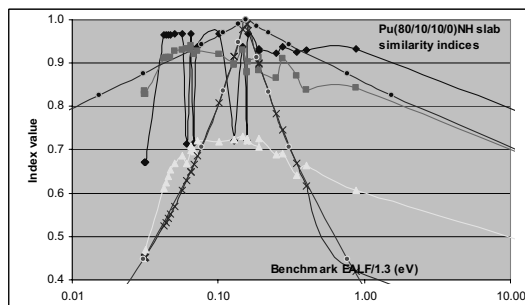


Figure H147. Pu(80/10/10/0)NH volume

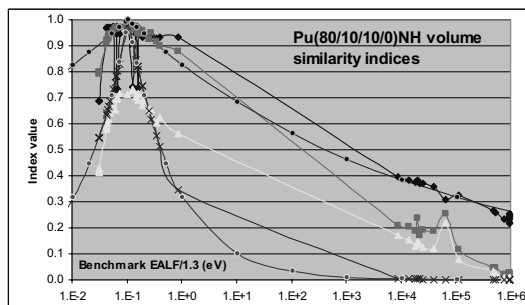


Figure H151. Pu(80/10/10/0)NH concentr.

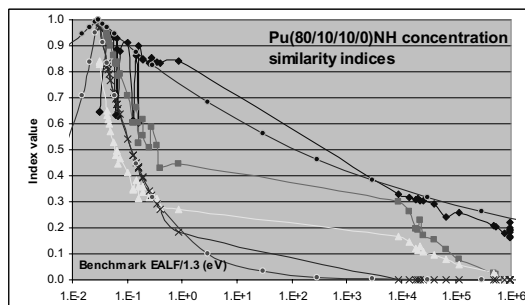


Figure H148. Pu(80/10/10/0)NH volume

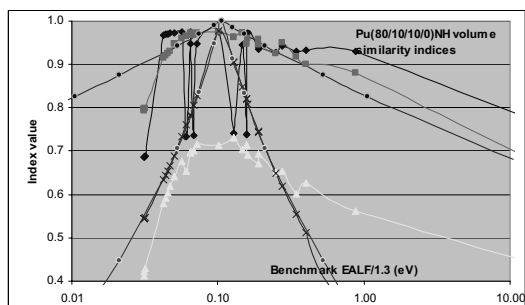


Figure H152. Pu(80/10/10/0)NH concentr.

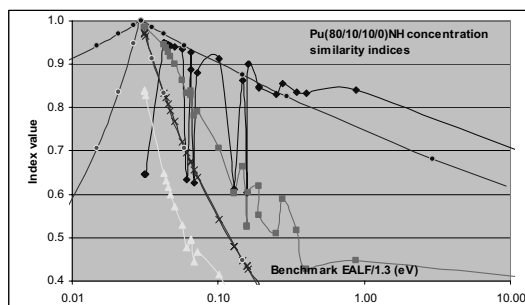


Table H19. Pu(80/10/10/0)NH - c_k , E_{sum} , G and R_{e2}

Pu(80/10/10/0)NH applications and experiments similarities – c_k , E_{sum} , G and R_{e2} in %																				
ICSBEP Id	Mass				Volume				Cvlinder				Slab				Concentration			
	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}
PMF01-1	20	0	0	0	22	2	1	0	22	3	1	0	22	4	1	0	17	0	0	0
PMF02-1	24	0	0	0	26	2	1	0	26	3	1	0	26	4	1	0	22	0	0	0
PMF03-1	28	18	19	0	31	26	22	0	31	26	22	0	31	27	23	0	24	12	8	0
PMF03-2	23	0	0	0	25	2	1	0	25	3	1	0	25	4	1	0	20	0	0	0
PMF03-3	21	0	0	0	23	3	1	0	24	3	1	0	24	4	1	0	18	0	0	0
PMF03-4	23	2	2	0	26	4	3	0	26	5	3	0	26	6	3	0	20	2	2	0
PMF03-5	22	0	0	0	24	3	1	0	24	3	1	0	25	4	1	0	19	0	0	0
PMF05-1	24	3	2	0	27	5	3	0	27	5	3	0	27	6	4	0	21	2	2	0
PMF11-1	22	0	0	0	24	3	1	0	24	3	1	0	25	4	1	0	19	0	0	0
PMF16-1	21	0	0	0	23	2	1	0	23	2	1	0	23	4	1	0	18	0	0	0
PMF22-1	37	23	15	0	40	21	17	0	40	23	18	0	40	29	20	0	33	30	17	0
PMF29-1	19	0	0	0	22	2	1	0	21	3	1	0	22	4	1	0	16	0	0	0
PMF37-1	30	9	7	0	32	12	8	0	32	12	8	0	33	14	9	0	26	8	6	0
PMF37-5	33	16	10	0	36	19	12	0	36	19	12	0	36	22	13	0	29	15	10	0
PMF37-7	34	17	10	0	37	19	12	0	37	20	13	0	37	23	14	0	30	17	11	0
PMF37-10	35	21	13	0	38	24	15	0	38	25	15	0	38	27	17	0	31	19	11	0
PMF37-12	35	18	11	0	38	19	13	0	38	20	14	0	38	24	15	0	31	20	12	0
PMF37-15	36	22	14	0	38	20	15	0	38	22	16	0	39	25	17	0	32	26	15	0
PMF37-16	34	18	12	0	37	17	14	0	37	19	15	0	37	23	16	0	30	23	13	0
PST09-1	69	96	60	87	69	80	43	55	69	81	44	53	67	83	47	45	65	98	83	97
PST09-2	68	95	59	87	69	79	42	54	68	81	44	53	67	83	46	45	65	99	84	97
PST09-3	68	96	59	87	69	80	41	54	68	81	43	53	67	83	45	45	65	99	84	97
PST14-1	70	85	65	57	74	96	73	91	74	95	74	94	72	90	72	92	61	60	35	48
PST14-2	70	85	65	57	74	96	73	91	74	95	74	94	72	90	72	92	61	60	35	48
PST15-1	69	80	61	52	74	95	71	82	74	93	72	85	72	88	72	99	60	53	31	43
PST15-2	69	80	61	52	74	95	71	82	74	93	72	85	72	88	72	99	60	52	31	43
PST22-1	95	83	58	51	97	96	69	81	97	95	70	84	97	90	72	98	90	61	36	43
PST22-2	96	90	63	64	97	97	71	98	97	96	72	94	97	92	72	81	91	71	41	54
PST22-3	97	96	71	80	98	97	70	78	97	96	70	76	97	93	70	65	93	83	49	68
PST22-4	97	97	73	86	97	96	68	73	97	96	69	71	97	93	69	61	93	86	53	72
PST22-5	97	98	74	91	97	95	64	69	97	95	65	66	97	93	67	57	94	90	57	77
PST22-6	97	98	74	94	97	93	62	67	97	93	63	64	97	91	65	55	94	92	60	79
PST22-7	97	99	74	96	97	93	61	65	97	93	62	63	97	91	64	54	95	93	62	81
PST22-8	97	99	74	98	97	92	59	64	97	92	60	62	97	91	62	53	95	94	63	82
PST22-9	97	99	73	99	97	91	58	63	97	92	59	61	96	91	61	53	95	95	65	83
PST25-1	71	96	70	83	73	96	65	76	73	96	67	73	71	93	67	63	63	83	48	70
PST25-7	94	96	71	80	95	97	70	78	95	97	71	76	94	94	71	65	89	84	50	67
PST25-14	92	87	59	53	95	97	70	85	94	97	71	88	94	93	73	98	86	66	38	45
PST25-21	90	83	56	47	94	96	67	75	93	95	68	77	93	91	71	90	85	62	36	39
PST25-28	91	81	53	39	94	95	65	62	94	94	66	64	94	91	69	75	85	59	34	33
PST25-34	89	75	48	35	93	92	60	55	93	91	61	57	93	87	64	67	84	52	31	29
PST25-39	89	69	44	22	93	88	56	35	93	87	57	36	93	84	61	42	84	45	27	18
PST26-1	70	94	72	78	74	97	70	81	73	96	70	78	72	92	70	67	63	78	44	66
PST26-4	93	94	70	76	95	97	72	83	95	97	72	80	94	93	72	69	88	79	47	64
PST26-9	91	80	58	47	94	95	69	74	94	93	70	77	93	88	73	90	85	55	34	39
PST26-15	89	76	54	41	93	93	65	65	93	91	66	67	92	87	69	78	83	51	32	34
PST26-17	89	70	50	32	93	90	63	51	93	89	63	53	93	84	66	62	83	43	28	27

Figure H153. Pu(90/10/0/0)NH mass

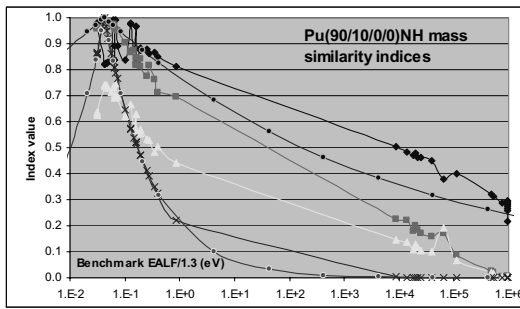


Figure H157. Pu(90/10/0/0)NH cylinder

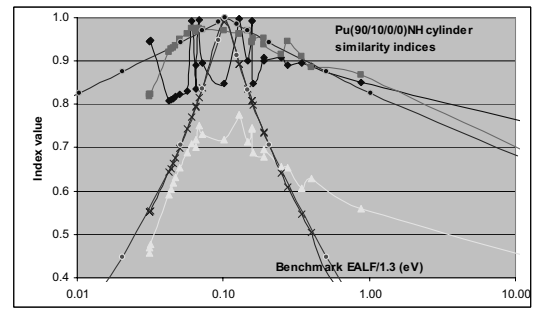


Figure H154. Pu(90/10/0/0)NH mass,

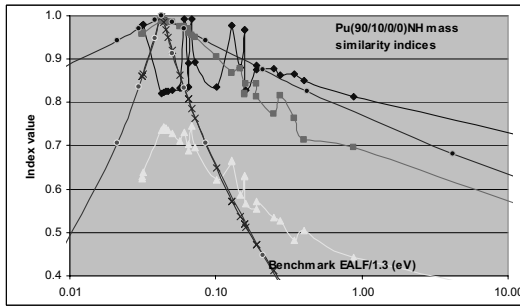


Figure H158. Pu(90/10/0/0)NH slab

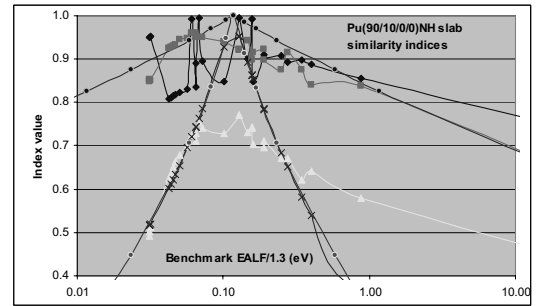


Figure H155. Pu(90/10/0/0)NH volume

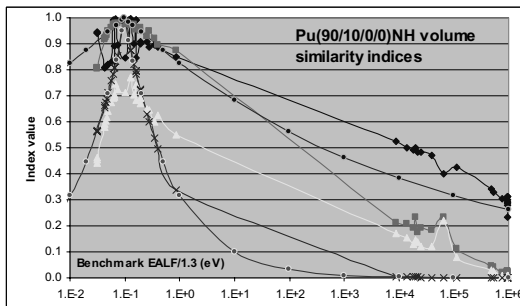


Figure H159. Pu(90/10/0/0)NH concentr.

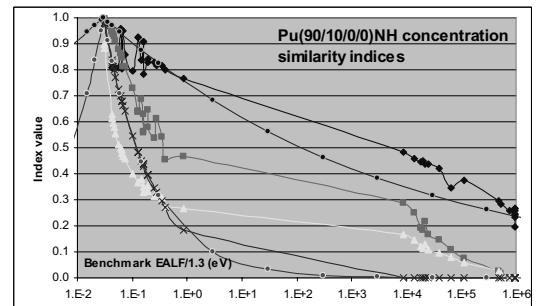


Figure H156. Pu(90/10/0/0)NH volume

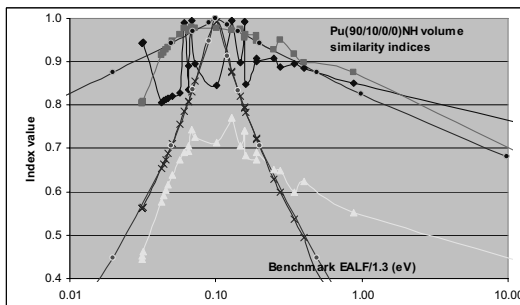


Figure H160. Pu(90/10/0/0)NH concentr.

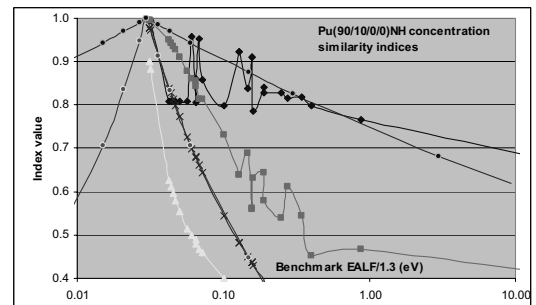


Table H20. Pu(90/10/0/0)NH - c_k , E_{sum} , G and R_{e2}

Pu(90/10/0/0)NH applications and experiments similarities $\bar{n}$ c_k , E_{sum} , G and R_{e2} in %																				
ICSBEF Id	Mass				Volume				Cylinder				Slab				Concentration			
	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}
PMF01-1	27	0	0	0	29	2	1	0	29	2	1	0	29	3	1	0	24	0	0	0
PMF02-1	22	0	0	0	23	2	1	0	23	2	1	0	24	3	1	0	20	0	0	0
PMF03-1	38	17	19	0	40	23	22	0	40	23	22	0	41	24	23	0	35	11	8	0
PMF03-2	26	0	0	0	28	2	1	0	28	2	1	0	28	3	1	0	23	0	0	0
PMF03-3	28	0	0	0	30	2	1	0	30	3	1	0	31	3	1	0	26	0	0	0
PMF03-4	31	2	2	0	33	4	2	0	33	4	3	0	34	5	3	0	29	2	2	0
PMF03-5	29	0	0	0	31	2	1	0	31	3	1	0	32	3	1	0	27	0	0	0
PMF05-1	32	3	2	0	34	5	3	0	34	5	3	0	35	5	3	0	29	2	2	0
PMF11-1	29	0	0	0	31	2	1	0	31	3	1	0	32	3	1	0	27	0	0	0
PMF16-1	29	0	0	0	30	2	1	0	30	2	1	0	31	3	1	0	26	0	0	0
PMF22-1	51	23	15	0	52	21	17	0	53	23	18	0	53	28	20	0	48	29	17	0
PMF29-1	27	0	0	0	29	2	1	0	29	2	1	0	30	3	1	0	25	0	0	0
PMF37-1	40	9	7	0	42	11	8	0	42	12	8	0	43	13	9	0	37	8	6	0
PMF37-5	45	16	10	0	47	18	12	0	47	19	12	0	48	20	13	0	42	15	10	0
PMF37-7	46	17	11	0	48	19	12	0	49	20	13	0	49	21	14	0	44	17	11	0
PMF37-10	48	20	13	0	50	23	15	0	50	24	15	0	50	26	16	0	45	19	11	0
PMF37-12	47	18	11	0	49	19	13	0	49	20	14	0	50	23	14	0	45	19	12	0
PMF37-15	48	22	14	0	50	21	15	0	50	22	16	0	51	24	17	0	46	25	15	0
PMF37-16	46	18	12	0	48	17	14	0	48	19	14	0	49	22	16	0	44	22	13	0
PST09-1	98	96	64	86	95	81	46	56	95	82	48	56	95	85	51	52	100	99	88	97
PST09-2	98	96	63	86	94	80	45	56	95	82	47	55	95	85	50	52	100	100	90	98
PST09-3	98	96	62	86	94	81	44	56	95	82	46	55	95	85	49	52	100	100	90	98
PST14-1	98	87	67	57	100	97	77	88	100	96	78	89	100	92	77	95	92	64	37	48
PST14-2	98	87	67	57	100	97	77	88	100	96	78	89	100	92	77	95	92	64	37	48
PST15-1	97	82	63	52	99	96	74	79	99	94	75	81	99	90	74	86	91	56	33	44
PST15-2	97	82	63	52	99	96	74	79	99	94	74	81	99	90	74	86	91	56	33	44
PST22-1	83	84	57	51	85	96	68	78	85	95	69	80	85	92	70	85	78	63	35	43
PST22-2	84	91	62	65	85	98	71	99	85	97	72	99	85	94	73	93	80	73	40	54
PST22-3	84	96	69	81	84	97	69	81	84	97	70	79	84	95	71	74	81	84	48	68
PST22-4	83	97	71	86	83	96	67	76	83	96	69	74	83	95	70	70	81	88	51	73
PST22-5	83	98	73	92	82	95	64	71	82	95	65	70	82	94	68	65	81	91	55	77
PST22-6	83	98	74	95	82	93	62	69	82	94	63	68	82	93	67	63	81	93	58	80
PST22-7	82	99	74	97	81	93	60	67	81	93	62	66	81	93	65	62	81	94	60	81
PST22-8	82	99	74	98	81	92	59	66	81	93	61	65	81	93	64	61	81	94	61	83
PST22-9	82	99	74	100	81	91	58	65	81	92	59	64	81	93	62	60	81	95	63	84
PST25-1	99	98	73	83	99	98	69	79	99	98	71	77	99	96	72	72	96	86	50	70
PST25-7	89	97	70	81	89	98	71	81	89	98	72	79	89	96	73	74	86	86	49	68
PST25-14	88	88	59	54	90	98	71	82	90	97	71	84	90	94	73	89	84	69	38	45
PST25-21	89	84	56	47	91	96	67	72	91	95	68	74	91	92	70	79	84	64	35	40
PST25-28	86	82	53	39	89	95	65	60	89	94	66	61	89	92	67	65	82	61	33	33
PST25-34	86	76	48	35	90	92	60	54	90	91	61	55	90	88	62	58	82	54	31	29
PST25-39	81	70	44	22	85	88	55	34	85	87	56	34	86	84	58	37	77	47	27	18
PST26-1	99	96	75	79	99	98	74	83	99	98	75	82	99	95	75	76	95	81	47	66
PST26-4	89	95	70	76	90	98	73	85	90	97	73	84	90	95	74	79	86	81	46	64
PST26-9	88	81	57	47	90	95	69	72	90	94	70	73	90	90	71	78	83	58	33	40
PST26-15	88	77	53	41	91	93	65	63	91	92	66	64	91	88	67	68	83	54	31	35
PST26-17	85	71	50	32	89	90	62	50	89	88	63	50	89	84	64	54	80	45	28	27

Figure H161. Pu(80/15/5/0)NH mass

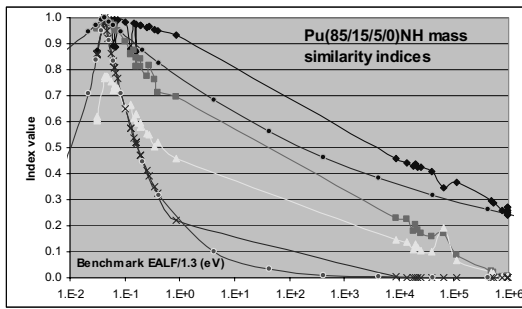


Figure H165. Pu(80/15/5/0)NH cylinder

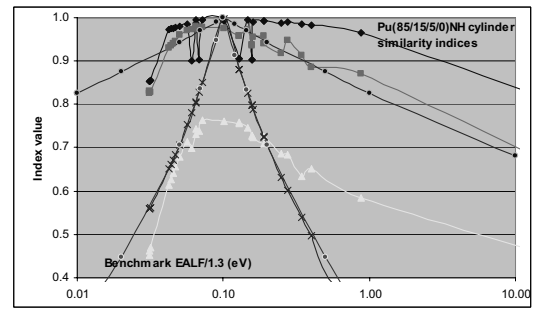


Figure H162. Pu(80/15/5/0)NH mass

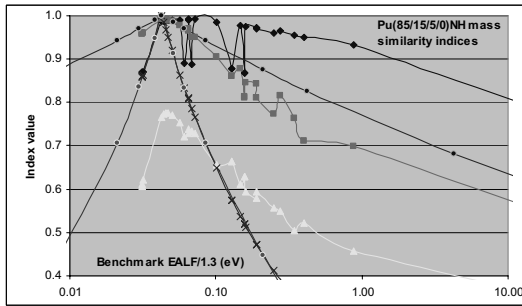


Figure H166. Pu(80/15/5/0)NH slab

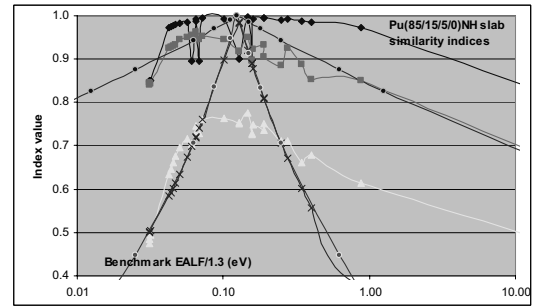


Figure H163. Pu(80/15/5/0)NH volume

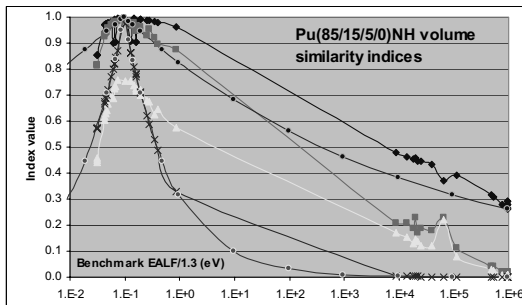


Figure H167. Pu(80/15/5/0)NH concentr

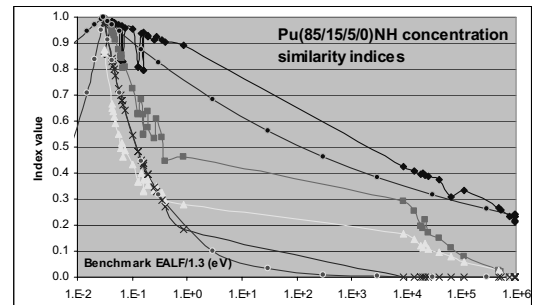


Figure H164. Pu(80/15/5/0)NH volume

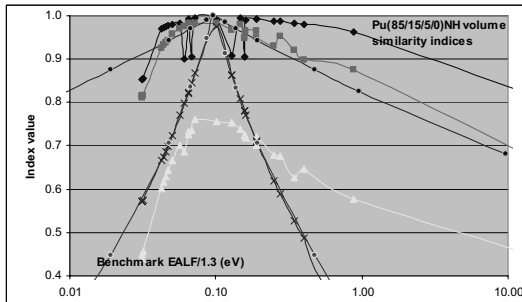


Figure H168. Pu(80/15/5/0)NH concentr

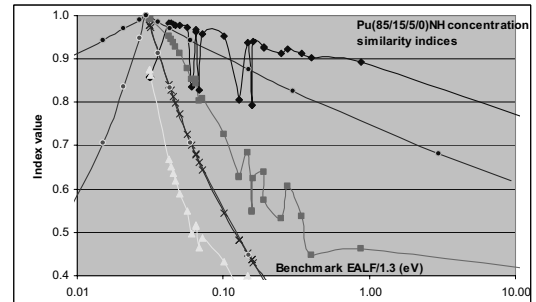


Table H21. Pu(80/15/5/0)NH – c_k , E_{sum} , G and R_{e2}

Pu(80/15/5/0)NH applications and experiments similarities $\bar{n}$ c_k , E_{sim} , G and R_{e2} in %																				
ICSBEP Id	Mass				Volume				Cylinder				Slab				Concentration			
	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}
PMF01-1	24	0	0	0	26	2	1	0	26	2	1	0	27	3	1	0	22	0	0	0
PMF02-1	25	0	0	0	27	2	1	0	27	2	1	0	27	3	1	0	23	0	0	0
PMF03-1	35	17	19	0	37	23	22	0	37	23	22	0	37	24	23	0	31	11	8	0
PMF03-2	26	0	0	0	28	2	1	0	28	2	1	0	28	3	1	0	23	0	0	0
PMF03-3	26	0	0	0	28	2	1	0	28	2	1	0	29	3	1	0	23	0	0	0
PMF03-4	29	2	2	0	31	4	2	0	31	4	3	0	31	5	3	0	26	2	2	0
PMF03-5	27	0	0	0	29	2	1	0	29	2	1	0	30	3	1	0	24	0	0	0
PMF05-1	30	3	2	0	32	4	3	0	32	4	3	0	32	5	3	0	27	2	2	0
PMF11-1	27	0	0	0	29	2	1	0	29	2	1	0	30	3	1	0	24	0	0	0
PMF16-1	26	0	0	0	28	2	1	0	28	2	1	0	28	3	1	0	23	0	0	0
PMF22-1	46	23	15	0	48	21	17	0	48	23	18	0	49	28	20	0	43	29	17	0
PMF29-1	24	0	0	0	26	2	1	0	26	2	1	0	27	3	1	0	21	0	0	0
PMF37-1	37	9	7	0	39	11	8	0	39	11	8	0	40	12	9	0	33	8	6	0
PMF37-5	41	16	10	0	43	18	12	0	43	18	12	0	44	20	13	0	37	15	10	0
PMF37-7	42	17	11	0	45	19	12	0	45	20	13	0	45	21	14	0	39	17	11	0
PMF37-10	44	20	13	0	46	23	15	0	46	24	15	0	47	26	16	0	40	19	11	0
PMF37-12	43	18	11	0	45	19	13	0	45	20	14	0	46	22	15	0	40	19	12	0
PMF37-15	44	22	14	0	46	21	15	0	46	22	16	0	47	24	17	0	41	26	15	0
PMF37-16	42	18	12	0	45	17	14	0	45	18	14	0	45	21	16	0	39	22	13	0
PST09-1	87	96	62	86	86	82	46	57	86	83	47	56	85	84	49	50	86	99	86	97
PST09-2	87	96	61	86	85	81	45	57	85	83	46	56	85	84	48	50	86	99	88	98
PST09-3	87	96	61	86	85	82	44	57	85	83	45	56	85	85	47	50	86	99	87	98
PST14-1	88	86	66	57	91	97	75	86	91	96	76	88	90	92	75	98	81	63	37	48
PST14-2	88	86	66	57	91	97	75	86	91	96	76	88	90	92	75	98	81	63	37	48
PST15-1	87	81	63	52	90	95	73	78	90	94	73	80	90	90	73	89	79	55	33	44
PST15-2	87	81	63	52	90	95	72	78	90	94	73	80	90	90	73	89	79	55	33	44
PST22-1	98	84	60	51	99	97	72	77	99	96	72	79	99	92	75	88	94	63	38	43
PST22-2	98	91	66	65	99	98	76	97	99	97	76	100	99	94	76	90	95	73	43	54
PST22-3	99	96	73	81	99	98	73	82	99	97	73	80	99	95	73	72	97	84	51	68
PST22-4	99	98	75	86	98	97	70	77	98	97	71	75	99	95	72	68	97	88	55	73
PST22-5	99	99	77	92	98	96	67	72	98	96	68	71	98	95	70	63	98	91	59	77
PST22-6	99	99	78	95	98	94	64	70	98	94	66	68	98	93	68	61	98	93	62	80
PST22-7	99	99	78	97	97	94	63	69	98	94	64	67	98	93	66	60	98	94	64	81
PST22-8	99	99	77	98	97	93	62	68	97	94	63	66	98	93	65	59	98	95	65	83
PST22-9	99	99	77	100	97	93	60	67	97	93	61	65	97	93	63	58	98	95	67	84
PST25-1	89	97	72	83	90	98	69	80	90	97	70	78	89	95	70	70	83	85	50	70
PST25-7	99	97	74	81	99	98	73	82	99	98	74	81	99	96	75	72	96	85	52	68
PST25-14	98	88	61	54	100	98	74	81	100	97	75	83	100	95	77	92	94	68	40	45
PST25-21	97	84	58	47	99	96	70	71	99	96	71	73	99	93	74	81	93	64	37	40
PST25-28	96	82	55	39	99	95	68	59	99	95	68	60	99	93	71	67	92	61	35	33
PST25-34	96	76	50	35	98	92	63	53	98	91	63	54	99	89	66	60	91	54	33	29
PST25-39	93	70	46	22	96	88	58	33	97	87	58	34	97	85	61	38	89	46	28	19
PST26-1	89	95	73	79	90	98	73	85	90	97	74	83	90	94	73	74	83	80	46	66
PST26-4	99	95	73	77	100	98	76	87	100	98	76	85	99	95	76	76	96	81	49	64
PST26-9	97	81	59	47	99	95	72	71	99	94	73	72	99	90	75	81	92	57	36	40
PST26-15	96	77	56	41	99	93	68	62	99	92	69	63	99	89	71	71	91	53	33	35
PST26-17	95	71	52	32	98	90	65	49	98	89	65	50	99	85	68	56	90	45	29	27

Figure H169. Pu(71/17/11/1)NH mass

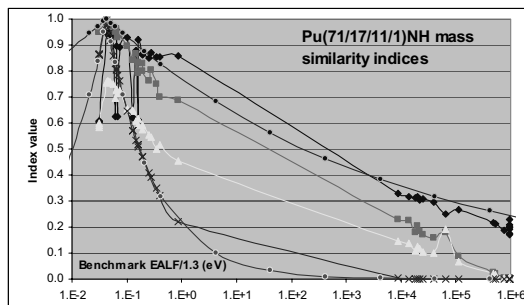


Figure H173. Pu(71/17/11/1)NH cylinder

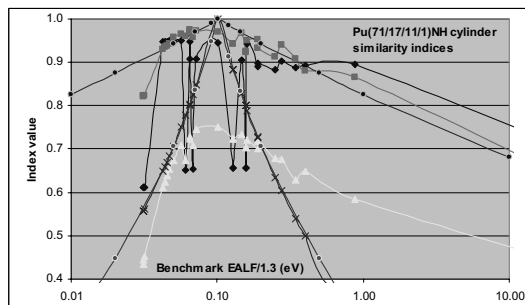


Figure H170. Pu(71/17/11/1)NH mass

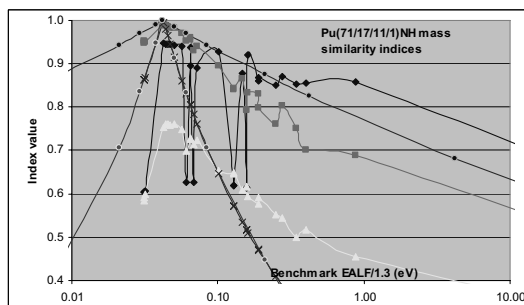


Figure H174. Pu(71/17/11/1)NH slab

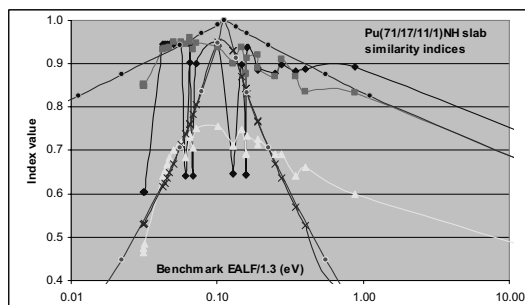


Figure H171. Pu(71/17/11/1)NH volume

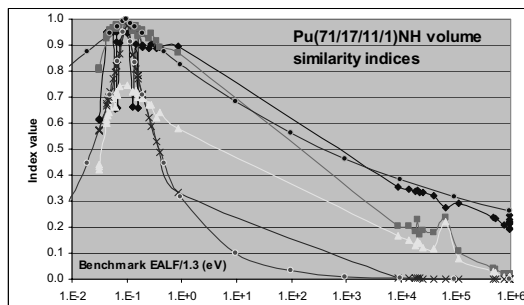


Figure H175. Pu(71/17/11/1)NH concent

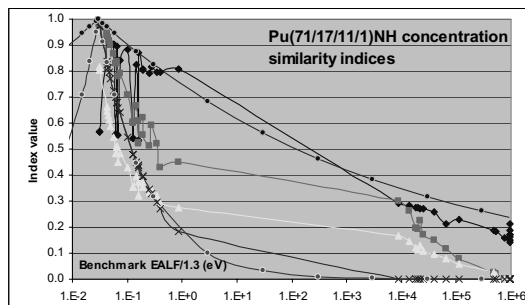


Figure H172. Pu(71/17/11/1)NH volume

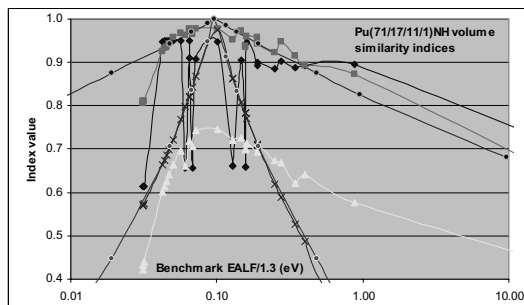


Figure H176. Pu(71/17/11/1)NH concent

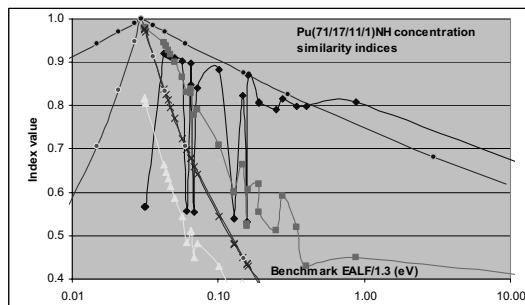


Table H22. Pu(71/17/11/1)NH - c_k , E_{sum} , G and R_{e2}

Pu(71/17/11/1)NH applications and experiments similarities $\bar{n}$ c_k , E_{sum} , G and R_{e2} in %																				
ICSBE Id	Mass				Volume				Cylinder				Slab				Concentration			
	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}	c_k	E_s	G	R_{e2}
PMF01-1	18	0	0	0	20	2	1	0	20	2	1	0	19	2	1	0	15	0	0	0
PMF02-1	23	0	0	0	25	2	1	0	25	2	1	0	25	2	1	0	21	0	0	0
PMF03-1	25	18	19	0	27	24	22	0	27	24	22	0	27	24	23	0	21	12	8	0
PMF03-2	21	0	0	0	23	2	1	0	23	2	1	0	23	2	1	0	19	0	0	0
PMF03-3	19	0	0	0	21	2	1	0	21	2	1	0	21	3	1	0	16	0	0	0
PMF03-4	21	2	2	0	23	4	2	0	23	4	3	0	23	5	3	0	18	2	2	0
PMF03-5	20	0	0	0	22	2	1	0	22	2	1	0	22	3	1	0	17	0	0	0
PMF05-1	22	2	2	0	24	4	3	0	24	4	3	0	24	5	3	0	19	2	2	0
PMF11-1	20	0	0	0	22	2	1	0	22	2	1	0	22	3	1	0	17	0	0	0
PMF16-1	19	0	0	0	21	2	1	0	21	2	1	0	20	2	1	0	16	0	0	0
PMF22-1	33	23	15	0	35	21	17	0	35	22	18	0	35	27	19	0	29	30	17	0
PMF29-1	17	0	0	0	19	2	1	0	19	2	1	0	19	2	1	0	14	0	0	0
PMF37-1	27	9	7	0	29	11	8	0	29	11	8	0	29	12	8	0	23	8	6	0
PMF37-5	30	16	10	0	32	18	12	0	32	18	12	0	32	20	13	0	26	15	10	0
PMF37-7	31	17	11	0	33	19	12	0	33	19	13	0	33	21	14	0	27	17	11	0
PMF37-10	32	20	13	0	34	23	15	0	34	24	15	0	34	25	16	0	28	19	11	0
PMF37-12	31	18	11	0	34	18	13	0	34	19	13	0	33	22	14	0	27	20	12	0
PMF37-15	32	22	14	0	34	20	15	0	34	21	16	0	34	23	16	0	28	26	15	0
PMF37-16	31	18	12	0	33	17	14	0	33	18	14	0	33	21	16	0	27	23	13	0
PST09-1	61	95	60	87	62	81	44	57	61	82	45	56	60	85	48	53	57	98	81	97
PST09-2	61	95	59	86	61	81	43	57	61	82	45	56	60	85	48	53	57	98	82	98
PST09-3	60	95	58	86	61	81	42	57	61	82	44	56	60	85	47	53	57	98	82	98
PST14-1	62	84	65	57	66	95	72	86	66	94	72	88	65	90	71	93	54	60	36	48
PST14-2	62	84	65	57	66	95	72	86	66	94	72	88	65	90	71	93	54	60	35	48
PST15-1	61	79	62	52	66	94	70	78	66	92	70	80	64	88	69	84	53	53	32	44
PST15-2	61	79	62	52	66	94	70	78	66	92	70	80	64	88	69	84	53	52	32	44
PST22-1	92	83	59	51	94	96	71	77	94	95	72	79	94	91	73	83	87	61	37	43
PST22-2	93	90	65	65	95	98	75	98	95	97	75	100	94	94	76	95	88	71	43	54
PST22-3	94	96	73	81	95	97	72	82	95	97	72	80	94	95	73	76	90	83	51	68
PST22-4	94	97	75	86	95	97	70	77	95	97	71	75	95	95	72	71	90	86	54	72
PST22-5	94	98	76	92	95	96	66	72	95	96	67	71	95	95	70	67	91	90	59	77
PST22-6	95	98	76	95	95	94	64	70	95	94	65	68	95	94	68	65	91	92	61	80
PST22-7	95	99	76	96	95	94	63	69	95	94	64	67	95	94	67	64	92	93	63	81
PST22-8	95	99	76	98	95	93	61	67	95	94	63	66	95	94	65	63	92	94	65	83
PST22-9	95	99	75	99	95	93	60	66	95	93	61	65	95	93	64	62	92	95	66	84
PST25-1	63	95	70	83	66	96	66	80	65	96	67	78	64	94	68	74	56	83	48	70
PST25-7	89	96	73	80	91	98	72	82	91	98	73	80	90	96	74	76	85	84	51	68
PST25-14	88	86	61	53	91	97	73	81	90	97	73	83	90	94	75	87	82	66	40	45
PST25-21	86	83	58	47	89	96	69	71	89	95	70	73	89	92	71	77	80	62	37	40
PST25-28	87	80	55	39	90	95	67	59	90	94	68	60	90	91	69	64	82	59	35	33
PST25-34	85	75	50	35	89	92	62	53	89	91	63	54	88	87	64	57	80	52	32	29
PST25-39	86	69	45	22	90	87	58	33	90	87	59	34	89	83	60	36	81	45	28	18
PST26-1	63	93	71	78	66	96	71	84	65	96	71	82	64	93	71	78	55	78	45	66
PST26-4	89	94	72	76	91	98	74	87	91	97	75	85	90	95	75	80	84	79	48	64
PST26-9	87	80	59	47	90	94	71	71	90	93	72	73	89	89	73	77	81	55	35	40
PST26-15	85	76	55	41	89	92	67	62	88	91	68	63	88	87	69	67	79	51	33	35
PST26-17	86	70	52	32	89	89	64	49	89	88	65	50	89	83	66	53	80	43	29	27

Appendix I

BIASES CAUSED BY CODES AND CROSS-SECTIONS

The biases and uncertainties in the calculation methods can be determined from calculation of benchmarks. The bias Dk_b in each calculated $k_{\text{eff}}(k_c)$ is related to the real $k_{\text{eff}}(k_r)$ as

$$k_c = k_r + \Delta k_c$$

The k_{eff} calculation bias is thus the difference between k_c and k_r . A statistical evaluation of many benchmark calculations may give a reasonably correct bias for the calculation method. A combination of different uncertainties should be associated with the bias determination. Ideally, each benchmark calculation should be weighted individually according to the accuracy of the benchmark specifications and to the similarity to the application. The study demonstrates some of the complexities of validation, methods to deal with them and includes examples.

A calculated reference value V_{rc} is related to the real reference value V_{rr} through the reference value calculation bias DV_{rc} as

$$V_{rc} = V_{rr} + \Delta V_{rc}$$

The sensitivities (S_{vk}) of reference values (V_r) to small variations of k_{eff} are given in Appendix D linear, which means that a real change, different from the k_{eff} change used to determine the sensitivity, leads to an error. It is also important to understand that a bias in the k_{eff} calculation result leads to a bias with reversed sign (positive/negative) in the calculated reference value (V_{rc}). E.g., an over-estimation of k_{eff} leads to an under-estimation of the real critical mass.

The real reference value V_{rr} can be expressed as

$$V_{rr} = V_{rc} - DV_{rc} = V_{rc} + S_{vk} * Dk_c$$

The product $S_{vk} * Dk_c$ is a bias correction of the calculated reference value.

Validation of the evaluation of reference values for nuclear criticality safety involves consideration of many potential error sources. The Expert Group selected reference values for 110 applications (concentration and moderation ratio are identical applications). With at least 13 methods, the number of bias evaluations should be at least 1 400. At this time, individual evaluation of each bias is not possible.

Input data include material properties such as atomic densities (or other specifications from which the code system can determine atomic densities), cross-sections for reactions between free neutrons and atoms, fission properties (number and energies of fission neutrons), etc.

The geometry input for the application is a potential error source, even when the specifications are very simple.

Other input data will determine the behaviour of the calculation method for each application. Default input data prepared by the code system may be adapted to certain types of applications and may not be appropriate for other types.

Biases and uncertainties due to calculation methods are primary objectives. Discrepancies are identified and explained when possible. Calculation results that do not appear correct or consistent with other results may be corrected or removed from evaluations of best estimate values.

In the evaluation of biases and uncertainties, the only parameters selected are ratios $^{235}\text{U}/\text{U}_{\text{total}}$, moderation of uranium and moderation of plutonium. Variation of the plutonium isotope distribution is not evaluated at this time. The bias influence of nitrogen in nitrate systems is not evaluated.

A parameter that is not evaluated is water reflection. Many of the benchmark models based on critical experiments have little or essentially no reflection at all. In particular for metal systems, the moderation in the reflector changes the average system properties significantly. Biases for internally and externally moderated systems may be quite different, even when average properties are similar.

Biases and uncertainties due to different geometries (sphere, cylinder, and slab) are not considered. Discrepancies are more likely related to convergence, geometry mesh, angular quadrature order, etc.

Cross-sections that are processed in essentially identical ways are expected to give very close results, independent of whether Monte Carlo or deterministic codes are used. This is based on the expectation that the codes can take advantage of the properties of the cross section libraries and that the codes are used properly to take this into account. These properties of cross-sections and the appropriate use of codes need to be verified. As an example, a diffusion theory code could not directly use the same properties of a general cross-section library as a Monte-Carlo code. After additional application-dependent cross-section processing, the diffusion code may be used with confidence.

Five different groups of biases and uncertainties are defined:

- fast systems with high-enriched uranium;
- slow (usually thermal) systems with high-enriched uranium;
- slow (usually thermal) systems with low-enriched uranium;
- fast systems with plutonium;
- slow (usually thermal) systems with plutonium.

The moderation parameter is considered in the form of EALF; the energy corresponding to average lethargy of neutrons causing fission.

The identification of calculation methods in the tables is shortened. S or S5 stands for SCALE 5 while M or M5 stands for MCNP5. After S, the numbers 8, 7 and 4 refer to the 238-group, the 27-group and the 44-group cross-section libraries. After M, the numbers 50, 5F, 62, 66, 68, 7P refer to ENDF/B releases, 22 and 30 refer to JEFF releases while 32 and 33 refer to JENDL releases.

Table I1. EALF values for all applications

EALF values for applications (eV)						
Material	Isotopes	Mass	Volume	Cylinder	Slab	Concentration
UO ₂	100	0.0413	11153	4599	385	0.0305
	20	0.0434	0.1289	0.1325	0.1624	0.0312
	5	0.0514	0.0965	0.0974	0.1089	0.0344
	4	0.0531	0.0981	0.0858	0.1049	0.0357
	3	0.0617	0.1011	0.1031	0.1092	0.0380
UNH	100	0.0416	0.1708	0.1633	0.1953	0.0306
	20	0.0436	0.0770	0.0807	0.0859	0.0316
	5	0.0534	0.0709	0.0713	0.0735	0.0361
	4	0.0572	0.0730	0.0727	0.0753	0.0384
	3	0.0689	0.0809	0.0808	0.0804	0.0438
PuO ₂	100/0/0/0	0.0547	26164	8785	252	0.0193
	95/5/0/0	0.0550	29639	10364	405	0.0194
	80/10/10/0	0.0543	27949	10118	396	0.0193
	90/10/0/0	0.0552	31053	11354	510	0.0196
	80/15/5/0	0.0551	30557	11465	551	0.0196
	71/17/11/1	0.0547	29755	11234	542	0.0195
PuNH	100/0/0/0	0.0548	0.3097	0.3562	0.5620	0.0194
	95/5/0/0	0.0551	0.1443	0.1525	0.1811	0.0195
	80/10/10/0	0.0544	0.1371	0.1470	0.2012	0.0193
	90/10/0/0	0.0552	0.1292	0.1342	0.1537	0.0196
	80/15/5/0	0.0553	0.1246	0.1304	0.1635	0.0196
	71/17/11/1	0.0547	0.1247	0.1298	0.1473	0.0195

Fast high-enriched uranium systems

The three applications included in this group are U(100)O₂ systems for which critical volume, cylinder diameter and slab thickness are minimized. The EALF values for the three applications are 11000, 4600 and 385.

The number of benchmarks is too low to get a high-quality determination of biases and uncertainties. Unfortunately, the degree of reflection seems to be a significant factor. Most of the selected systems are bare (unreflected) while the applications are reflected (or infinite). The uncertainty for experiment HEU-MF-004 is very low and for demonstration only, this single experiment is used to determine biases and uncertainties for fast, high-enriched systems; see Table I2.

If HEU-MF-004 is treated in SCALE 5 TSUNAMI-IP as an application, it can be evaluated against other benchmarks. As expected, the other HEU-MF experiments are the only ones with high similarities. C_k and E_{sum} values are higher than 0.90 while G values are around 0.60. The completeness parameter is 0.36 and the penalty summary shows an uncertainty of 0.22 % due to uncovered sensitivity coefficients. The R_{e2} values showing EALF similarities are low; 0.24 for HEU-MF-020 (some polyethylene reflection) and about 0.18 for the others (bare).

As can be seen in Table I2. , the SCALE TSUNAMI parameters C_k and E_{sum} for similarity between the three applications and the HEU-MF-004 are above 0.90. The G parameter values are 0.84, 0.78 and 0.58 for volume, cylinder and slab. The EALF values for the three applications (11000, 4600, 385) are very different and this shows in the R_{e2} values 0.61, 0.40 and 0.11.

Evaluation of completeness parameters and penalties were made with all uranium benchmarks included. The completeness parameters for the three reference systems are 0.3258, 0.3831 and 0.5449. This corresponds to the inverse EALF values for the systems (more moderation gives better parameters). The penalties due to uncovered sensitivity coefficients in the form of relative standard deviations are 0.1588, 0.2112 and 1.1234 % respectively.

The low experimental model uncertainty, the wide experience in evaluating the experiment, the results of similarity tests and the lack of other similar benchmarks together lead to the conclusion that HEU-MF-004 alone is adequate for determining biases for different methods (input data and codes).

The sensitivities of reference values to small keff variations, specified in Appendix D, are used to derive biases and uncertainties for the different reference parameters volume, cylinder diameter and slab thickness.

Table I2. B for fast U(100)O₂

Biases for U(100)O ₂ volume (V), cylinder (Φ) and slab (S) geometry (mk)														
Method		S58	S57	S54	M50	M62	M66	M68	M7P	M22	M30	M32	M33	IPPE
V	B	0.0	9.0	3.5	-2.5	-1.0	-3.5	-3.0	-1.5	-2.5	-3.0	2.0	4.0	2.0
	U*	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Φ	B	0.0	9.0	3.5	-2.5	-1.0	-3.5	-3.0	-1.5	-2.5	-3.0	2.0	4.0	2.0
	U*	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
S	B	0.0	9.0	3.5	-2.5	-1.0	-3.5	-3.0	-1.5	-2.5	-3.0	2.0	4.0	2.0
	U*	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0

Table I3. BC for fast U(100)O₂

Bias corrections for U(100)O ₂ volume (V), cylinder (Φ) and slab (S) geometry (rvu ^{**})														
Method		S58	S57	S54	M50	M62	M66	M68	M7P	M22	M30	M32	M33	IPPE
V (ml)	BC	0.0	169.2	65.8	-47.0	-18.8	-65.8	-56.4	-28.2	-47.0	-56.4	37.6	75.2	37.6
	U [*]													
Φ (mm)	BC													
	U [*]													
S (mm)	BC	0.00	1.23	0.48	-0.34	-0.14	-0.48	-0.41	-0.21	-0.34	-0.41	0.27	0.55	0.27
	U [*]													

Thermal high-enriched uranium systems

The five U(20)O₂, the two remaining (mass and concentration) U(100)O₂, the five U(20)NH and the five U(100)NH applications are included in this group.

The primary selection basis for the validation is each benchmark model uncertainty. Models with larger uncertainties (1 s or about 67 % confidence) than 3 mk are rejected in this demonstration. The included benchmarks are HEU-MT-011 (cases 1, 3, 5, 7, 35, 37, 39, 41 and 43), HEU-ST-010 (cases 1-4), HEU-ST-011 (cases 1, 2), HEU-ST-025 (case 1), HEU-ST-028 (case 1), HEU-ST-038 (case 1), HEU-ST-042 (case 3) and HEU-ST-043 (cases 1-3). No further weighting due to expected correlations between benchmarks was carried out.

The SCALE 5 TSUNAMI-IP similarity evaluations show good values (above 0.90) for C_k and E_{sum}. G values are more scattered but usually above 0.60 and in a few cases above 0.90. R_{e2} values were not used in the evaluation (shown in tables).

The TSUNAMI-IP results show that for high-enriched uranium (HEU) concentration applications, the benchmark model HEUST042 case 3 is particularly good. All the four similarity parameters C_k, E_{sum}, G and R_{e2} are well above 0.90 and often close to 1.00. Other benchmarks with low uncertainties are not as good for these applications. This benchmark series is weighted higher due to the TSUNAMI results. All the HEUST042 cases 1-8 in the evaluation were included, in spite of larger uncertainties, rather than only case 3.

The benchmarks HEU-MT-011 (cases 1, 3, 5, 7, 35, 37, 39, 41 and 43) are the only ones with very low uncertainties. Except for concentrations, they give very good results for C_k and E_{sum} and quite good results (>0.60) for the G parameter. The biases are checked for consistency with these benchmarks (giving them a higher weight) for all applications except concentrations.

Evaluation of completeness parameters were made with all uranium benchmarks included. The completeness parameters are at least 0.591. The penalties have not been considered.

* Uncertainties have not been evaluated. The example values are often too low.

** Uncertainties have not been evaluated. The example values are often too low.

Table I4. B for thermal HEU UO₂ and UNH

Biases (mk) for thermal HEU UO ₂ and UNH systems														
Method		S58	S57	S54	M50	M62	M66	M68	M7P	M22	M30	M32	M33	IPPE
M	B	2.3	3.8	2.9	2.8	-0.8	0.9	0.4	-1.1	0.5	0.5	5.2	1.5	1.0
	U*	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
V	B	2.3	3.8	2.9	2.8	-0.8	0.9	0.4	-1.1	0.5	0.5	5.2	1.5	1.0
	U*	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Φ	B	2.3	3.8	2.9	2.8	-0.8	0.9	0.4	-1.1	0.5	0.5	5.2	1.5	1.0
	U*	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
S	B													
	U*	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
C	B	2.8	5.7	3.7	3.8	-0.5	1.3	0.6	-1.7	1.2	1.1	6.1	1.7	2.5
	U*	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0

Table I5. BC for thermal U(100)O₂

Bias corrections (reference value units) for thermal U(100)O ₂ systems														
Method		S58	S57	S54	M50	M62	M66	M68	M7P	M22	M30	M32	M33	IPPE
M (g)	BC	8.2	13.5	10.3	9.9	-2.8	3.2	1.4	-3.9	1.8	1.8	18.5	5.3	3.6
	U*													
C (g/l)	BC	0.066	0.134	0.087	0.089	-0.012	0.031	0.014	-0.040	0.028	0.026	0.143	0.040	0.059
	U*													

Table I6. BC for thermal U(20)O₂

Bias corrections (reference value units) for thermal U(20)O ₂ systems														
Method		S58	S57	S54	M50	M62	M66	M68	M7P	M22	M30	M32	M33	IPPE
M (g)	BC													
	U*													
V (ml)	BC	115	191	146	141	-40	45	20	-55	25	25	261	75	50
	U*													
Φ (mm)	BC	0.75	1.23	0.94	0.91	-0.26	0.29	0.13	-0.36	0.16	0.16	1.68	0.49	0.32
	U*													
S (mm)	BC	0.49	0.80	0.61	0.59	-0.17	0.19	0.08	-0.23	0.11	0.11	1.10	0.32	0.21
	U*													
C (g/l)	BC													
	U*													

* Uncertainties have not been evaluated. The example values are often too low.

Thermal low-enriched uranium systems

Both moderation (EALF) and ^{235}U enrichment (wt-%) trends are evaluated. The EALF-related biases are determined from a sub-selection of benchmarks with reasonably low uncertainties. These benchmarks were LEUCT002 (cases 1 and 4), LEUCT013 (case 1), LEUCT014 (case 1), LEUCT039 (case 1), LEUCT061 (case 1), LEUCT070 (case 1), LEUST007 (cases 1-5), LEUST016 (cases 1-7), LEUST017 (cases 1-6), LEUST020 (cases 1-4) and LEUST021 (cases 1-4).

The results indicate that the trend against EALF is quite strong. For ^{235}U enrichment, the trends are not so strong, in particular for newer cross-section libraries. It seems practical to limit the bias determination to EALF trends only.

The EALF values for the low-enriched uranium systems are found in Table I1.

Even though there are many benchmarks, the spread in results for similar systems indicates larger uncertainties in the benchmarks than the ICSBEP Handbook specifies. All trends of biases against EALF have a negative slope, except the ABBN-93 results. Different modelling of a few benchmarks in the MCNP/SCALE calculations than in the ABBN-93 calculations could result in such a change in slope. There are only three different input models involved; SCALE, MCNP and ABBN-93.

The SCALE5 TSUNAMI evaluations indicate that the benchmarks and the applications are very similar. The completeness parameters are above 0.77. The penalties have not been considered. For the low-enriched uranium systems, the biases are calculated from the equations generated by Microsoft Excel from the results for benchmarks with low uncertainties. All equations are in the form:

$$\text{Bias}(\text{EALF}) = a \cdot \ln(\text{EALF}) + b$$

Table I9. Equation constants for low-enriched U

Constants a and b generated to fit the equation $y = a \cdot \ln(\text{EALF}) + b$ to benchmark calculation results														
	S5-238	S5-27	S5-44	M5-E50	M5-E5X	M5-E62	M5-E66	M5-E68	M5-E7P	M5-F22	M5-F30	M5-J32	M5-J33	ABBN-93
a	-2.91	-2.08	-1.04	-2.47	-2.47	-2.09	-3.04	-3.01	-1.25	-0.38	-2.08	-1.79	-1.63	1.66
b	-7.24	-5.84	-0.90	-4.54	-4.54	-8.09	-8.39	-8.54	-3.85	-0.03	-5.60	1.23	-2.78	5.46

The corresponding biases in k_{eff} (mk) and bias corrections in reference value units are displayed in the following tables for the different methods.

A study of published evaluations of cross-section validation would help in finding likely causes or parameters for trends. Further, potential discrepancies between benchmarks may have been examined. The trends generated in this study are not very reliable. They are used as examples.

Table I10. B for low-enriched UO₂

Biases (B) and uncertainties (U) for low-enriched UO ₂ applications (mk)														
Method	Type	S58	S57	S54	M50	M62	M66	M68	M7P	M22	M30	M32	M33	IPPE
M U(5)O ₂	B	1.39	0.33	2.17	2.78	-1.89	0.63	0.40	-0.14	1.12	0.58	6.54	2.06	0.52
	U*													
V U(5)O ₂	B	1.30	0.26	2.14	2.70	-1.96	0.54	0.30	-0.18	1.10	0.51	6.49	2.01	0.57
	U*													
Φ U(5)O ₂	B	0.86	-0.05	1.99	2.33	-2.27	0.08	-0.15	-0.37	1.05	0.19	6.22	1.77	0.82
	U*													
S U(5)O ₂	B													
	U*													
C U(5)O ₂	B	-0.49	-1.02	1.50	1.19	-3.24	-1.33	-1.55	-0.95	0.87	-0.77	5.39	1.01	1.59
	U*													
M U(4)O ₂	B	-0.58	-1.08	1.47	1.11	-3.30	-1.42	-1.64	-0.99	0.86	-0.83	5.33	0.96	1.64
	U*													
V U(4)O ₂	B	-0.47	-1.00	1.51	1.20	-3.22	-1.31	-1.53	-0.94	0.87	-0.76	5.40	1.02	1.58
	U*													
Φ U(4)O ₂	B													
	U*													
S U(4)O ₂	B	-0.63	-1.12	1.45	1.06	-3.34	-1.48	-1.70	-1.01	0.85	-0.87	5.30	0.93	1.68
	U*													
C U(4)O ₂	B	-0.79	-1.23	1.40	0.93	-3.46	-1.65	-1.86	-1.08	0.83	-0.99	5.20	0.84	1.77
	U*													
M U(3)O ₂	B	-0.69	-1.16	1.43	1.02	-3.38	-1.54	-1.75	-1.03	0.84	-0.91	5.27	0.90	1.71
	U*													
V U(3)O ₂	B													
	U*													
Φ U(3)O ₂	B	2.55	1.16	2.59	3.77	-1.05	1.85	1.61	0.36	1.27	1.41	7.26	2.72	-0.15
	U*													
S U(3)O ₂	B	2.45	1.09	2.55	3.68	-1.12	1.75	1.50	0.32	1.26	1.34	7.20	2.66	-0.09
	U*													
C U(3)O ₂	B	2.27	0.95	2.49	3.52	-1.26	1.55	1.31	0.24	1.23	1.20	7.08	2.56	0.02
	U*													

* Uncertainties have not been evaluated. The example values are often too low.

Table I11. B for low-enriched UNH

Biases (B) and uncertainties (U) for low-enriched UNH applications (mk)														
Method	Type	S58	S57	S54	M50	M62	M66	M68	M7P	M22	M30	M32	M33	IPPE
M U(5)O ₂	B	1.28	0.25	2.14	2.69	-1.97	0.52	0.28	-0.19	1.10	0.50	6.48	2.00	0.58
	U*													
V U(5)O ₂	B	1.08	0.10	2.06	2.51	-2.11	0.31	0.07	-0.27	1.07	0.35	6.35	1.89	0.70
	U*													
Φ U(5)O ₂	B	0.54	-0.28	1.87	2.06	-2.50	-0.26	-0.48	-0.51	1.00	-0.03	6.02	1.59	1.01
	U*													
S U(5)O ₂	B													
	U*													
C U(5)O ₂	B	0.37	-0.40	1.81	1.91	-2.62	-0.43	-0.66	-0.58	0.98	-0.16	5.92	1.49	1.10
	U*													
M U(4)O ₂	B	0.07	-0.61	1.70	1.66	-2.84	-0.74	-0.97	-0.71	0.94	-0.37	5.73	1.33	1.27
	U*													
V U(4)O ₂	B	0.44	-0.35	1.84	1.97	-2.57	-0.36	-0.59	-0.55	0.99	-0.11	5.96	1.53	1.06
	U*													
Φ U(4)O ₂	B													
	U*													
S U(4)O ₂	B	0.07	-0.61	1.71	1.66	-2.83	-0.74	-0.96	-0.71	0.94	-0.37	5.73	1.33	1.27
	U*													
C U(4)O ₂	B	0.35	-0.41	1.80	1.90	-2.63	-0.45	-0.68	-0.59	0.98	-0.17	5.90	1.48	1.11
	U*													
M U(3)O ₂	B	0.28	-0.47	1.78	1.84	-2.69	-0.53	-0.75	-0.62	0.97	-0.22	5.86	1.44	1.15
	U*													
V U(3)O ₂	B													
	U*													
Φ U(3)O ₂	B	2.42	1.06	2.54	3.65	-1.15	1.71	1.47	0.30	1.25	1.31	7.18	2.64	-0.07
	U*													
S U(3)O ₂	B	2.24	0.93	2.48	3.50	-1.28	1.52	1.28	0.22	1.23	1.18	7.07	2.54	0.03
	U*													
C U(3)O ₂	B	1.85	0.66	2.34	3.17	-1.56	1.12	0.88	0.06	1.18	0.91	6.83	2.32	0.25
	U*													

* Uncertainties have not been evaluated. The example values are often too low.

Table I12. BC for low-enriched UO₂

Bias corrections for low-enriched UO ₂ applications (reference value units)														
Method	B/U	S58	S57	S54	M50	M62	M66	M68	M7P	M22	M30	M32	M33	IPPE
M (g)	BC	333	78	522	667	-453	152	95	-34	268	138	1571	495	125
U(5)O ₂	U*													
V (ml)	BC	-73	-163	253	204	-532	-212	-249	-154	145	-122	899	172	260
U(5)O ₂	U*													
Φ (mm)	BC	-0.26	-0.56	0.85	0.68	-1.82	-0.74	-0.86	-0.53	0.49	-0.43	3.05	0.58	0.89
U(5)O ₂	U*													
S (mm)	BC													
U(5)O ₂	U*													
C (g/l)	BC	1.71	0.78	1.74	2.52	-0.70	1.24	1.08	0.24	0.85	0.95	4.87	1.82	-0.10
U(5)O ₂	U*													
M (g)	BC	511	103	844	1064	-770	212	119	-71	435	201	2556	793	225
U(4)O ₂	U*													
V (ml)	BC	-112	-233	344	271	-742	-305	-355	-217	199	-176	1234	231	365
U(4)O ₂	U*													
Φ (mm)	BC													
U(4)O ₂	U*													
S (mm)	BC	-0.29	-0.49	0.61	0.44	-1.44	-0.66	-0.75	-0.44	0.36	-0.39	2.25	0.38	0.73
U(4)O ₂	U*													
C (g/l)	BC	2.21	0.98	2.30	3.31	-1.01	1.57	1.35	0.28	1.13	1.20	6.47	2.39	-0.08
U(4)O ₂	U*													
M (g)	BC	677	-42	1568	1839	-1794	61	-121	-292	826	154	4911	1395	650
U(3)O ₂	U*													
V (ml)	BC													
U(3)O ₂	U*													
Φ (mm)	BC	-0.54	-0.96	1.24	0.91	-2.86	-1.27	-1.45	-0.86	0.73	-0.75	4.53	0.79	1.43
U(3)O ₂	U*													
S (mm)	BC	-0.45	-0.69	0.78	0.51	-1.93	-0.92	-1.04	-0.60	0.46	-0.55	2.89	0.47	0.99
U(3)O ₂	U*													
C (g/l)	BC	3.06	1.29	3.37	4.77	-1.70	2.10	1.77	0.32	1.67	1.63	9.58	3.46	0.02
U(3)O ₂	U*													

* Uncertainties have not been evaluated. The example values are often too low.

Table I13. BC for low-enriched UNH

Bias corrections for low-enriched UNH applications (reference value units)														
Method	B/U	S58	S57	S54	M50	M62	M66	M68	M7P	M22	M30	M32	M33	IPPE
M (kg) U(5)NH	BC	0.8	0.2	1.4	1.8	-1.3	0.3	0.2	-0.1	0.7	0.3	4.3	1.3	0.4
	U*													
V (l) U(5)NH	BC	0.30	-0.23	1.23	1.32	-1.71	-0.23	-0.38	-0.36	0.66	-0.06	3.97	1.03	0.70
	U*													
Φ (mm) U(5)NH	BC	0.46	-0.37	1.95	2.09	-2.73	-0.38	-0.62	-0.58	1.05	-0.11	6.32	1.62	1.13
	U*													
S (mm) U(5)NH	BC													
	U*													
C (g/l) U(5)NH	BC	1.96	0.86	2.06	2.96	-0.93	1.39	1.19	0.25	1.02	1.07	5.82	2.14	-0.06
	U*													
M (kg) U(4)NH	BC	1.7	0.2	3.2	3.9	-3.3	0.5	0.1	-0.4	1.7	0.5	9.8	2.9	1.1
	U*													
V (l) U(4)NH	BC	0.52	-0.56	2.54	2.68	-3.67	-0.61	-0.92	-0.81	1.37	-0.22	8.28	2.09	1.54
	U*													
Φ (mm) U(4)NH	BC													
	U*													
S (mm) U(4)NH	BC	0.28	-0.46	1.77	1.83	-2.67	-0.52	-0.75	-0.62	0.96	-0.22	5.83	1.43	1.15
	U*													
C (g/l) U(4)NH	BC	2.62	1.09	2.90	4.10	-1.50	1.78	1.50	0.26	1.44	1.39	8.27	2.97	0.04
	U*													
M (kg) U(3)NH	BC	4.0	-2.1	14.1	15.5	-18.8	-1.9	-3.6	-3.8	7.6	-0.3	45.3	11.9	7.6
	U*													
V (l) U(3)NH	BC													
	U*													
Φ (mm) U(3)NH	BC	0.25	-2.06	5.73	5.59	-9.52	-2.49	-3.24	-2.37	3.16	-1.23	19.27	4.46	4.27
	U*													
S (mm) U(3)NH	BC	0.19	-1.31	3.71	3.64	-6.12	-1.57	-2.06	-1.52	2.05	-0.77	12.46	2.90	2.74
	U*													
C (g/l) U(3)NH	BC	3.94	1.40	4.98	6.76	-3.32	2.38	1.87	0.12	2.51	1.93	14.55	4.95	0.54
	U*													

* Uncertainties have not been evaluated. The example values are often too low.

Fast plutonium systems

The applications involve both fast and thermal systems. There is also a wide range of plutonium isotopic distributions. Unlike with uranium, the isotopic distributions don't change the main properties of the systems, such as going from fast to thermal systems when the distribution changes. The influence of plutonium isotopes due to various cross-section libraries will vary.

Only trends against EALF will be evaluated. Potential influences of changed plutonium distributions may be detected but the number of benchmarks is not sufficient to rely on that information.

As with fast uranium systems, many of the fast plutonium systems involve bare (unreflected) systems. There are six benchmarks with low uncertainties; PuMF001, PuMF002, PuMF005, PuMF011, PuMF022 and PuMF029. Other benchmarks are PuMF003 (cases 1-5) and PuMF037 (cases 1, 5, 7, 10, 12, 15 and 16). Even though they have larger uncertainties they are valuable in showing trends against EALF.

One benchmark, PuMF011, both has a low uncertainty and also appears to be particularly similar to the applications. It is given a high weight when the biases are determined. SCALE 5 TSUNAMI results confirm the similarity.

The TSUNAMI-IP completeness parameters for the fast PuO₂ systems are quite high, between 0.55 and 0.80, for all plutonium isotope distributions. The penalties have not been considered.

Differences between results for benchmarks PuMF001 and PuMF002 may be caused by the different plutonium distributions. Further confirmation would be needed to draw such conclusions.

The trends of biases against EALF appear to have significant negative slopes for all cross-section libraries, except for JEFF-3.0. This library also has the smallest spread of biases even though it is still very large. The spread may be more due to uncertainties in the benchmarks than in the cross-sections. The negative slopes are not obvious, considering the correlation between many of the benchmarks.

The overall information leads to the conclusion that the single benchmark PuMF011 gives a reasonable basis for the biases. The result for SCALE 5 with the 27group library appears to be high and the uncertainty should be increased for this reason.

MCNP5 calculations with JEFF 3.0, JENDL-3.2 and JENDL-3.3 libraries indicate significant bias differences between results for benchmarks PuMF001 and PuMF002. This may be due to other plutonium isotopes than ²³⁹Pu.

The fast plutonium systems are very sensitive to the ENDF/B-5 cross-section set used for ²³⁹Pu. The .50c set should be seen as an "interim" set, while the .55c set should be seen as the final version. This is important when comparisons are made with older cross-section libraries, in particular when benchmarks are re-calculated by people who are not as aware of the differences as the users of the library at the peak time of its popularity.

The EALF values in the X scale of the plutonium charts (Figure F75 to F91.) were divided by a suitable factor to allow the logarithmic scale to be used well.

Table I14. B for fast plutonium

Biases for fast plutonium: Volume (V), cylinder (Φ) and slab (S) geometry (mk)															
Method		S58	S57	S54	M50	M5F	M62	M66	M68	M7P	M22	M30	M32	M33	IPPE
V	B	-2.1	3.8	-0.1	9.3	0.1	-2.4	-2.8	-3.2	-1.2	-3.5	-2.6	-2.6	-1.9	-0.2
	U*														
Φ	B	-2.1	3.8	-0.1	9.3	0.1	-2.4	-2.8	-3.2	-1.2	-3.5	-2.6	-2.6	-1.9	-0.2
	U*														
S	B	-2.1	3.8	-0.1	9.3	0.1	-2.4	-2.8	-3.2	-1.2	-3.5	-2.6	-2.6	-1.9	-0.2
	U*														

* Uncertainties have not been evaluated. The example values are often too low.

Table I15. BC for fast PuO₂

Bias corrections for fast PuO ₂ : Volume (V), cylinder (Φ) and slab (S) geometry (reference value units)															
Method		S58	S57	S54	M50	M5F	M62	M66	M68	M7P	M22	M30	M32	M33	IPPE
V (ml) 100/0/0/0	BC	-8.8	16.3	-0.3	39.4	0.6	-10.2	-11.8	-13.4	-5.0	-14.7	-10.9	-11.0	-8.2	-0.9
	U*														
Φ (mm) 100/0/0/0	BC	-0.24	0.44	-0.01	1.07	0.02	-0.28	-0.32	-0.37	-0.14	-0.40	-0.30	-0.30	-0.22	-0.02
	U*														
S (mm) 100/0/0/0	BC	-0.13	0.24	-0.01	0.58	0.01	-0.15	-0.17	-0.20	-0.07	-0.22	-0.16	-0.16	-0.12	-0.01
	U*														
V (ml) 95/5/0/0	BC	-9.2	16.9	-0.4	40.7	0.6	-10.6	-12.2	-13.9	-5.2	-15.2	-11.3	-11.4	-8.4	-0.9
	U*														
Φ (mm) 95/5/0/0	BC														
	U*														
S (mm) 95/5/0/0	BC	-0.14	0.25	-0.01	0.60	0.01	-0.16	-0.18	-0.21	-0.08	-0.23	-0.17	-0.17	-0.13	-0.01
	U*														
V (ml) 80/10/10/0	BC	-10.0	18.3	-0.4	44.4	0.6	-11.5	-13.3	-15.1	-5.7	-16.6	-12.3	-12.4	-9.2	-1.0
	U*														
Φ (mm) 80/10/10/0	BC	-0.25	0.47	-0.01	1.13	0.02	-0.29	-0.34	-0.39	-0.14	-0.42	-0.31	-0.32	-0.23	-0.03
	U*														
S (mm) 80/10/10/0	BC	-0.14	0.26	-0.01	0.64	0.01	-0.16	-0.19	-0.22	-0.08	-0.24	-0.18	-0.18	-0.13	-0.01
	U*														
V (ml) 90/10/0/0	BC														
	U*														
Φ (mm) 90/10/0/0	BC	-0.25	0.47	-0.01	1.13	0.02	-0.29	-0.34	-0.39	-0.14	-0.42	-0.31	-0.32	-0.23	-0.03
	U*														
S (mm) 90/10/0/0	BC	-0.14	0.26	-0.01	0.63	0.01	-0.16	-0.19	-0.22	-0.08	-0.24	-0.18	-0.18	-0.13	-0.01
	U*														
V (ml) 80/15/5/0	BC														
	U*														
Φ (mm) 80/15/5/0	BC	-0.26	0.48	-0.01	1.17	0.02	-0.30	-0.35	-0.40	-0.15	-0.44	-0.32	-0.33	-0.24	-0.03
	U*														
S (mm) 80/15/5/0	BC	-0.14	0.27	-0.01	0.64	0.01	-0.17	-0.19	-0.22	-0.08	-0.24	-0.18	-0.18	-0.13	-0.01
	U*														
V (ml) 71/17/11/1	BC	-10.9	20.1	-0.4	48.7	0.7	-12.6	-14.6	-16.6	-6.2	-18.2	-13.5	-13.6	-10.1	-1.1
	U*														
Φ (mm) 71/17/11/1	BC	-0.26	0.49	-0.01	1.18	0.02	-0.30	-0.35	-0.40	-0.15	-0.44	-0.33	-0.33	-0.24	-0.03
	U*														
S (mm) 71/17/11/1	BC														
	U*														

* Uncertainties have not been evaluated. The example values are often too low.

Thermal plutonium systems

The bias trends against EALF have strong negative slopes for all methods. Two series of benchmarks, PuST022 and PuST025, had been found to be particularly important. The corresponding trend lines are for almost all methods consistent with the trend lines based on all benchmarks (not so surprising since they contain more than half of the selected benchmarks).

The TSUNAMI-IP evaluations show that the thermal PuO₂ systems have completeness parameters between 0.19 and 0.48. The penalties have not been considered.

As was done for the low-enriched uranium systems, biases will be determined from the equations generated by Microsoft Excel. All equations are in the form

$$\text{Bias(EALF)} = a \cdot \ln(\text{EALF}) + b$$

Table I16. Equation constants for thermal Pu

Constants a and b generated to fit the equation $y = a \cdot \ln(\text{EALF}) + b$ to benchmark calculation results														
	S5-238	S5-27	S5-44	M5-E50	M5-E5X	M5-E62	M5-E66	M5-E68	M5-E7P	M5-F22	M5-F30	M5-J32	M5-J33	ABBN-93
a	-5.33	-3.29	-4.75	-5.05	-5.34	-4.93	-4.62	-4.71	-4.49	-3.38	-3.78	-5.00	-4.18	-3.84
b	-10.5	3.58	-6.61	-7.28	-8.74	-13.1	-10.8	-11.5	-10.4	-3.44	-7.17	-8.34	-6.01	-13.0

The corresponding biases in keff (mk) and in application value units are displayed in Table I17. - Table I24. for the different methods.

Table I17. B: Thermal Pu(100, 95/5, 80/10/10)O₂

Biases for thermal Pu(100/0/0/0)O ₂ , Pu(95/5/0/0)O ₂ and Pu(80/10/10/0)O ₂ applications (mk)															
Method		S58	S57	S54	M50	M5F	M62	M66	M68	M7P	M22	M30	M32	M33	IPPE
M PuO ₂ 100/0/0/0	B	4.96	13.15	7.20	7.39	6.76	1.17	2.67	2.20	2.65	6.38	3.80	6.18	6.15	-1.87
	U*														
C PuO ₂ 100/0/0/0	B	10.5	16.6	12.1	12.6	12.3	6.26	7.45	7.08	7.30	9.88	7.70	11.3	10.5	2.10
	U*														
M PuO ₂ 95/5/0/0	B	4.94	13.14	7.18	7.38	6.74	1.15	2.65	2.18	2.63	6.37	3.78	6.16	6.13	-1.88
	U*														
C PuO ₂ 95/5/0/0	B	10.5	16.6	12.1	12.6	12.3	6.29	7.47	7.10	7.32	9.90	7.72	11.4	10.5	2.12
	U*														
M PuO ₂ 80/10/10/0	B	5.00	13.18	7.23	7.43	6.80	1.20	2.70	2.24	2.68	6.41	3.82	6.22	6.18	-1.84
	U*														
C PuO ₂ 80/10/10/0	B	10.5	16.6	12.1	12.6	12.3	6.26	7.44	7.07	7.29	9.88	7.70	11.3	10.5	2.10
	U*														

* Uncertainties have not been evaluated. The example values are often too low.

Table I18. BC: Thermal Pu(100, 95/5, 80/10/10)O₂

Bias corrections for thermal Pu(100/0/0/0)O ₂ , Pu(95/5/0/0)O ₂ and Pu(80/10/10/0)O ₂ (ref. value units)															
Method		S58	S57	S54	M50	M5F	M62	M66	M68	M7P	M22	M30	M32	M33	IPPE
M 100/0/0/0	BC	12	31	17	17	16	3	6	5	6	15	9	15	14	-4
	U*														
C 100/0/0/0	BC	1.45	2.28	1.67	1.74	1.69	0.86	1.03	0.98	1.01	1.36	1.06	1.57	1.44	0.29
	U*														
M 95/5/0/0	BC	14	38	21	22	20	3	8	6	8	19	11	18	18	-6
	U*														
C 95/5/0/0	BC	1.62	2.55	1.87	1.95	1.90	0.97	1.15	1.09	1.13	1.52	1.19	1.75	1.62	0.33
	U*														
M 80/10/10/0	BC	17	44	24	25	23	4	9	8	9	22	13	21	21	-6
	U*														
C 80/10/10/0	BC	1.70	2.68	1.96	2.04	1.99	1.01	1.21	1.15	1.18	1.60	1.25	1.84	1.70	0.34
	U*														

Table I19. B: Thermal Pu(90/10, 80/15/5, 71/17/11/1)O₂

Biases for thermal Pu(90/10/0/0)O ₂ , Pu(80/15/5/0)O ₂ and Pu(71/17/11/1)O ₂ applications (mk)															
Method		S58	S57	S54	M50	M5F	M62	M66	M68	M7P	M22	M30	M32	M33	IPPE
M PuO ₂ 90/10/0/0	B	4.92	13.13	7.16	7.36	6.72	1.13	2.64	2.17	2.62	6.36	3.77	6.14	6.11	-1.90
	U*														
C PuO ₂ 90/10/0/0	B	10.5	16.6	12.1	12.7	12.3	6.30	7.48	7.11	7.33	9.91	7.73	11.4	10.5	2.13
	U*														
M PuO ₂ 80/15/5/0	B	4.92	13.13	7.16	7.36	6.72	1.13	2.64	2.17	2.62	6.36	3.77	6.14	6.12	-1.90
	U*														
C PuO ₂ 80/15/5/0	B	10.4	16.5	12.1	12.6	12.2	6.22	7.41	7.04	7.26	9.86	7.67	11.3	10.4	2.07
	U*														
M PuO ₂ 71/17/11/1	B	4.97	13.16	7.21	7.40	6.77	1.17	2.68	2.21	2.66	6.39	3.80	6.19	6.15	-1.86
	U*														
C PuO ₂ 71/17/11/1	B	10.4	16.5	12.1	12.6	12.2	6.22	7.41	7.04	7.26	9.85	7.67	11.3	10.4	2.07
	U*														

Table I20. BC: Thermal Pu(90/10, 80/15/5, 71/17/11/1)O₂

Bias corrections for thermal Pu(90/10/0/0)O ₂ , Pu(80/15/5/0)O ₂ and Pu(71/17/11/1)O ₂ (ref. value units)															
Method		S58	S57	S54	M50	M5F	M62	M66	M68	M7P	M22	M30	M32	M33	IPPE
M PuO ₂ 90/10/0/0	BC	19	50	27	28	25	4	10	8	10	24	14	23	23	-7
	U*														
C PuO ₂ 90/10/0/0	BC	1.80	2.84	2.08	2.16	2.11	1.08	1.28	1.22	1.25	1.69	1.32	1.95	1.80	0.36
	U*														
M PuO ₂ 80/15/5/0	BC	23	61	33	34	31	5	12	10	12	30	17	29	28	-9
	U*														
C PuO ₂ 80/15/5/0	BC	1.97	3.12	2.28	2.38	2.31	1.18	1.40	1.33	1.37	1.86	1.45	2.14	1.97	0.39
	U*														
M PuO ₂ 71/17/11/1	BC	24	63	34	35	32	6	13	11	13	31	18	30	29	-9
	U*														
C PuO ₂ 71/17/11/1	BC	2.03	3.22	2.35	2.45	2.39	1.21	1.44	1.37	1.42	1.92	1.50	2.20	2.03	0.40
	U*														

* Uncertainties have not been evaluated. The example values are often too low.

Table I21. B: Thermal Pu(100, 95/5, 80/10/10)NH

Biases for thermal Pu(100/0/0/0)NH, Pu(95/5/0/0)NH and Pu(80/10/10/0)NH applications (mk)															
Method		S58	S57	S54	M50	M5F	M62	M66	M68	M7P	M22	M30	M32	M33	IPPE
M PuNH 100/0/0/0	B	4.96	13.1	7.19	7.39	6.76	1.16	2.66	2.20	2.65	6.38	3.79	6.17	6.14	-1.87
	U*														
V PuNH 100/0/0/0	B	-4.27	7.4	-1.04	-1.36	-2.49	-7.37	-5.34	-5.97	-5.14	0.52	-2.75	-2.48	-1.10	-8.52
	U*														
Φ PuNH 100/0/0/0	B														
	U*														
S PuNH 100/0/0/0	B	-7.45	5.48	-3.87	-4.37	-5.67	-10.31	-8.09	-8.77	-7.81	-1.49	-5.00	-5.46	-3.60	-10.8
	U*														
C PuNH 100/0/0/0	B	10.5	16.6	12.1	12.6	12.3	6.29	7.47	7.10	7.32	9.90	7.72	11.4	10.5	2.12
	U*														
M PuNH 95/5/0/0	B	4.93	13.1	7.17	7.36	6.73	1.14	2.64	2.17	2.62	6.36	3.77	6.15	6.12	-1.89
	U*														
V PuNH 95/5/0/0	B	-0.20	10.0	2.59	2.50	1.59	-3.61	-1.81	-2.37	-1.70	3.11	0.14	1.34	2.09	-5.59
	U*														
Φ PuNH 95/5/0/0	B														
	U*														
S PuNH 95/5/0/0	B	-1.41	9.21	1.51	1.35	0.38	-4.73	-2.86	-3.44	-2.72	2.34	-0.72	0.20	1.14	-6.46
	U*														
C PuNH 95/5/0/0	B	10.5	16.6	12.1	12.6	12.3	6.26	7.44	7.07	7.29	9.88	7.70	11.3	10.5	2.10
	U*														
M PuNH 80/10/10/0	B	5.00	13.2	7.23	7.43	6.80	1.20	2.70	2.23	2.68	6.41	3.82	6.21	6.17	-1.85
	U*														
V PuNH 80/10/10/0	B	0.07	10.1	2.83	2.76	1.86	-3.35	-1.57	-2.12	-1.47	3.28	0.33	1.59	2.31	-5.39
	U*														
Φ PuNH 80/10/10/0	B	-0.30	9.90	2.50	2.40	1.49	-3.70	-1.89	-2.45	-1.79	3.04	0.07	1.24	2.01	-5.66
	U*														
S PuNH 80/10/10/0	B	-1.97	8.87	1.01	0.82	-0.18	-5.24	-3.34	-3.93	-3.20	1.98	-1.12	-0.33	0.70	-6.87
	U*														
C PuNH 80/10/10/0	B	10.5	16.6	12.1	12.7	12.3	6.30	7.48	7.11	7.33	9.91	7.73	11.4	10.5	2.13
	U*														

* Uncertainties have not been evaluated. The example values are often too low.

BC: Thermal Pu(100, 95/5, 80/10/10)NH Table I22.

Bias corrections for thermal Pu(100/0/0/0)NH, Pu(95/5/0/0)NH and Pu(80/10/10/0)NH (ref. value units)															
Method		S58	S57	S54	M50	M5F	M62	M66	M68	M7P	M22	M30	M32	M33	IPPE
M (g) 100/0/0/0	BC	12	31	17	17	16	3	6	5	6	15	9	14	14	-4
	U*														
V (ml) 100/0/0/0	BC	-138	241	-34	-44	-81	-239	-173	-193	-166	17	-89	-80	-36	-276
	U*														
Φ (mm) 100/0/0/0	BC														
	U*														
S (mm) 100/0/0/0	BC	-1.27	1.46	2.30	1.69	1.76	1.71	0.87	1.04	0.99	1.02	1.38	1.07	1.58	1.46
	U*														
C (g/cm ³) 100/0/0/0	BC	1.46	2.30	1.69	1.76	1.71	0.87	1.04	0.99	1.02	1.38	1.07	1.58	1.46	0.29
	U*														
M (g) 95/5/0/0	BC	15	40	22	22	20	3	8	7	8	19	11	19	19	-6
	U*														
V (ml) 95/5/0/0	BC	-10	497	129	125	79	-180	-90	-118	-85	155	7	67	104	-279
	U*														
Φ (mm) 95/5/0/0	BC														
	U*														
S (mm) 95/5/0/0	BC	-0.30	1.62	2.57	1.88	1.96	1.90	0.97	1.15	1.10	1.13	1.53	1.19	1.76	1.62
	U*														
C (g/cm ³) 95/5/0/0	BC	1.62	2.57	1.88	1.96	1.90	0.97	1.15	1.10	1.13	1.53	1.19	1.76	1.62	0.32
	U*														
M (g) 80/10/10/0	BC	18	47	26	26	24	4	10	8	9	23	14	22	22	-7
	U*														
V (ml) 80/10/10/0	BC	4	594	166	162	109	-197	-92	-124	-86	192	19	93	135	-316
	U*														
Φ (mm) 80/10/10/0	BC	-0.11	-0.46	2.07	0.24	0.19	-0.04	-1.22	-0.78	-0.92	-0.75	0.46	-0.26	-0.08	0.16
	U*														
S (mm) 80/10/10/0	BC	-0.46	1.72	2.72	1.99	2.08	2.02	1.03	1.23	1.17	1.20	1.62	1.27	1.87	1.72
	U*														
C (g/cm ³) 80/10/10/0	BC	1.72	2.72	1.99	2.08	2.02	1.03	1.23	1.17	1.20	1.62	1.27	1.87	1.72	0.35
	U*														

* Uncertainties have not been evaluated. The example values are often too low.

Table I23. B: Thermal Pu(90/10, 80/15/5, 71/17/11/1)NH

Biases for thermal Pu(90/10/0/0)NH, Pu(80/15/5/0)NH and Pu(71/17/11/1)NH applications (mk)															
Method		S58	S57	S54	M50	M5F	M62	M66	M68	M7P	M22	M30	M32	M33	IPPE
M PuNH 90/10/0/0	B	4.91	13.1	7.16	7.35	6.71	1.12	2.63	2.16	2.61	6.35	3.76	6.13	6.11	-1.90
	U*														
V PuNH 90/10/0/0	B	0.39	10.3	3.12	3.06	2.18	-3.06	-1.30	-1.85	-1.21	3.48	0.55	1.89	2.55	-5.17
	U*														
Φ PuNH 90/10/0/0	B														
	U*														
S PuNH 90/10/0/0	B	-0.54	9.75	2.29	2.18	1.25	-3.92	-2.10	-2.66	-1.99	2.89	-0.10	1.02	1.83	-5.83
	U*														
C PuNH 90/10/0/0	B	10.4	16.5	12.1	12.6	12.2	6.22	7.41	7.04	7.26	9.86	7.67	11.3	10.4	2.07
	U*														
M PuNH 80/15/5/0	B	4.91	13.1	7.15	7.34	6.71	1.12	2.62	2.16	2.61	6.35	3.76	6.13	6.10	-1.91
	U*														
V PuNH 80/15/5/0	B	0.58	10.4	3.29	3.24	2.37	-2.89	-1.13	-1.68	-1.05	3.60	0.69	2.07	2.70	-5.03
	U*														
Φ PuNH 80/15/5/0	B														
	U*														
S PuNH 80/15/5/0	B	-0.87	9.55	2.00	1.87	0.92	-4.22	-2.38	-2.95	-2.26	2.68	-0.33	0.71	1.57	-6.07
	U*														
C PuNH 80/15/5/0	B	10.4	16.5	12.1	12.6	12.2	6.22	7.41	7.04	7.26	9.85	7.67	11.3	10.4	2.07
	U*														
M PuNH 71/17/11/1	B	4.96	13.2	7.20	7.40	6.76	1.17	2.67	2.20	2.65	6.38	3.80	6.18	6.15	-1.87
	U*														
V PuNH 71/17/11/1	B	0.57	10.4	3.28	3.23	2.37	-2.89	-1.14	-1.68	-1.05	3.60	0.69	2.06	2.70	-5.03
	U*														
Φ PuNH 71/17/11/1	B	0.36	10.31	3.10	3.03	2.16	-3.08	-1.32	-1.87	-1.23	3.46	0.54	1.87	2.54	-5.18
	U*														
S PuNH 71/17/11/1	B	-0.31	9.89	2.49	2.40	1.48	-3.71	-1.90	-2.46	-1.80	3.04	0.06	1.23	2.01	-5.67
	U*														
C PuNH 71/17/11/1	B	10.5	16.5	12.1	12.6	12.3	6.25	7.44	7.06	7.29	9.87	7.69	11.3	10.5	2.09
	U*														

* Uncertainties have not been evaluated. The example values are often too low.

Table I24. BC: Thermal Pu(90/10, 80/15/5, 71/17/11/1)NH

Bias corrections for thermal Pu(90/10/0/0)NH, Pu(80/15/5/0)NH and Pu(71/17/11/1)NH (ref. value units)															
Method		S58	S57	S54	M50	M5F	M62	M66	M68	M7P	M22	M30	M32	M33	IPPE
M (g) 90/10/0/0	BC	19	51	28	29	26	4	10	8	10	25	15	24	24	-7
	U*														
V (ml) 90/10/0/0	BC	25	675	204	200	142	-200	-85	-121	-79	228	36	123	167	-338
	U*														
Φ (mm) 90/10/0/0	BC														
	U*														
S (mm) 90/10/0/0	BC	-1.27	0.94	-0.66	-0.75	-0.97	-1.76	-1.38	-1.50	-1.34	-0.26	-0.85	-0.93	-0.61	-1.85
	U*														
C (g/cm ³) 90/10/0/0	BC	1.80	2.86	2.09	2.18	2.12	1.08	1.28	1.22	1.26	1.71	1.33	1.96	1.81	0.36
	U*														
M (g) 80/15/5/0	BC	23	62	34	35	32	5	12	10	12	30	18	29	29	-9
	U*														
V (ml) 80/15/5/0	BC	46	823	259	255	187	-227	-89	-132	-82	284	54	163	213	-396
	U*														
Φ (mm) 80/15/5/0	BC														
	U*														
S (mm) 80/15/5/0	BC	-0.30	1.94	0.32	0.29	0.08	-1.00	-0.60	-0.72	-0.57	0.49	-0.15	0.04	0.24	-1.36
	U*														
C (g/cm ³) 80/15/5/0	BC	1.98	3.14	2.29	2.39	2.32	1.18	1.41	1.34	1.38	1.87	1.46	2.15	1.98	0.39
	U*														
M (g) 71/17/11/1	BC	26	69	38	39	36	6	14	12	14	34	20	33	32	-10
	U*														
V (ml) 71/17/11/1	BC	48	863	272	268	196	-239	-94	-139	-87	298	57	171	223	-416
	U*														
Φ (mm) 71/17/11/1	BC	0.15	-0.08	2.67	0.67	0.65	0.40	-1.00	-0.51	-0.66	-0.48	0.82	0.02	0.33	0.54
	U*														
S (mm) 71/17/11/1	BC	-0.46	2.07	0.24	0.19	-0.04	-1.22	-0.78	-0.92	-0.75	0.46	-0.26	-0.08	0.16	-1.60
	U*														
C (g/cm ³) 71/17/11/1	BC	2.04	3.23	2.36	2.46	2.39	1.22	1.45	1.38	1.42	1.93	1.50	2.21	2.04	0.41
	U*														

* Uncertainties have not been evaluated. The example values are often too low.

Summary of bias corrections for all methods

Table I25. BC - SCALE 5 + 238 group cross-sections

Bias corrections (rvu ^{**}) for applications – SCALE 5 with 238-group cross-sections						
Material	Isotopes	Mass (kg)	Volume (l)	Cylinder (cm)	Slab (cm)	Conc. (g/cm ³)
UO ₂	100	0.0082	0.0000	0.0000	0.0000	0.0658
	20	0.0600	0.1155	0.0745	0.0485	0.3668
	5	0.3333	-0.0732	-0.0264	-0.0289	1.7117
	4	0.5107	-0.1123	-0.0067	-0.0293	2.2053
	3	0.6770	-0.2295	-0.0543	-0.0446	3.0646
UNH	100	0.0082	0.0639	0.0564	0.0359	0.0666
	20	0.0718	0.1794	0.0879	0.0575	0.3780
	5	0.8413	0.3016	0.0464	0.0239	1.9630
	4	1.6584	0.5162	0.0592	0.0277	2.6199
	3	4.0466	0.4196	0.0249	0.0194	3.9441
PuO ₂	100/0/0/0	0.0117	-0.0088	-0.0241	-0.0130	0.1445
	95/5/0/0	0.0144	-0.0092	-0.0250	-0.0136	0.1617
	80/10/10/0	0.0169	-0.0100	-0.0254	-0.0143	0.1696
	90/10/0/0	0.0186	-0.0100	-0.0254	-0.0142	0.1797
	80/15/5/0	0.0228	-0.0105	-0.0262	-0.0144	0.1972
	71/17/11/1	0.0238	-0.0109	-0.0264	-0.0147	0.2033
PuNH	100/0/0/0	0.0116	-0.1384	-0.1335	-0.1274	0.1460
	95/5/0/0	0.0149	-0.0101	-0.0162	-0.0298	0.1623
	80/10/10/0	0.0177	0.0042	-0.0107	-0.0460	0.1724
	90/10/0/0	0.0192	0.0253	0.0070	-0.0130	0.1805
	80/15/5/0	0.0233	0.0456	0.0138	-0.0234	0.1981
	71/17/11/1	0.0261	0.0475	0.0152	-0.0084	0.2039

Table I26. BC - SCALE 5 + 27 group cross-sections

Bias corrections (rvu**) for applications – SCALE 5 with 27-group cross-sections						
Material	Isotopes	Mass (kg)	Volume (l)	Cylinder (cm)	Slab (cm)	Conc. (g/cm ³)
UO ₂	100	0.0135	0.1692	0.1998	0.1233	0.1340
	20	0.0992	0.1908	0.1231	0.0802	0.7467
	5	0.0785	-0.1628	-0.0564	-0.0449	0.7773
	4	0.1027	-0.2327	-0.0488	-0.0493	0.9776
	3	-0.0420	-0.4282	-0.0957	-0.0690	1.2896
UNH	100	0.0136	0.1056	0.0931	0.0593	0.1357
	20	0.1186	0.2964	0.1452	0.0950	0.7695
	5	0.1633	-0.2277	-0.0374	-0.0283	0.8630
	4	0.1601	-0.5629	-0.0609	-0.0464	1.0936
	3	-2.1201	-3.6338	-0.2058	-0.1306	1.4010
PuO ₂	100/0/0/0	0.0309	0.0163	0.0444	0.0240	0.2285
	95/5/0/0	0.0384	0.0169	0.0460	0.0250	0.2553
	80/10/10/0	0.0444	0.0183	0.0467	0.0263	0.2682
	90/10/0/0	0.0496	0.0185	0.0467	0.0261	0.2835
	80/15/5/0	0.0609	0.0193	0.0483	0.0265	0.3125
	71/17/11/1	0.0629	0.0201	0.0486	0.0272	0.3223
PuNH	100/0/0/0	0.0308	0.2412	0.1858	0.0937	0.2304
	95/5/0/0	0.0398	0.4970	0.3188	0.1944	0.2566
	80/10/10/0	0.0466	0.5936	0.3514	0.2066	0.2719
	90/10/0/0	0.0512	0.6752	0.3815	0.2350	0.2860
	80/15/5/0	0.0623	0.8229	0.4200	0.2578	0.3140
	71/17/11/1	0.0692	0.8634	0.4320	0.2671	0.3227

Table I27. BC - SCALE 5 + 44 group cross-sections

Bias corrections (rvu ^{**}) for applications – SCALE 5 with 44-group cross-sections						
Material	Isotopes	Mass (kg)	Volume (l)	Cylinder (cm)	Slab (cm)	Conc. (g/cm ³)
UO ₂	100	0.0103	0.0658	0.0777	0.0480	0.0870
	20	0.0757	0.1456	0.0940	0.0612	0.4847
	5	0.5220	0.2526	0.0853	0.0508	1.7358
	4	0.8438	0.3445	0.1088	0.0613	2.2965
	3	1.5682	0.5848	0.1242	0.0776	3.3655
UNH	100	0.0104	0.0806	0.0711	0.0452	0.0881
	20	0.0905	0.2262	0.1108	0.0725	0.4995
	5	1.4052	1.2260	0.1946	0.1229	2.0623
	4	3.1778	2.5352	0.2814	0.1770	2.8995
	3	14.0888	10.0743	0.5731	0.3713	4.9841
PuO ₂	100/0/0/0	0.0169	-0.0003	-0.0009	-0.0005	0.1672
	95/5/0/0	0.0210	-0.0004	-0.0010	-0.0005	0.1870
	80/10/10/0	0.0244	-0.0004	-0.0010	-0.0005	0.1962
	90/10/0/0	0.0271	-0.0004	-0.0010	-0.0005	0.2077
	80/15/5/0	0.0332	-0.0004	-0.0010	-0.0006	0.2283
	71/17/11/1	0.0344	-0.0004	-0.0010	-0.0006	0.2354
PuNH	100/0/0/0	0.0168	-0.0337	-0.0454	-0.0662	0.1688
	95/5/0/0	0.0217	0.1293	0.0759	0.0319	0.1877
	80/10/10/0	0.0256	0.1661	0.0888	0.0235	0.1992
	90/10/0/0	0.0279	0.2038	0.1099	0.0552	0.2090
	80/15/5/0	0.0340	0.2590	0.1254	0.0539	0.2294
	71/17/11/1	0.0379	0.2715	0.1297	0.0674	0.2360

Table I28. BC: MCNP5 + ENDF/B-50 cross-sections

Bias corrections (rvu**) for applications – MCNP 5 with ENDF/B-50 cross-sections						
Material	Isotopes	Mass (kg)	Volume (l)	Cylinder (cm)	Slab (cm)	Conc. (g/cm ³)
UO ₂	100	0.0099	-0.0470	-0.0555	-0.0343	0.0893
	20	0.0731	0.1406	0.0907	0.0591	0.4978
	5	0.6670	0.2037	0.0679	0.0338	2.5245
	4	1.0640	0.2715	0.1003	0.0436	3.3098
	3	1.8392	0.4411	0.0909	0.0514	4.7656
UNH	100	0.0100	0.0778	0.0686	0.0437	0.0904
	20	0.0874	0.2184	0.1070	0.0700	0.5130
	5	1.7672	1.3223	0.2091	0.1293	2.9634
	4	3.8725	2.6796	0.2984	0.1828	4.0954
	3	15.4898	9.8198	0.5592	0.3640	6.7557
PuO ₂	100/0/0/0	0.0174	0.0394	0.1074	0.0581	0.1741
	95/5/0/0	0.0215	0.0407	0.1111	0.0604	0.1948
	80/10/10/0	0.0250	0.0444	0.1130	0.0636	0.2044
	90/10/0/0	0.0278	0.0447	0.1130	0.0631	0.2164
	80/15/5/0	0.0341	0.0468	0.1167	0.0642	0.2378
	71/17/11/1	0.0354	0.0487	0.1176	0.0657	0.2452
PuNH	100/0/0/0	0.0173	-0.0441	-0.0550	-0.0747	0.1758
	95/5/0/0	0.0223	0.1247	0.0724	0.0285	0.1955
	80/10/10/0	0.0263	0.1616	0.0854	0.0191	0.2075
	90/10/0/0	0.0287	0.1999	0.1072	0.0525	0.2176
	80/15/5/0	0.0349	0.2552	0.1228	0.0505	0.2389
	71/17/11/1	0.0389	0.2675	0.1272	0.0647	0.2458

Table I29. BC: MCNP5 + ENDF/B-5F (.55c for ^{239}Pu)

Bias corrections (rvu**) for applications – MCNP 5 with ENDF/B-5F cross-sections (.55c for ^{239}Pu)						
Material	Isotopes	Mass (kg)	Volume (l)	Cylinder (cm)	Slab (cm)	Conc. (g/cm ³)
UO ₂	100	0.0099	-0.0470	-0.0555	-0.0343	0.0893
	20	0.0731	0.1406	0.0907	0.0591	0.4978
	5	0.6670	0.2037	0.0679	0.0338	2.5245
	4	1.0640	0.2715	0.1003	0.0436	3.3098
	3	1.8392	0.4411	0.0909	0.0514	4.7656
UNH	100	0.0100	0.0778	0.0686	0.0437	0.0904
	20	0.0874	0.2184	0.1070	0.0700	0.5130
	5	1.7672	1.3223	0.2091	0.1293	2.9634
	4	3.8725	2.6796	0.2984	0.1828	4.0954
	3	15.4898	9.8198	0.5592	0.3640	6.7557
PuO ₂	100/0/0/0	0.0159	0.0006	0.0015	0.0008	0.1695
	95/5/0/0	0.0197	0.0006	0.0016	0.0008	0.1896
	80/10/10/0	0.0229	0.0006	0.0016	0.0009	0.1989
	90/10/0/0	0.0254	0.0006	0.0016	0.0009	0.2107
	80/15/5/0	0.0312	0.0007	0.0016	0.0009	0.2314
	71/17/11/1	0.0324	0.0007	0.0017	0.0009	0.2386
PuNH	100/0/0/0	0.0158	-0.0806	-0.0860	-0.0969	0.1711
	95/5/0/0	0.0204	0.0793	0.0422	0.0080	0.1903
	80/10/10/0	0.0241	0.1092	0.0529	-0.0043	0.2020
	90/10/0/0	0.0262	0.1425	0.0740	0.0301	0.2118
	80/15/5/0	0.0319	0.1868	0.0869	0.0249	0.2325
	71/17/11/1	0.0356	0.1957	0.0903	0.0400	0.2392

Table I30. BC: MCNP5 + ENDF/B-62 cross-sections

Bias corrections (rvu**) for applications – MCNP 5 with ENDF/B-62 cross-sections						
Material	Isotopes	Mass (kg)	Volume (l)	Cylinder (cm)	Slab (cm)	Conc. (g/cm ³)
UO	100	-0.0028	-0.0188	-0.0222	-0.0137	-0.0118
	20	-0.0209	-0.0402	-0.0259	-0.0169	-0.0655
	5	-0.4534	-0.5318	-0.1818	-0.1258	-0.7043
	4	-0.7705	-0.7418	-0.1959	-0.1443	-1.0107
	3	-1.7942	-1.3109	-0.2858	-0.1929	-1.7039
UNH	100	-0.0029	-0.0222	-0.0196	-0.0125	-0.0119
	20	-0.0250	-0.0624	-0.0306	-0.0200	-0.0675
	5	-1.2950	-1.7059	-0.2726	-0.1794	-0.9308
	4	-3.2541	-3.6706	-0.4049	-0.2673	-1.4952
	3	-18.8302	-16.7596	-0.9521	-0.6125	-3.3150
PuO	100/0/0/0	0.0027	-0.0102	-0.0278	-0.0150	0.0864
	95/5/0/0	0.0034	-0.0106	-0.0288	-0.0156	0.0968
	80/10/10/0	0.0041	-0.0115	-0.0293	-0.0165	0.1014
	90/10/0/0	0.0043	-0.0116	-0.0293	-0.0163	0.1077
	80/15/5/0	0.0053	-0.0121	-0.0302	-0.0166	0.1176
	71/17/11/1	0.0056	-0.0126	-0.0305	-0.0170	0.1213
PuNH	100/0/0/0	0.0027	-0.2388	-0.2144	-0.1762	0.0874
	95/5/0/0	0.0034	-0.1800	-0.1265	-0.0997	0.0970
	80/10/10/0	0.0042	-0.1966	-0.1313	-0.1222	0.1033
	90/10/0/0	0.0044	-0.2003	-0.1215	-0.0945	0.1077
	80/15/5/0	0.0053	-0.2274	-0.1268	-0.1140	0.1181
	71/17/11/1	0.0061	-0.2390	-0.1292	-0.1001	0.1218

Table I31. BC: MCNP5 + ENDF/B-66 cross-sections

Bias corrections (rvu**) for applications – MCNP 5 with ENDF/B-66 cross-sections						
Material	Isotopes	Mass (kg)	Volume (l)	Cylinder (cm)	Slab (cm)	Conc. (g/cm ³)
UO ₂	100	0.0032	-0.0658	-0.0777	-0.0480	0.0306
	20	0.0235	0.0452	0.0292	0.0190	0.1703
	5	0.1522	-0.2125	-0.0738	-0.0600	1.2420
	4	0.2116	-0.3049	-0.0612	-0.0656	1.5708
	3	0.0614	-0.5650	-0.1268	-0.0923	2.0980
UNH	100	0.0032	0.0250	0.0221	0.0140	0.0309
	20	0.0281	0.0702	0.0344	0.0225	0.1755
	5	0.3414	-0.2297	-0.0382	-0.0308	1.3894
	4	0.4740	-0.6061	-0.0650	-0.0524	1.7827
	3	-1.9315	-4.3992	-0.2490	-0.1573	2.3820
PuO ₂	100/0/0/0	0.0063	-0.0118	-0.0321	-0.0174	0.1028
	95/5/0/0	0.0077	-0.0122	-0.0332	-0.0181	0.1151
	80/10/10/0	0.0091	-0.0133	-0.0338	-0.0190	0.1206
	90/10/0/0	0.0100	-0.0134	-0.0338	-0.0189	0.1279
	80/15/5/0	0.0122	-0.0140	-0.0349	-0.0192	0.1401
	71/17/11/1	0.0128	-0.0146	-0.0352	-0.0196	0.1445
PuNH	100/0/0/0	0.0062	-0.1729	-0.1592	-0.1384	0.1039
	95/5/0/0	0.0080	-0.0902	-0.0673	-0.0603	0.1154
	80/10/10/0	0.0096	-0.0921	-0.0672	-0.0779	0.1227
	90/10/0/0	0.0102	-0.0849	-0.0550	-0.0506	0.1282
	80/15/5/0	0.0125	-0.0892	-0.0547	-0.0644	0.1408
	71/17/11/1	0.0140	-0.0939	-0.0552	-0.0514	0.1450

Table I32. BC: MCNP5 + ENDF/B-8 cross-sections

Bias corrections (rvu**) for applications – MCNP 5 with ENDF/B-68 cross-sections						
Material	Isotopes	Mass (kg)	Volume (l)	Cylinder (cm)	Slab (cm)	Conc. (g/cm ³)
UO ₂	100	0.0014	-0.0564	-0.0666	-0.0411	0.0141
	20	0.0104	0.0201	0.0130	0.0084	0.0786
	5	0.0955	-0.2488	-0.0861	-0.0678	1.0762
	4	0.1189	-0.3549	-0.0759	-0.0748	1.3492
	3	-0.1212	-0.6513	-0.1453	-0.1043	1.7669
UNH	100	0.0014	0.0111	0.0098	0.0062	0.0143
	20	0.0125	0.0312	0.0153	0.0100	0.0810
	5	0.1866	-0.3811	-0.0623	-0.0462	1.1897
	4	0.1147	-0.9232	-0.1001	-0.0749	1.4966
	3	-3.6490	-5.7207	-0.3241	-0.2059	1.8692
PuO ₂	100/0/0/0	0.0052	-0.0134	-0.0367	-0.0198	0.0977
	95/5/0/0	0.0064	-0.0139	-0.0379	-0.0206	0.1094
	80/10/10/0	0.0075	-0.0151	-0.0386	-0.0217	0.1146
	90/10/0/0	0.0082	-0.0153	-0.0386	-0.0215	0.1216
	80/15/5/0	0.0101	-0.0160	-0.0398	-0.0219	0.1331
	71/17/11/1	0.0106	-0.0166	-0.0401	-0.0224	0.1372
PuNH	100/0/0/0	0.0051	-0.1933	-0.1762	-0.1501	0.0987
	95/5/0/0	0.0066	-0.1180	-0.0856	-0.0725	0.1096
	80/10/10/0	0.0079	-0.1245	-0.0871	-0.0916	0.1166
	90/10/0/0	0.0084	-0.1207	-0.0756	-0.0642	0.1218
	80/15/5/0	0.0102	-0.1320	-0.0770	-0.0797	0.1337
	71/17/11/1	0.0116	-0.1389	-0.0782	-0.0665	0.1377

Table I33. BC: MCNP5 + ENDF/B-7P cross-sections

Bias corrections (rvu**) for applications – MCNP 5 with ENDF/B-7P cross-sections						
Material	Isotopes	Mass (kg)	Volume (l)	Cylinder (cm)	Slab (cm)	Conc. (g/cm ³)
UO ₂	100	-0.0039	-0.0282	-0.0333	-0.0206	-0.0400
	20	-0.0287	-0.0552	-0.0356	-0.0232	-0.2227
	5	-0.0338	-0.1540	-0.0530	-0.0393	0.2417
	4	-0.0712	-0.2173	-0.0517	-0.0441	0.2849
	3	-0.2919	-0.3917	-0.0864	-0.0603	0.3194
UNH	100	-0.0039	-0.0306	-0.0270	-0.0172	-0.0405
	20	-0.0343	-0.0858	-0.0420	-0.0275	-0.2295
	5	-0.1238	-0.3618	-0.0583	-0.0400	0.2457
	4	-0.4234	-0.8112	-0.0890	-0.0615	0.2632
	3	-3.8171	-4.1813	-0.2373	-0.1518	0.1242
PuO ₂	100/0/0/0	0.0062	-0.0050	-0.0137	-0.0074	0.1007
	95/5/0/0	0.0077	-0.0052	-0.0142	-0.0077	0.1128
	80/10/10/0	0.0090	-0.0057	-0.0144	-0.0081	0.1182
	90/10/0/0	0.0099	-0.0057	-0.0144	-0.0080	0.1253
	80/15/5/0	0.0122	-0.0060	-0.0149	-0.0082	0.1373
	71/17/11/1	0.0127	-0.0062	-0.0150	-0.0084	0.1415
PuNH	100/0/0/0	0.0062	-0.1664	-0.1534	-0.1336	0.1018
	95/5/0/0	0.0080	-0.0850	-0.0637	-0.0575	0.1131
	80/10/10/0	0.0095	-0.0864	-0.0635	-0.0745	0.1202
	90/10/0/0	0.0102	-0.0790	-0.0515	-0.0479	0.1257
	80/15/5/0	0.0124	-0.0824	-0.0509	-0.0611	0.1379
	71/17/11/1	0.0139	-0.0868	-0.0514	-0.0485	0.1421

Table I34. BC: MCNP5 + JEF-2.2 cross-sections

Bias corrections (rvu**) for applications – MCNP 5 with JEF-2.2 cross-sections						
Material	Isotopes	Mass (kg)	Volume (l)	Cylinder (cm)	Slab (cm)	Conc. (g/cm ³)
UO ₂	100	0.0018	-0.0470	-0.0555	-0.0343	0.0282
	20	0.0131	0.0251	0.0162	0.0106	0.1572
	5	0.2678	0.1450	0.0491	0.0301	0.8509
	4	0.4348	0.1986	0.0608	0.0359	1.1296
	3	0.8258	0.3397	0.0725	0.0460	1.6664
UNH	100	0.0018	0.0139	0.0123	0.0078	0.0286
	20	0.0156	0.0390	0.0191	0.0125	0.1620
	5	0.7246	0.6606	0.1049	0.0666	1.0155
	4	1.6547	1.3731	0.1523	0.0964	1.4370
	3	7.5534	5.5638	0.3165	0.2048	2.5069
PuO ₂	100/0/0/0	0.0150	-0.0147	-0.0401	-0.0217	0.1364
	95/5/0/0	0.0186	-0.0152	-0.0415	-0.0226	0.1525
	80/10/10/0	0.0216	-0.0166	-0.0422	-0.0238	0.1601
	90/10/0/0	0.0240	-0.0167	-0.0422	-0.0236	0.1694
	80/15/5/0	0.0295	-0.0175	-0.0436	-0.0240	0.1863
	71/17/11/1	0.0305	-0.0182	-0.0439	-0.0245	0.1921
PuNH	100/0/0/0	0.0149	0.0169	0.0013	-0.0255	0.1376
	95/5/0/0	0.0193	0.1550	0.0952	0.0493	0.1531
	80/10/10/0	0.0227	0.1922	0.1080	0.0462	0.1625
	90/10/0/0	0.0248	0.2276	0.1254	0.0697	0.1705
	80/15/5/0	0.0302	0.2838	0.1407	0.0725	0.1872
	71/17/11/1	0.0336	0.2976	0.1452	0.0820	0.1925

Table I35. BC: MCNP5 + JEFF-3.0 cross-sections

Bias corrections (rvu ^{**}) for applications – MCNP 5 with JEFF-3.0 cross-sections						
Material	Isotopes	Mass (kg)	Volume (l)	Cylinder (cm)	Slab (cm)	Conc. (g/cm ³)
UO ₂	100	0.0018	-0.0564	-0.0666	-0.0411	0.0259
	20	0.0131	0.0251	0.0162	0.0106	0.1441
	5	0.1381	-0.1220	-0.0426	-0.0359	0.9450
	4	0.2005	-0.1765	-0.0325	-0.0389	1.2025
	3	0.1536	-0.3308	-0.0747	-0.0553	1.6276
UNH	100	0.0018	0.0139	0.0123	0.0078	0.0262
	20	0.0156	0.0390	0.0191	0.0125	0.1485
	5	0.3267	-0.0633	-0.0112	-0.0114	1.0659
	4	0.5420	-0.2174	-0.0226	-0.0219	1.3858
	3	-0.2594	-2.1778	-0.1230	-0.0771	1.9317
PuO ₂	100/0/0/0	0.0089	-0.0109	-0.0298	-0.0161	0.1063
	95/5/0/0	0.0110	-0.0113	-0.0308	-0.0168	0.1189
	80/10/10/0	0.0129	-0.0123	-0.0314	-0.0177	0.1247
	90/10/0/0	0.0142	-0.0124	-0.0314	-0.0175	0.1321
	80/15/5/0	0.0175	-0.0130	-0.0324	-0.0178	0.1450
	71/17/11/1	0.0182	-0.0135	-0.0326	-0.0182	0.1495
PuNH	100/0/0/0	0.0089	-0.0890	-0.0871	-0.0854	0.1073
	95/5/0/0	0.0114	0.0069	-0.0023	-0.0152	0.1193
	80/10/10/0	0.0135	0.0194	0.0024	-0.0260	0.1267
	90/10/0/0	0.0147	0.0363	0.0154	-0.0024	0.1327
	80/15/5/0	0.0179	0.0544	0.0212	-0.0090	0.1457
	71/17/11/1	0.0200	0.0569	0.0226	0.0017	0.1499

Table I36. BC: MCNP5 + JENDL-3.2 cross-sections

Bias corrections (rvu**) for applications – MCNP 5 with JENDL-3.2 cross-sections						
Material	Isotopes	Mass (kg)	Volume (l)	Cylinder (cm)	Slab (cm)	Conc. (g/cm ³)
UO ₂	100	0.0185	0.0376	0.0444	0.0274	0.1434
	20	0.1357	0.2610	0.1685	0.1097	0.7991
	5	1.5705	0.8993	0.3046	0.1893	4.8652
	4	2.5558	1.2336	0.3725	0.2249	6.4718
	3	4.9110	2.1172	0.4530	0.2894	9.5835
UNH	100	0.0186	0.1446	0.1274	0.0811	0.1452
	20	0.1622	0.4056	0.1986	0.1300	0.8235
	5	4.2612	3.9745	0.6316	0.4021	5.8220
	4	9.7817	8.2822	0.9182	0.5831	8.2687
	3	45.3284	33.8797	1.9268	1.2464	14.5452
PuO ₂	100/0/0/0	0.0145	-0.0110	-0.0300	-0.0162	0.1566
	95/5/0/0	0.0180	-0.0114	-0.0311	-0.0169	0.1752
	80/10/10/0	0.0209	-0.0124	-0.0316	-0.0178	0.1838
	90/10/0/0	0.0232	-0.0125	-0.0316	-0.0176	0.1946
	80/15/5/0	0.0285	-0.0131	-0.0326	-0.0179	0.2137
	71/17/11/1	0.0296	-0.0136	-0.0329	-0.0184	0.2204
PuNH	100/0/0/0	0.0144	-0.0804	-0.0846	-0.0934	0.1581
	95/5/0/0	0.0186	0.0667	0.0345	0.0042	0.1758
	80/10/10/0	0.0220	0.0933	0.0441	-0.0076	0.1867
	90/10/0/0	0.0239	0.1234	0.0636	0.0246	0.1956
	80/15/5/0	0.0291	0.1629	0.0752	0.0192	0.2148
	71/17/11/1	0.0325	0.1706	0.0782	0.0333	0.2210

Table I37. BC: MCNP5 + JENDL-3.2 cross-sections

Bias corrections (rvu**) for applications – MCNP 5 with JENDL-3.3 cross-sections						
Material	Isotopes	Mass (kg)	Volume (l)	Cylinder (cm)	Slab (cm)	Conc. (g/cm ³)
UO ₂	100	0.0053	0.0752	0.0888	0.0548	0.0400
	20	0.0392	0.0753	0.0486	0.0317	0.2227
	5	0.4955	0.1723	0.0577	0.0306	1.8214
	4	0.7929	0.2313	0.0813	0.0385	2.3926
	3	1.3952	0.3815	0.0794	0.0466	3.4582
UNH	100	0.0054	0.0417	0.0368	0.0234	0.0405
	20	0.0468	0.1170	0.0573	0.0375	0.2295
	5	1.3177	1.0252	0.1623	0.1009	2.1436
	4	2.9097	2.0890	0.2324	0.1434	2.9735
	3	11.9483	7.8314	0.4458	0.2898	4.9503
PuO ₂	100/0/0/0	0.0144	-0.0082	-0.0223	-0.0120	0.1445
	95/5/0/0	0.0179	-0.0084	-0.0230	-0.0125	0.1616
	80/10/10/0	0.0208	-0.0092	-0.0234	-0.0132	0.1696
	90/10/0/0	0.0231	-0.0093	-0.0234	-0.0131	0.1795
	80/15/5/0	0.0284	-0.0097	-0.0242	-0.0133	0.1973
	71/17/11/1	0.0294	-0.0101	-0.0244	-0.0136	0.2035
PuNH	100/0/0/0	0.0144	-0.0358	-0.0449	-0.0615	0.1459
	95/5/0/0	0.0185	0.1044	0.0606	0.0241	0.1622
	80/10/10/0	0.0218	0.1351	0.0715	0.0163	0.1722
	90/10/0/0	0.0238	0.1670	0.0896	0.0440	0.1806
	80/15/5/0	0.0290	0.2131	0.1026	0.0424	0.1982
	71/17/11/1	0.0323	0.2233	0.1062	0.0542	0.2039

Table I38. BC: IPPE-ABBN93 (ABBN-93)

Bias corrections (rvu**) for applications – ABBN-93						
Material	Isotopes	Mass (kg)	Volume (l)	Cylinder (cm)	Slab (cm)	Conc. (g/cm ³)
UO ₂	100	0.0036	0.0376	0.0444	0.0274	0.0588
	20	0.0261	0.0502	0.0324	0.0211	0.3275
	5	0.1245	0.2600	0.0892	0.0644	-0.0996
	4	0.2253	0.3651	0.0908	0.0729	-0.0813
	3	0.6504	0.6529	0.1434	0.0987	0.0233
UNH	100	0.0036	0.0278	0.0245	0.0156	0.0595
	20	0.0312	0.0780	0.0382	0.0250	0.3375
	5	0.3829	0.7023	0.1127	0.0758	-0.0582
	4	1.0739	1.5438	0.1698	0.1148	0.0374
	3	7.5764	7.5243	0.4272	0.2740	0.5406
PuO ₂	100/0/0/0	-0.0044	-0.0009	-0.0024	-0.0013	0.0290
	95/5/0/0	-0.0055	-0.0009	-0.0025	-0.0014	0.0327
	80/10/10/0	-0.0062	-0.0010	-0.0026	-0.0014	0.0340
	90/10/0/0	-0.0072	-0.0010	-0.0026	-0.0014	0.0364
	80/15/5/0	-0.0088	-0.0011	-0.0026	-0.0015	0.0391
	71/17/11/1	-0.0089	-0.0011	-0.0027	-0.0015	0.0403
PuNH	100/0/0/0	-0.0044	-0.2761	-0.2410	-0.1849	0.0295
	95/5/0/0	-0.0057	-0.2789	-0.1892	-0.1363	0.0325
	80/10/10/0	-0.0065	-0.3161	-0.2010	-0.1600	0.0349
	90/10/0/0	-0.0074	-0.3379	-0.1986	-0.1406	0.0358
	80/15/5/0	-0.0091	-0.3962	-0.2122	-0.1639	0.0393
	71/17/11/1	-0.0098	-0.4161	-0.2172	-0.1530	0.0407

Appendix J
“RAW” AND BIAS-CORRECTED AVERAGE VALUES

If the validation process has worked properly, the bias-corrected results should agree within statistical boundaries, independent of the accuracy of the methods. This should not be expected in this initial study, for several reasons. The benchmarks are not sufficient or have not been used for verifying nuclide densities, many benchmarks are correlated, modelling of benchmarks is correlated, the evaluation process was simplified too much, etc.

If a validation process works properly, the bias-corrected results should be much more accurate than most of the individual benchmarks. This may have been achieved already, since many of the benchmarks have large uncertainties. However, the bias-correction can easily be improved significantly.

A comparison of the standard deviations from the mean value of calculated-only and bias-corrected results gives some information about the success of the cross-section related validation.

Table J1. Average “raw” and bias-corrected reference values with standard deviations

Mean values and standard deviations																					
Isotopes		Mass (kg)				Volume (l)				Cylinder (cm)				Slab (cm)				Conc. (g/cm ³)			
		$\overline{m}_c$	σ_c	$\overline{m}_{bc}$	σ_{bc}	$\overline{V}_c$	σ_c	$\overline{V}_{bc}$	σ_{bc}	$\overline{\Phi}_c$	σ_c	$\overline{\Phi}_{bc}$	σ_{bc}	$\overline{t}_c$	σ_c	$\overline{t}_{bc}$	σ_{bc}	$\overline{C}_c$	σ_c	$\overline{C}_{bc}$	σ_{bc}
U(100)O ₂	20	0.793	0.009	0.798	0.003	4.219	0.092	4.223	0.043	12.30	0.108	12.31	0.050	3.377	0.072	3.381	0.039	12.161	0.038	12.20	0.066
	5	5.191	0.057	5.225	0.022	10.73	0.166	10.79	0.107	17.93	0.105	17.97	0.062	7.190	0.105	7.218	0.076	63.92	0.189	64.17	0.277
	4	36.91	0.485	37.15	0.285	27.86	0.445	28.11	0.270	25.68	0.152	25.72	0.087	12.16	0.115	12.16	0.074	286.2	1.134	286.2	1.090
U(100)NH	20	0.793	0.009	0.798	0.003	4.219	0.092	4.223	0.043	12.30	0.108	12.31	0.050	3.377	0.072	3.381	0.039	12.161	0.038	12.20	0.066
	5	5.191	0.057	5.225	0.022	10.73	0.166	10.79	0.107	17.93	0.105	17.97	0.062	7.190	0.105	7.218	0.076	63.92	0.189	64.17	0.277
	4	36.91	0.485	37.15	0.285	27.86	0.445	28.11	0.270	25.68	0.152	25.72	0.087	12.16	0.115	12.16	0.074	286.2	1.134	286.2	1.090
Pu(100)O ₂	20	0.793	0.009	0.798	0.003	4.219	0.092	4.223	0.043	12.30	0.108	12.31	0.050	3.377	0.072	3.381	0.039	12.161	0.038	12.20	0.066
	5	5.191	0.057	5.225	0.022	10.73	0.166	10.79	0.107	17.93	0.105	17.97	0.062	7.190	0.105	7.218	0.076	63.92	0.189	64.17	0.277
	4	36.91	0.485	37.15	0.285	27.86	0.445	28.11	0.270	25.68	0.152	25.72	0.087	12.16	0.115	12.16	0.074	286.2	1.134	286.2	1.090
Pu(100)NH	20	0.793	0.009	0.798	0.003	4.219	0.092	4.223	0.043	12.30	0.108	12.31	0.050	3.377	0.072	3.381	0.039	12.161	0.038	12.20	0.066
	5	5.191	0.057	5.225	0.022	10.73	0.166	10.79	0.107	17.93	0.105	17.97	0.062	7.190	0.105	7.218	0.076	63.92	0.189	64.17	0.277
	4	36.91	0.485	37.15	0.285	27.86	0.445	28.11	0.270	25.68	0.152	25.72	0.087	12.16	0.115	12.16	0.074	286.2	1.134	286.2	1.090
Pu(100)O ₂	20	0.793	0.009	0.798	0.003	4.219	0.092	4.223	0.043	12.30	0.108	12.31	0.050	3.377	0.072	3.381	0.039	12.161	0.038	12.20	0.066
	5	5.191	0.057	5.225	0.022	10.73	0.166	10.79	0.107	17.93	0.105	17.97	0.062	7.190	0.105	7.218	0.076	63.92	0.189	64.17	0.277
	4	36.91	0.485	37.15	0.285	27.86	0.445	28.11	0.270	25.68	0.152	25.72	0.087	12.16	0.115	12.16	0.074	286.2	1.134	286.2	1.090
Pu(100)O ₂	20	0.793	0.009	0.798	0.003	4.219	0.092	4.223	0.043	12.30	0.108	12.31	0.050	3.377	0.072	3.381	0.039	12.161	0.038	12.20	0.066
	5	5.191	0.057	5.225	0.022	10.73	0.166	10.79	0.107	17.93	0.105	17.97	0.062	7.190	0.105	7.218	0.076	63.92	0.189	64.17	0.277
	4	36.91	0.485	37.15	0.285	27.86	0.445	28.11	0.270	25.68	0.152	25.72	0.087	12.16	0.115	12.16	0.074	286.2	1.134	286.2	1.090
Pu(100)O ₂	20	0.793	0.009	0.798	0.003	4.219	0.092	4.223	0.043	12.30	0.108	12.31	0.050	3.377	0.072	3.381	0.039	12.161	0.038	12.20	0.066
	5	5.191	0.057	5.225	0.022	10.73	0.166	10.79	0.107	17.93	0.105	17.97	0.062	7.190	0.105	7.218	0.076	63.92	0.189	64.17	0.277
	4	36.91	0.485	37.15	0.285	27.86	0.445	28.11	0.270	25.68	0.152	25.72	0.087	12.16	0.115	12.16	0.074	286.2	1.134	286.2	1.090
Pu(100)O ₂	20	0.793	0.009	0.798	0.003	4.219	0.092	4.223	0.043	12.30	0.108	12.31	0.050	3.377	0.072	3.381	0.039	12.161	0.038	12.20	0.066
	5	5.191	0.057	5.225	0.022	10.73	0.166	10.79	0.107	17.93	0.105	17.97	0.062	7.190	0.105	7.218	0.076	63.92	0.189	64.17	0.277
	4	36.91	0.485	37.15	0.285	27.86	0.445	28.11	0.270	25.68	0.152	25.72	0.087	12.16	0.115	12.16	0.074	286.2	1.134	286.2	1.090
Pu(100)O ₂	20	0.793	0.009	0.798	0.003	4.219	0.092	4.223	0.043	12.30	0.108	12.31	0.050	3.377	0.072	3.381	0.039	12.161	0.038	12.20	0.066
	5	5.191	0.057	5.225	0.022	10.73	0.166	10.79	0.107	17.93	0.105	17.97	0.062	7.190	0.105	7.218	0.076	63.92	0.189	64.17	0.277
	4	36.91	0.485	37.15	0.285	27.86	0.445	28.11	0.270	25.68	0.152	25.72	0.087	12.16	0.115	12.16	0.074	286.2	1.134	286.2	1.090
Pu(100)O ₂	20	0.793	0.009	0.798	0.003	4.219	0.092	4.223	0.043	12.30	0.108	12.31	0.050	3.377	0.072	3.381	0.039	12.161	0.038	12.20	0.066
	5	5.191	0.057	5.225	0.022	10.73	0.166	10.79	0.107	17.93	0.105	17.97	0.062	7.190	0.105	7.218	0.076	63.92	0.189	64.17	0.277
	4	36.91	0.485	37.15	0.285	27.86	0.445	28.11	0.270	25.68	0.152	25.72	0.087	12.16	0.115	12.16	0.074	286.2	1.134	286.2	1.090
Pu(100)O ₂	20	0.793	0.009	0.798	0.003	4.219	0.092	4.223	0.043	12.30	0.108	12.31	0.050	3.377	0.072	3.381	0.039	12.161	0.038	12.20	0.066
	5	5.191	0.057	5.225	0.022	10.73	0.166	10.79	0.107	17.93	0.105	17.97	0.062	7.190	0.105	7.218	0.076	63.92	0.189	64.17	0.277
	4	36.91	0.485	37.15	0.285	27.86	0.445	28.11	0.270	25.68	0.152	25.72	0.087	12.16	0.115	12.16	0.074	286.2	1.134	286.2	1.090
Pu(100)O ₂	20	0.793	0.009	0.798	0.003	4.219	0.092	4.223	0.043	12.30	0.108	12.31	0.050	3.377	0.072	3.381	0.039	12.161	0.038	12.20	0.066
	5	5.191	0.057	5.225	0.022	10.73	0.166	10.79	0.107	17.93	0.105	17.97	0.062	7.190	0.105	7.218	0.076	63.92	0.189	64.17	0.277
	4	36.91	0.485	37.15	0.285	27.86	0.445	28.11	0.270	25.68	0.152	25.72	0.087	12.16	0.115	12.16	0.074	286.2	1.134	286.2	1.090
Pu(100)O ₂	20	0.793	0.009	0.798	0.003	4.219	0.092	4.223	0.043	12.30	0.108	12.31	0.050	3.377	0.072	3.381	0.039	12.161	0.038	12.20	0.066
	5	5.191	0.057	5.225	0.022	10.73	0.166	10.79	0.107	17.93	0.105	17.97	0.062	7.190	0.105	7.218	0.076	63.92	0.189	64.17	0.277
	4	36.91	0.485	37.15	0.285	27.86	0.445	28.11	0.270	25.68	0.152	25.72	0.087	12.16	0.115	12.16	0.074	286.2	1.134	286.2	1.090
Pu(100)O ₂	20	0.793	0.009	0.798	0.003	4.219	0.092	4.223	0.043	12.30	0.108	12.31	0.050	3.377	0.072	3.381	0.039	12.161	0.038	12.20	0.066
	5	5.191	0.057	5.225	0.022	10.73	0.166	10.79	0.107	17.93	0.105	17.97	0.062	7.190	0.105	7.218	0.076	63.92	0.189	64.17	0.277
	4	36.91	0.485	37.15	0.285	27.86	0.445	28.11	0.270	25.68	0.152	25.72	0.087	12.16	0.115	12.16	0.074	286.2	1.134	286.2	1.090
Pu(100)O ₂	20	0.793	0.009	0.798	0.003	4.219	0.092	4.223	0.043	12.30	0.108	12.31	0.050	3.377	0.072	3.381	0.039	12.161	0.038	12.20	0.066
	5	5.191	0.057	5.225	0.022	10.73	0.166	10.79	0.107	17.93	0.105	17.97	0.062	7.190	0.105	7.218	0.076	63.92	0.189	64.17	0.277
	4	36.91	0.485	37.15	0.285	27.86	0.445	28.11	0.270	25.68	0.152	25.72	0.087	12.16	0.115	12.16	0.074	286.2	1.134	286.2	1.090
Pu(100)O ₂	20	0.793	0.009	0.798	0.003	4.219	0.092	4.223	0.043	12.30	0.108	12.31	0.050	3.377	0.072	3.381	0.039	12.161	0.038	12.20	0.066
	5	5.191	0.057	5.225	0.022	10.73	0.166	10.79	0.107	17.93	0.105	17.97	0.062	7.190	0.105	7.218	0.076	63.92	0.189	64.17	0.277
	4	36.91	0.485	37.15	0.285	27.86	0.445	28.11	0.270	25.68	0.152	25.72	0.087	12.16	0.115	12.16	0.074	286.2	1.134	286.2	1.090
Pu(100)O ₂	20	0.793	0.009	0.798	0.003	4.219	0.092	4.223	0.043	12.30	0.108	12.31	0.050	3.377	0.072	3.381	0.039	12.161	0.038	12.20	0.066
	5	5.191	0.057	5.225	0.022	10.73	0.166	10.79	0.107	17.93	0.105	17.97	0.062	7.190	0.105	7.218	0.076	63.92	0.189	64.17	0.277
	4	36.91	0.485	37.15	0.285	27.86	0.445	28.11	0.270	25.68	0.152	25.72	0.087	12.16	0.115	12.16	0.074	286.2	1.134	286.2	1.090
Pu(100)O ₂	20	0.793	0.009	0.798	0.003	4.219	0.092	4.223	0.043	12.30	0.108	12.31	0.050	3.377	0.072	3.381	0.039	12.161	0.038	12.20	0.066
	5	5.191	0.057	5.225	0.022	10.73	0.166	10.79	0.107	17.93	0.105	17.97	0.062	7.190	0.105	7.218	0.076	63.92	0.189	64.17	0.277
	4	36.91	0.485	37.15	0.285	27.86	0.445	28.11	0.270	25.68	0.152	25.72	0.087	12.16	0.115	12.16	0.074	286.2	1.134	286.2	1.090
Pu(100)O ₂	20	0.793	0.009	0.798	0.003	4.219	0.092	4.223	0.043	12.30	0.108	12.31	0.050	3.377	0.072	3.381	0.039	12.161	0.038	12.20	0.066
	5	5.191	0.057	5.22																	

Appendix K

NUCLIDE DENSITY METHODS AND VERIFICATION

The cross-sections for interaction between free neutrons and nuclides bound in various materials are important input data for the estimation of the reference values selected for this study. The issue of validation is often limited to this issue. It is not sufficient.

Other input data issues are nuclide density relationships, optimum moderation, other nuclear constants than cross-sections, geometry models, etc. At the moment, the density relationships and the optimum moderation determination are considered significant contributors to the uncertainty.

Essential parameters are stoichiometric formula, theoretical density (depends on isotope distribution), atomic weights, Avogadro's number, mixture and solution properties, temperature, pressure, valence numbers, etc.

Without verification of the nuclide density determination methods, the validation of the reference values is not complete or reliable.

Theoretical densities

The theoretical density of a material is an important concept for determining nuclide densities. A mixture is assumed to be specified by the volume fractions (actual density divided by the theoretical density) of each constituent material. Including a void fraction, the sum of the volume fractions is exactly one. The mixture density is a sum of the products volume fraction times theoretical density for each constituent.

There are different types of materials. In this study, two types will be considered: compounds and solutions. They may be mixed, using the non-dissolved compound and the solution fractional volumes to determine the mixture. A compound is based on one or more elements, but it is not a mixture of "free" elements. The same is true for a solution. The compound or solution has chemical, physical and other properties that separate it from a mixture of "free" elements.

The theoretical density of an element depends on its isotopic distribution. It is assumed here that the theoretical atomic number density of an element is constant, whatever the isotopic distribution. This means that if the theoretical density of one isotope or of one isotopic distribution is known, others can be calculated if the atomic masses of each isotope are known. This theory is used in evaluations of criticality properties of all actinide nuclides [95] and in other studies, including the Japanese Handbook [23], [24]. The IRSN CRISTAL method contains a preprocessing code CIGALES that takes the distributions of uranium and plutonium isotopes into account.

In this study, the theoretical density variations due to varying isotopic distributions are not considered important for well-moderated mixtures and solutions. For solid high-density uranium dioxide in particular but also for plutonium dioxides, the variations are potentially important. This covers the reference parameters volume, cylinder diameter and slab thickness for uranium with 100

percent ^{235}U by mass and for all plutonium isotopic distributions.

The theoretical density for UO_2 with natural uranium (essentially ^{238}U) is 10.96 g/cm^3 . If all the ^{238}U atoms are replaced with ^{235}U atoms, retaining the material structure, the density will be reduced to 10.838 g/cm^3 in direct agreement with information in the Japanese Handbook [23], [24].

A similar determination of the theoretical densities for the various plutonium isotope distributions in dioxide form was made. It is based on the theoretical density for plutonium dioxide with ^{239}Pu as the only isotope and on atomic masses for the isotopes. The theoretical density is given as 11.46 g/cm^3 in SCALE 5. The following table uses the same isotope specifications as in other parts of the report. For uranium, the enrichment is given ^{235}U . For plutonium, the mass percentage of each isotope is given in the order of ^{239}Pu , ^{240}Pu , ^{241}Pu and ^{242}Pu . Trailing zero values may be omitted ($\text{Pu}(100)\text{O}_2$ is identical to $\text{Pu}(100/0/0/0)\text{O}_2$).

Table K1. Theoretical densities of uranium and plutonium dioxides

Theoretical densities for uranium and plutonium dioxides (g/cm^3)							
$\text{U}(\text{nat})\text{O}_2$	$\text{U}(100)\text{O}_2$	$\text{Pu}(100)\text{O}_2$	$\text{Pu}(95/5)\text{O}_2$	$\text{Pu}(80/10/10)\text{O}_2$	$\text{Pu}(90/10)\text{O}_2$	$\text{Pu}(80/15/5)\text{O}_2$	$\text{Pu}(71/17/11/1)\text{O}_2$
10.960	10.838	11.460	11.462	11.473	11.464	11.471	11.478

For this study, involving best estimates with high accuracy of reference values, the variation for uranium is most significant, while some of the variations for plutonium are also significant, but less so. They will be considered when the best estimate reference values are determined. In safety applications, a lack of consideration of the variation for uranium is conservative and small. For plutonium, the variation is insignificant for safety applications.

IPPE has used a theoretical PuO_2 density of 11.44 g/cm^3 in their recent contribution using XSDRNP/S with ABBN-93a cross sections. At least for the minimum critical volumes this low value leads to an underestimation of the minimum critical volume by about 0.004 litres or 0.4 %.

Solutions

Only the two common nitrate solutions covered in this study are considered in this section. Several contributions from participants (IRSN, GRS, and JAERI) have pointed out the importance of including the overall determination of nuclide densities in the validation process.

The influence of uranium and plutonium isotopic distributions on the nuclide densities in solutions are not expected to be significant. For UNH, the high uranium densities, near crystal density, occur for low-enrichments of ^{235}U . This is where a changed density is expected to be significant. However, the change is very small if the density laws are based on natural uranium. For PuNH, the maximum plutonium density is around 700 g Pu/l, for slabs. It is near the solubility limit, but far from the crystal density.

The possibility of a significant reference value error due to element density changes caused by a change in the isotopic distribution was evaluated neither for UNH nor for PuNH. If the code is not already compensating for this effect, a manual modification of the input is needed. The atomic number densities of the elements need to be preserved.

Other chemical variations of the nitrate solution properties are not considered. In the evaluation of experiments and other measurements, the valence numbers of uranium and plutonium may be important. There can be several valences in the same solution. The number of water molecules tied to

the crystal may also vary. IPPE reports six water molecules for PuNH in the older contribution. Other contributions assume five (six for UNH). This could be an editorial mistake.

GRS has shown problems with some UO_2F_2 -solution density methods. This solution was included in the scope of the study but was left for a future phase.

Table K2. Theoretical densities of uranium and plutonium nitrate crystals

Theoretical crystal densities (g/cm^3)			
U(nat)NH	Pu(100)NH	U(nat)	Pu(100)
2.807	2.9	1.33	1.20

The crystal densities are important for safety evaluations and to test the range of applicability of the density methods. The other extreme covered by the equations is pure water which has a density of 0.9982. This is the total density that should be obtained when the actinide concentration is zero and there is no acidity (HNO_3).

Description of density relationships

The methods used for nuclide density determination in various handbooks and code systems are described next. A table from [37] is very useful to check the information from other reports and handbooks. The table contains limitations of the applicability of many methods. The limitations are not quoted for every method below, but in general most methods are determined for use far below the solubility limit for the actinide in the solution. Temperature limitations are also important.

The purpose of this compilation is limited to finding biases in the methods used to determine reference values for this report. Other applications and methods have not been covered.

GRS combination of IRSN isopiestic law with SCALE and MCNP

GRS tested the input densities obtained by IRSN from using the isopiestic law with SCALE 4 and MCNP4C to see the influence of nuclide densities versus the different cross-section libraries [32]. One of the reasons for the differences between the GRS results and the EMS results with the same methods, except that SCALE nuclide densities were used, is that the IRSN results are not quite optimized. The figures and tables in [43] and [44] show that the optimum H/Pu should be near the middle between 70 and 100. The optimum determined by EMS using SCALE 4 was obtained at an H/Pu ratio of 85. The different nuclide density laws in CRISTAL, SCALE 4 and SCALE 5 don't explain the differences in the results.

IRSN solution methods before 2001

The calculation methods [39]-[40] include implementation of the Leroy & Jouan method and what is referred to as the ARH-600 method for uranium and plutonium respectively. However, the methods are not based on the ARH-600 equation revised in 1972 but on an early edition (it was present in a revision from 102568, also in [37]). It is to be noted that the law implemented in the IRSN codes mixes the 1968 ARH-600 and the Leroy & Jouan laws. The Leroy & Jouan factor for acidity was used in the polynomial density equation. The method is referred to here as the "IRSN-Pre-Iso" method. IRSN has demonstrated how incorrect the results using the older method could be. For plutonium, under-estimations of k_{eff} of up to 3.4 % were found when calculating 40 ICSBEP Handbook benchmarks with the Pre-Iso method.

It is important to note that the “IRSN Pre-Iso” method results were reported by IRSN during 2001-2003 (see [40], [60] and [89]). The French Standard from 1978 [21] uses an old equation (revised 1/30/69 or earlier) that is based on section III of the revised ARH-600 handbook. This is the same as the 1972 revised equation in Section II, except that the revision includes consideration of the plutonium isotopes.

The two old ARH-600 methods are not consistent with each other. The H/U equation used in the French Standard de Criticité [21] is better; the density equation used in the French codes before CRISTAL or as an alternative to the isopiestic law in CRISTAL is not as good.

The Leroy & Jouan “law”, with M being the molarity in mol/l, is given as

$$\rho_{\text{tot}} = 1 + 32.5 \times 10^{-3} M_{\text{H}^+} + 0.32249 M_{\text{U}}$$

The Pre-Iso law, with H^+ being the acidity in mol/l, is given as

$$\rho_{\text{tot}} = 1 + 32.5 \times 10^{-3} M_{\text{H}^+} + 0.349016 M_{\text{Pu}}$$

Another source [37] defines the Pre-Iso equation slightly different, with C_{Pu} as the concentration in g/given for higher molarities, but it also requires high acidity. The following is the low Pu molarity equation:

$$\rho_{\text{tot}} = 1 + 0.031 M_{\text{H}^+} + 0.00146 C_{\text{Pu}}.$$

The uncertainty is quoted as $\pm 5\%$. The slight difference to the previous “molarity” equation is in the acidity (H^+) factor but since that will be zero for this study, the equations are equivalent. It has later been confirmed that IRSN indeed changed the 0.031 factor to 0.0325 in their implementation of the old ARH-600 method.

For low-concentration solutions, less than 100 g/l, the error in k_{eff} is not significant. The Leroy-Jouan method for uranium gives quite good results over the range of concentrations covered by the 40 ICSBEP benchmarks. A slight over-prediction of k_{eff} is seen. The big problem is the plutonium and it covers the concentration range where optimum moderation for critical geometry is obtained.

Of particular interest for this study is a comparison of the isopiestic law and the Pre-Iso law (the 1968 ARH-600 law used previously by IRSN). The minimum critical values for mass and volume were calculated for ^{239}Pu nitrate, zero acidity and water reflection. For mass, the optimum is for a low concentration, 30 g Pu/l, and the values are 512 g and 515 g ^{239}Pu respectively. This is good agreement. However, for volume, the optimum moderation occurs for much higher and different concentrations, 300 g Pu/l for the isopiestic law and 200 g Pu/l for the Pre-Iso law. The minimum critical volumes are 7.55 litres and 8.5 litres respectively. The difference is 11.2 % and indicates a non-conservative value for the Pre-Iso law.

The minimum critical volumes with the plutonium isotope distribution 71/17/11/1 were calculated as 15.6 litres using the isopiestic law and 16.70 litres using the old Pre-Iso law.

IRSN implementation of the extended isopiestic law for solutions in CRISTAL

IRSN has made significant efforts to obtain reliable, accurate and safe nuclide densities in solutions. Several reports with important information have been contributed to the study [39]- [42],

including translations from French to English.

The IRSN “isopiestic law” for solutions, and the associated implementation in the CRISTAL code system, has been verified by IRSN for many systems. Important changes compared with results based on previous methods have been reported for some systems. A recent improvement allows for automatic mixing of the isopiestic law for solutions with the volumetric method (traditional method for mixtures) for densities above saturation.

The implementation of the isopiestic law in CRISTAL gives solubility limits of 610 g U/l and 750 g Pu/l. The limits for the “isopiestic domain” are 885 g U/l and 917 g Pu/l. The “volume mixed” or “biphasic” extensions are limited to 1 330 g U/l and to 1 201 g Pu/l, which are the theoretical crystal densities of the chemical composition.

The isopiestic law is a combination of polynomial approximations of experimental data. Preliminary curve-fitting equations are given in [39] and [40]. For uranyl nitrate solution, the solution density ρ_{sol} in g/cm³ is calculated as a function of the actinide element molarity M_U (mol/l). The H/X atomic ratios and the actinide concentrations can easily be calculated from the total densities.

The following equations give close but not identical results to those reported in ([39] and [40]). The differences appear to be insignificant. It is important to note that they only cover the isopiestic range, not all the way to crystal form. The extended method is what appears to be a simple combination of these equations with a volume fraction based mixing. It is not so simple because the solubility limit needs to be established first.

$$\begin{aligned}\rho_{\text{U sol}} &= 0.997 + 0.322 * M_U - 0.000692 * (M_U)^2 + 0.000706 * (M_U)^3 - 0.00148 * (M_U)^4 + \\ &\quad 0.000490 * (M_U)^5 - 0.0000634 * (M_U)^6 \\ \rho_{\text{Pu sol}} &= 0.997 + 0.398 * M_{\text{Pu}} + 0.01222 * (M_{\text{Pu}})^2 - 0.0134 * (M_{\text{Pu}})^3 + 0.00481 * (M_{\text{Pu}})^4 - \\ &\quad 0.00091 * (M_{\text{Pu}})^5 + 0.0000700 * (M_{\text{Pu}})^6\end{aligned}$$

IRSN has validated ([39] and [40]) the isopiestic law by calculating 40 ICSBEP benchmarks, using the experimental information on the chemical properties rather than the benchmark nuclide densities. Good agreement between the nuclide densities obtained with the isopiestic law and the benchmark densities were reported. This means an average of +36.4 pcm for uranium and an average of -337 pcm for plutonium. The latter is much better than the previous Pre-Iso method.

The idea of verifying the nuclide density calculations by comparisons with the ICSBEP Handbook information is worth borrowing for a continuation of this study. The benchmarks used by IRSN were PU-SOL-THERM-001 (6 configurations), LEU-SOL-THERM-004 (7 configurations), LEU-SOL-THERM-016 (7 configurations), HEU-SOL-THERM-001 (10 configurations) and MIX-SOL-THERM-003 (10 configurations). The benchmarks LEU-SOL-THERM-016 and HEU-SOL-THERM-001 were included in the validation support for this study, see APPENDIX F, and the results from [39]-[40] are included.

Japanese Handbooks and associated nuclide densities for solutions

For UNH, the nuclide densities are determined according to the Moeken's equation. For PuNH, Maimoni's equation is used. Both are found on page 52 of [24]. Temperature dependence is considered. A Sakurai method is also quoted and referred to in the Expert Group documents.

Moeken's equation for UNH is given in two parts, one for the temperature 25°C and one for temperature adjustments. The equation for 25°C and zero acidity follows:

$$\rho_{\text{tot}25} = 1.0171 + 0.0012944 * C_U.$$

Maimoni's equation for PuNH also has a correction for temperature variations. The equation for 25°C and zero acidity follows:

$$\rho_{\text{tot}25} = 0.99708 + 0.00165625 * C_{\text{Pu}} - 3.418 * 10^{-8} * C_{\text{Pu}}^2$$

Sakurai's equation can be used for UNH, PuNH or a combination of these solutions. Important restrictions are that the uranium concentration is limited to less than 530 g/l and the plutonium concentration to less than 480 g/l (the mixed solution is limited to 350 g U+Pu/l). The Sakurai equation is similar to Maimoni's equation in that it includes correction for temperature variations from 25°C and that higher order corrections are included. The equation for 25°C and zero acidity follows:

$$\rho_{\text{tot}25} = 0.99833 + 0.0016903 * C_{\text{Pu}} + 0.001476 * C_U - 8.696 * 10^{-8} * C_{\text{Pu}}^2 - 1.0187 * 10^{-7} * C_{\text{Pu}}^3$$

JAERI has presented preliminary results [48] from the Data Collection 2 related to the Japanese Handbook. It was found that the Moeken equation over-predicted mass and volume reference values by more than 10 % for UNH with uranium containing 3 and 4% ²³⁵U by mass of uranium. The new Data Collection 2 will use another method.

IRSN [39]-[40] compared their new isopiestic law with the Japanese Sakurai and Maimoni laws. The application was the PU-SOL-THERM benchmarks from the ICSBEP Handbook. Both the Japanese laws are quoted in [39]-[40]. The conclusions are that the isopiestic law under-predicts k_{eff} by less than 500 pcm while the two other methods under-predict k_{eff} as much as 1 400 pcm.

MONK and associated nuclide densities for solutions

The nuclide densities are determined using the code CMC. This program assumes a mixture of nitrate crystals and water. The maximum permissible uranium concentration is given in some report as 1 257 g/l, which seems a bit low (results for higher densities are reported). The corresponding maximum for plutonium is given as 1 437 g/l, which is very high, in the same reports. However, in the latest contribution from 2003 [56], Serco gives a maximum plutonium concentration of 1.20 kg/l which is in agreement with other estimations at crystal density. The low uranium crystal density 1 257 kg U/l

was not modified, though. It is not consistent with the total crystal density. With M standing for HNO₃ molarity (mol/l) and C for actinide concentration in kg/l, the following relationships were used.

$$\rho_{\text{UNH}} = 0.998 + 0.03217 * M + 1.33 * C_{\text{U}}.$$

$$\rho_{\text{PuNH}} = 0.998 + 0.03217 * M + (1.72 - 0.0376 * M) * C_{\text{Pu}}.$$

SCALE 4 method for nuclide densities in solutions

The built-in determination of nuclide densities in UNH and PuNH solutions are based on the empirical equations in ARH-600 [14]. The user is warned when the fissionable element (U or Pu) density is above the estimated saturation point. The code stops with an error message if the ratio of actinide atoms to hydrogen atoms is higher than what corresponds to crystal density. SCALE 4 was used by NUPEC for a few calculations, by ORNL and by EMS in the first contribution. ORNL reports some value with a slightly higher density (1300 rather than 1 296 g U/l) than the crystal density. This is explained in the ORNL contribution report [52].

The Draft ORNL report [52] gives the nitrate density equations in the following form, where A_{NU} is the uranium isotopic mass (grams/mole) and ΔT is the temperature difference from 22.5°C:

$$\rho_{\text{UNH}} = (1.0012 + 317.7 * C_{\text{U}} / A_{\text{NU}} + 0.03096 * M_{\text{HNO}_3}) * (1 - 5 \times 10^{-4} \Delta T) + 1.45 * 10^{-4} \Delta T$$

$$\rho_{\text{PuNH}} = 0.998 * \rho_{\text{Pu}} / A_{\text{NPu}} (1.72 - 0.0376 * M) * (1 - 0.3619 * \rho_{\text{Pu}} - 0.0246 * M_{\text{HNO}_3}) + \rho_{\text{Pu(NO}_3)_4} + \rho_{\text{HNO}_3}$$

These equations appear to be identical to those in ARH-600. The DT in the handbook refers to 25°C (elimination of a constant). Even though SCALE 4 is based on ARH-600 equations, the problem does not seem to be as bad as indicated by IRSN for the Pre-Iso method and by the large deviations in some of the ARH-600 handbook values from what is believed to be correct values. The reason is that the IRSN Pre-Iso method was based on an early release of the ARH-600 handbook. The ARH-600 equation was revised 1972 or earlier.

SCALE 5 method for nuclide densities in solutions

The Pitzer method [90] has been introduced in SCALE 5, replacing the ARH-600 method as a built-in function. The method appears to be a significant improvement over the previous method, allowing for a wider range of temperatures. It may be adapted to other solutions and to other actinides than uranium and plutonium. However, the final evaluation leading to this report showed a significant problem in the implementation of the Pitzer method in SCALE 5.

SCALE 5 seems to work properly with a UNH-solution at the tropical temperature of 300K but at a room temperature (for participants in this study and for typical users of SCALE) of 293K, the code tells the user that any concentration over 1 001 g U/l is not acceptable because it is higher than the value that corresponds to the crystal density of the material. This is interesting since ORNL particularly emphasizes the maximum concentration 1 296 g U/l for 293K in their contribution to the study. The first EMS contribution from early 2001 also found this maximum. Both contributions were based on SCALE 4. All SCALE 5 calculations for solutions were made at a temperature of 300K. The real crystal density should be about 1 330 g U/l.

Recently, SCALE 5 was shown to give incorrect information on crystal densities also for PuNH. This time the temperature was 298K, the temperature for which the density parameters are best known.

The comparison of methods later in this Appendix will give even more recent results. The ORNL developers [53] have expressed their intent of changing the solution applications in SCALE 5.1 to make inappropriate use of those options more difficult. The Pitzer method is not the problem.

MCNP5 method for nuclide densities in solutions

The nuclide densities for MCNP5, for the reference value calculations made by EMS, were based on SCALE 5 calculations. The temperature for solutions was 293K (room temperature) for all materials except UNH-solutions with low-enriched uranium for which the temperature was set to 300K. The reason is described above under SCALE 5 methods. The nuclide densities for MCNP5 were determined with SCALE 5 before SCALE 5 was used to calculate reference values.

IPPE method for nuclide densities in solutions

In their new results reported in 2004, IPPE used simple volume mixing of the two solution ingredients actinide nitrate crystals (salt) and water. This seems to be a simple and usually better method than most others, at least for solutions without acidity.

Nuclide densities – A comparison of methods

The methods described here all have limitations in their applicability. The following methods are compared, usually without giving their limitations:

- The IRSN isopiestic law as implemented in CRISTAL.
- The IRSN “Pre-Iso” method used before the isopiestic law.
- Leroy & Jouan method for uranium used at IRSN before the isopiestic law.
- The ARH-600 equations from the handbook. Used in SCALE before release 5.

Note: The curves for UNH in Section III.B of the handbook are not based on these equations.

- The equations used in the CMC code to prepare input for MONK.
- SCALE 4.0 (based on ARH-600 handbook)
- SCALE 5.0 based on new Pitzer method. Three temperatures: 293K, 298K and 300K.
- Moeken’s equation for uranium used for the Japanese handbooks.
- Maimoni’s equation for plutonium described in the Japanese handbooks.
- Sakurai’s equation for plutonium described in the Japanese handbooks.
- IPPE’s simple method of mixing actinide nitrate crystals with water.

The crystal density for UNH is 2.807 g/cm^3 . This is based on uranium with natural uranium. Serco reports a density of 2.79 g/cm^3 for UNH with uranium containing 100% ^{235}U . The corresponding uranium density is 1.33 g/cm^3 .

The crystal density for PuNH is 2.9 g/cm^3 . This is based on plutonium with 100% ^{239}Pu . The corresponding plutonium concentration is 1.20 g/cm^3 . The 1972 revised ARH-600 equation takes the plutonium isotopes into account.

The IPPE-ABBN93 method has been taken as a reference for difference comparisons. The reason is not that it is better but because it is simple and is shown to be a reasonable approximation. It also shows the volume change due to the solution properties. The isopiestic law has been validated over all of the solubility range and will be the primary reference for validation purposes. The IPPE and the extended isopiestic methods are the only ones that give correct values for crystal form material.

The specifications of the specified fissionable systems were maybe not clear enough. From a chemist's point of view, information about solutions was requested. The crystal or precipitated forms are not really solutions. To the criticality safety specialists, the request is seen differently. Two steps are required. The first step is to determine the most dangerous form of the material and second to determine the associated reference values.

Homogeneity and uniformity are required so, e.g. a model with precipitation on the walls with solution in the centre is not considered. However, crystallisation (precipitation) and mixtures of crystals with other materials (e.g. undissolved U_3O_8) must be considered in a safety assessment. The only materials that are specified here are the salt (crystals) and water.

IRSN has used a homogeneous, uniform combination of solution and crystals for the high-density region. This appears to be a possible but maybe unlikely mixture. IPPE has assumed a homogeneous, uniform combination of crystals and water over the whole density range. This is even less probable, but the approximation appears to be reasonable for zero acidity and room temperature. It is correct for the precipitated form and probably close to that density.

Other contributions, including handbooks, don't seem to address the concentrations above the solubility limit or outside the limit of applicability of the density equations, correctly. This is usually a user responsibility, not a computer code system error. However, it is important that the documentation and code output helps the user to realise the method limitations and to see what is actually being calculated. The SCALE developers are planning a change in version 5.1 to prevent calculations at densities above the solubility limit [53]. This is a reasonable solution since the user can mix a saturated solution and crystals or any other combination that the user finds of interest.

Some of the equations given by the contributors involve actinide concentration in the solution while other equations involve H/X ratio. It would be easy to convert all H/X ratios to concentrations or vice versa and include the results in a single table. This has not been done.

The range of concentrations corresponding to all the reference systems has been included using orange markers in some of the figures.

Table K3. H/U versus uranium concentration for UNH

H/U atomic ratio as a function of uranium (natural or low-enriched) concentration								
C _U (g/l)	IRSN Isopiestic	Leroy & Jouan	ARH-600 Equation	SCALE 4.0	IPPE-04	SCALE5 293K	SCALE5 298K	SCALE5 300K
40	643.0	644.9	643.9	644.1	642.7	643.4	642.6	642.2
45	570.0	572.3	571.4	571.6	571.9	571.0	570.3	569.9
50	512.7	514.3	513.4	513.6	513.7	513.1	512.4	512.1
55	465.4	466.8	466.0	466.1	466.0	465.7	465.1	464.8
60	425.9	427.3	426.5	426.5	426.4	426.2	425.6	425.4
65	392.6	393.8	393.0	393.1	392.9	392.7	392.2	392.0
70	363.9	365.1	364.4	364.4	364.1	364.1	363.6	363.4
100	252.4	253.2	252.5	252.5	252.6	252.4	252.0	251.9
200	122.2	122.6	122.1	121.9	122.6	122.0	121.8	121.7
250	96.2	96.5	96.0	95.8	96.5	96.0	95.8	95.7
300	78.8	79.1	78.6	78.4	79.1	78.7	78.5	78.4
350	66.4	66.7	66.2	66.0	66.7	66.3	66.1	66.0
400	57.0	57.3	56.9	56.6	57.4	57.0	56.8	56.7
450	49.7	50.1	49.6	49.4	50.2	49.8	49.6	49.5
500	43.9	44.3	43.8	43.6	44.4	44.0	43.8	43.8
600	35.0	35.6	35.1	34.9	35.7	35.2	35.2	35.1
700	28.9	29.4	28.9	28.7	29.5	28.8	28.9	29.0
800	24.4	24.7	24.3	24.0	24.9	23.8	24.2	24.3
900	20.9	21.1	20.6	20.4	21.2	19.5	20.4	20.7
1000	18.1	18.2	17.7	17.5	18.3	(15.1)*	17.3	17.8
1100	15.8	15.8	15.4	15.1	16.0		14.4	15.4
1200	13.8	13.8	13.4	13.1	14.0		(12.03)**	13.4
1300	12.2	12.1	11.7	11.5	12.3			(12.0)***
1330****								

* SCALE 5 crystal density at 989 gU/l, 293K (20°C, room temperature).

** SCALE 5 crystal density at 1 179 gU/l, 298K (25°C, common reference temperature).

*** SCALE 5 crystal density at 1 276 gU/l, 300K (27°C, default temperature in SCALE 5).

**** Real crystal density: 1 330 gU/l for natural uranium.

Figure K1. H/U versus uranium concentration for UNH

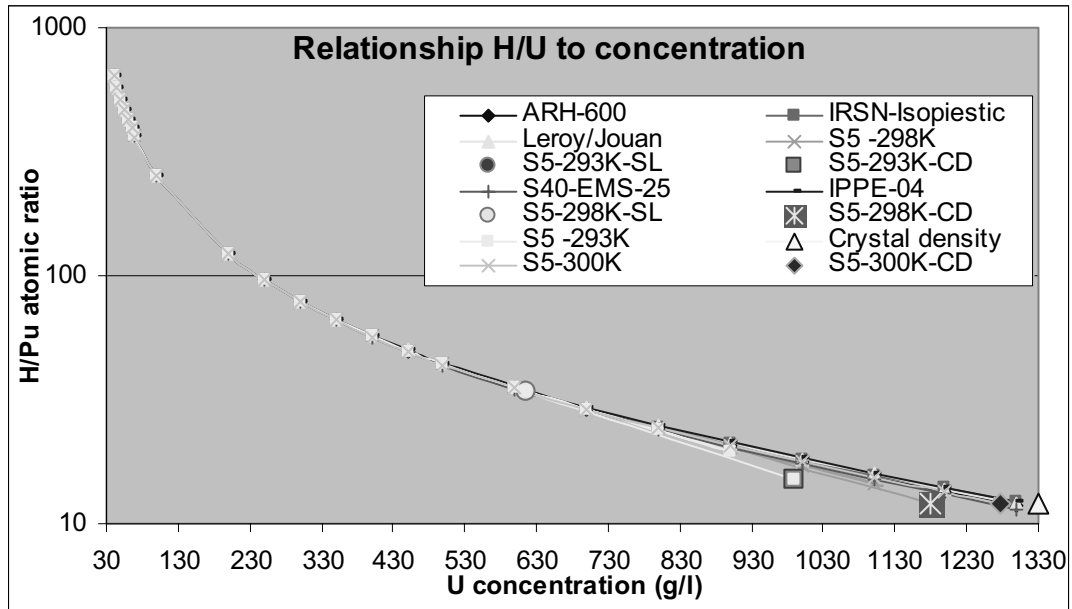


Figure K2. Differences: H/U versus uranium concentration for UNH

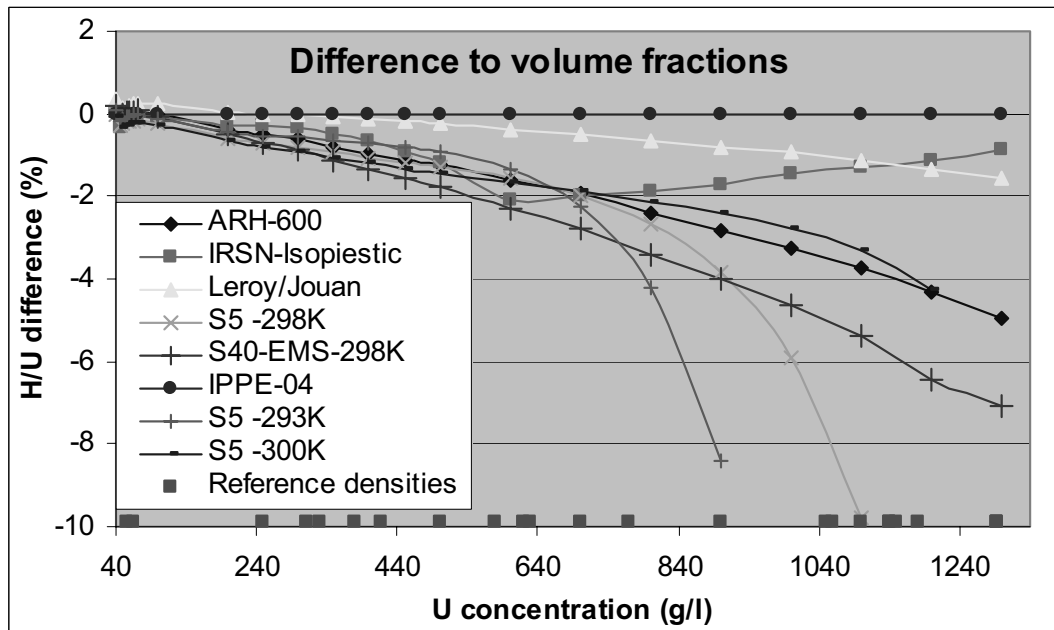


Table K4. Total density versus uranium concentration for UNH

Total UNH-solution density as a function of uranium (natural or low-enriched) concentration									
C _U (g/l)	IRSN Isopiestic	MONK	Moeken	Sakurai	SCALE 4.0	IPPE-04	SCALE5 293K	SCALE5 298K	SCALE5 300K
40	1.052	1.051	1.069	1.055	1.054	1.053	1.053	1.051	1.051
45	1.058	1.058	1.075	1.062	1.060	1.060	1.059	1.058	1.057
50	1.066	1.065	1.082	1.069	1.067	1.067	1.066	1.065	1.064
55	1.073	1.071	1.088	1.077	1.074	1.073	1.073	1.072	1.071
60	1.079	1.078	1.095	1.084	1.080	1.080	1.080	1.078	1.078
65	1.086	1.084	1.101	1.091	1.087	1.087	1.086	1.085	1.084
70	1.093	1.091	1.108	1.098	1.094	1.094	1.093	1.092	1.091
100	1.134	1.131	1.147	1.140	1.134	1.135	1.133	1.132	1.131
200	1.271	1.264	1.276	1.280	1.267	1.272	1.268	1.266	1.266
250	1.340	1.331	1.341	1.348	1.334	1.340	1.335	1.334	1.333
300	1.409	1.397	1.405	1.417	1.400	1.409	1.403	1.401	1.400
350	1.477	1.464	1.470	1.485	1.467	1.477	1.471	1.469	1.467
400	1.544	1.530	1.535	1.552	1.534	1.546	1.539	1.536	1.535
450	1.612	1.597	1.600	1.619	1.600	1.614	1.607	1.604	1.602
500	1.678	1.663	1.664	1.685	1.667	1.682	1.674	1.671	1.670
600	1.809	1.796	1.794	1.816	1.800	1.819	1.808	1.806	1.805
700	1.949	1.929	1.923	1.944	1.934	1.956	1.938	1.940	1.941
800	2.089	2.062	2.053	2.071	2.067	2.093	2.061	2.072	2.077
900	2.229	2.195	2.182	2.195	2.200	2.230	2.168	2.201	2.212
1000	2.369	2.328	2.312	2.317	2.334	2.366	(2.217)*	2.325	2.347
1100	2.508	2.461	2.441	2.437	2.467	2.503		2.437	2.481
1200	2.648	2.594	2.570	2.555	2.600	2.640		(2.505)**	2.612
1300	2.788	2.727	2.700	2.671	2.733	2.777			(2.712)**
1330 ****	2.807	2.767	2.739	2.705		2.807			

* SCALE 5 crystal density at 989 gU/l, 293K (20°C, room temperature).

** SCALE 5 crystal density at 1 179 gU/l, 298K (25°C).

*** SCALE 5 crystal density at 1 276 gU/l, 300K (27°C).

**** Real crystal density: 1 330 gU/l .

Figure K3. Total density versus uranium concentration for UNH

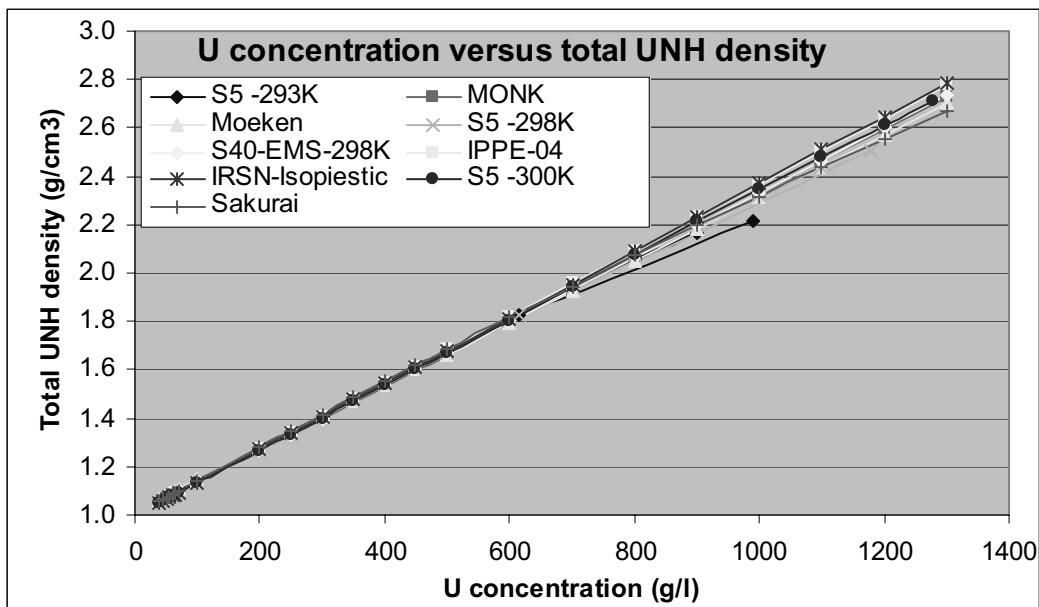


Figure K4. Differences: Total density versus uranium concentration for UNH

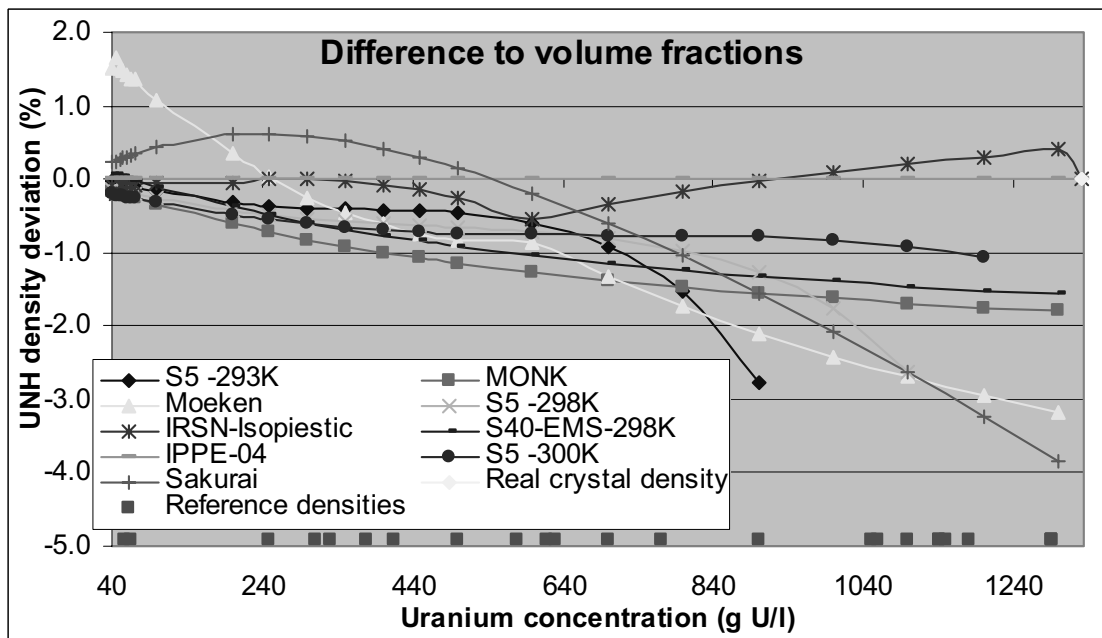


Table K5. H/Pu versus plutonium concentration for PuNH

H/Pu atomic ratio as a function of plutonium (²³⁹ Pu only) concentration								
C _{Pu} (g/l)	IRSN Isopiestic	IRSN Pre-Iso	ARH-600 Equation	SCALE 4.0	IPPE-04	SCALE5 293K	SCALE5 298K	SCALE5 300K
20	1313.0	1311.0	1317.1	1315.3	1316.7	1314.3	1312.6	1311.8
25	1048.0	1046.0	1051.8	1050.3	1048.4	1049.5	1048.1	1047.5
30	872.4	869.3	874.9	873.7	870.2	873.0	871.9	871.3
35	746.4	742.9	748.5	747.5	745.9	747.0	746.0	745.5
40	652.0	648.1	653.8	652.8	650.3	652.5	651.6	651.1
45	578.5	574.4	580.1	579.2	576.1	578.9	578.1	577.7
50	519.6	515.4	521.1	520.4	518.1	520.1	519.4	519.0
100	255.1	250.0	255.7	255.4	253.0	255.5	255.1	254.9
200	122.7	117.3	123.1	122.9	120.4	123.1	122.8	122.7
250	96.2	90.8	96.5	96.4	93.9	96.5	96.3	96.2
300	78.5	73.1	78.8	78.7	76.3	78.7	78.5	78.5
350	65.7	60.5	66.2	66.1	63.6	66.0	65.8	65.7
400	56.2	51.0	56.7	56.7	54.2	56.4	56.2	56.1
500	42.6	37.8	43.5	43.4	40.9	42.6	42.5	42.4
600	33.4	28.9	34.6	34.6	32.1	32.9	32.8	32.7
700	26.6	22.6	28.3	28.3	25.8	24.9	24.7	24.6
800	21.5	17.8	23.6	23.5	21.1	(20.5)*	(20.5)**	(20.5)**
900	17.7	14.2	19.9	19.9	17.4			
1000	14.6	11.2	16.9	16.9	14.4			
1200****	10.0		12.5		10			

* SCALE 5 crystal density at 747.14 g Pu/l, 293K (20°C, room temperature).

** SCALE 5 crystal density at 743.6 g Pu/l, 298K (25°C, common reference temperature).

*** SCALE 5 crystal density at 742.1 g Pu/l, 293K (27°C, default temperature in SCALE 5).

**** Real crystal density is at 1 201 g Pu/l for ²³⁹Pu.

Figure K5. H/Pu versus plutonium concentration for PuNH

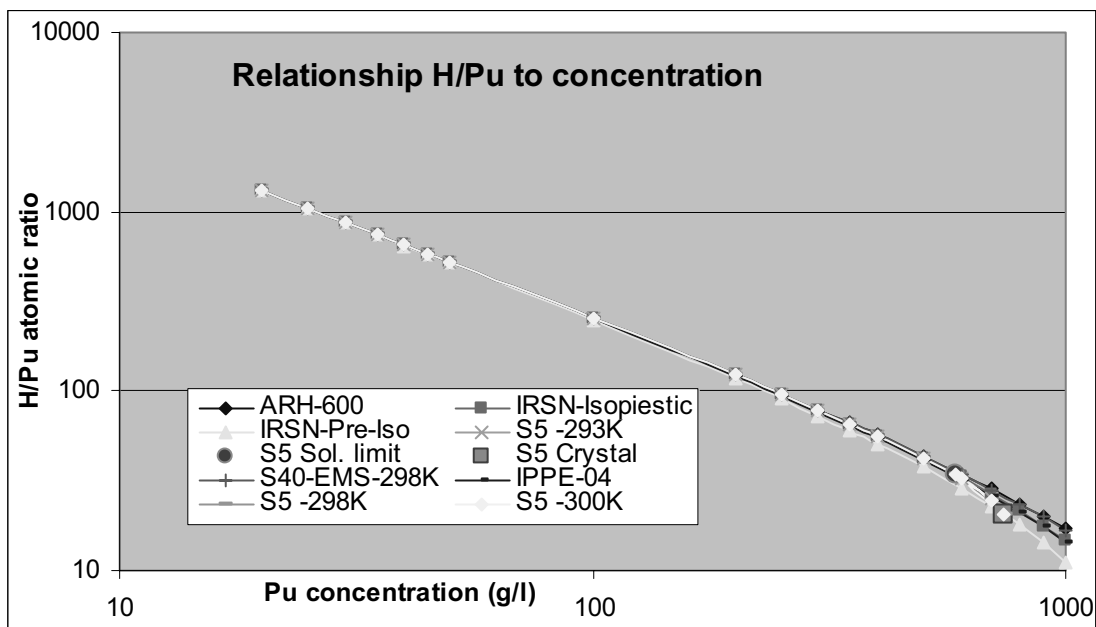


Figure K6. Differences: H/Pu versus plutonium concentration for PuNH

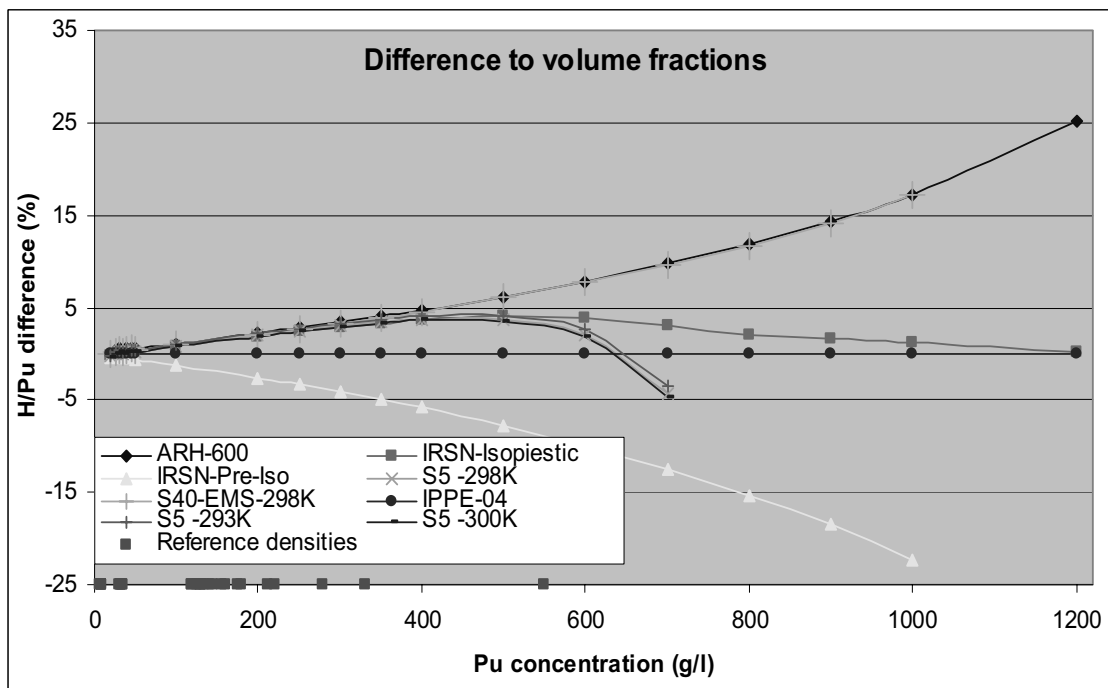


Table K6. Total density versus plutonium concentration for PuNH

H/Pu atomic ratio as a function of plutonium (^{239}Pu only) concentration											
C_{Pu} (g/l)	IRSN Isopiestic	IRSN Pre-Iso	ARH-600 equation	SCALE 4.0	IPPE -04	MONK	Mai moni	Sakurai	SCALE5 293K	SCALE5 298K	SCALE5 300K
20	1.029	1.028	1.032	1.032	1.030	1.032	1.030	1.032	1.031	1.030	1.029
25	1.037	1.035	1.041	1.040	1.038	1.041	1.039	1.041	1.039	1.038	1.037
30	1.046	1.043	1.049	1.049	1.046	1.050	1.047	1.049	1.048	1.046	1.046
35	1.055	1.050	1.058	1.057	1.054	1.058	1.055	1.057	1.056	1.055	1.054
40	1.063	1.057	1.066	1.065	1.062	1.067	1.063	1.066	1.065	1.063	1.063
45	1.072	1.065	1.074	1.074	1.069	1.075	1.072	1.074	1.073	1.072	1.071
50	1.080	1.072	1.083	1.082	1.077	1.084	1.080	1.083	1.082	1.080	1.080
100	1.164	1.145	1.166	1.166	1.157	1.170	1.163	1.166	1.166	1.165	1.164
200	1.331	1.291	1.334	1.333	1.315	1.342	1.330	1.333	1.335	1.333	1.332
250	1.415	1.364	1.418	1.417	1.394	1.428	1.413	1.415	1.418	1.416	1.415
300	1.497	1.437	1.502	1.501	1.473	1.514	1.497	1.498	1.501	1.499	1.498
350	1.579	1.510	1.585	1.585	1.552	1.600	1.581	1.579	1.583	1.581	1.580
400	1.661	1.583	1.669	1.669	1.631	1.686	1.665	1.661	1.664	1.662	1.661
500	1.820	1.729	1.837	1.836	1.790	1.858	1.834	1.822	1.821	1.818	1.817
600	1.976	1.875	2.004	2.004	1.948	2.030	2.003	1.981	1.967	1.963	1.962
700	2.127	2.021	2.172	2.171	2.106	2.202	2.173	2.139	2.083	2.077	2.075
800	2.277	2.167	2.340	2.339	2.265	2.374	2.344	2.295	(2.098)*	(2.089)**	(2.086)***
900	2.432	2.313	2.507	2.507	2.423	2.546	2.515	2.449			
1000	2.587	2.459	2.675	2.674	2.581	2.718	2.688	2.602			
1200 ****	2.900	2.753			2.900	3.062	3.034	2.901			

* SCALE 5 crystal density at 747.14 g Pu/l, 293K (20°C, room temperature).

** SCALE 5 crystal density at 743.6 g Pu/l, 298K (25°C, common reference temperature).

*** SCALE 5 crystal density at 742.1 g Pu/l, 293K (27°C, default temperature in SCALE 5).

**** Real crystal density is at 1 201 g Pu/l for ^{239}Pu .

Figure K7. Total density versus plutonium concentration for PuNH

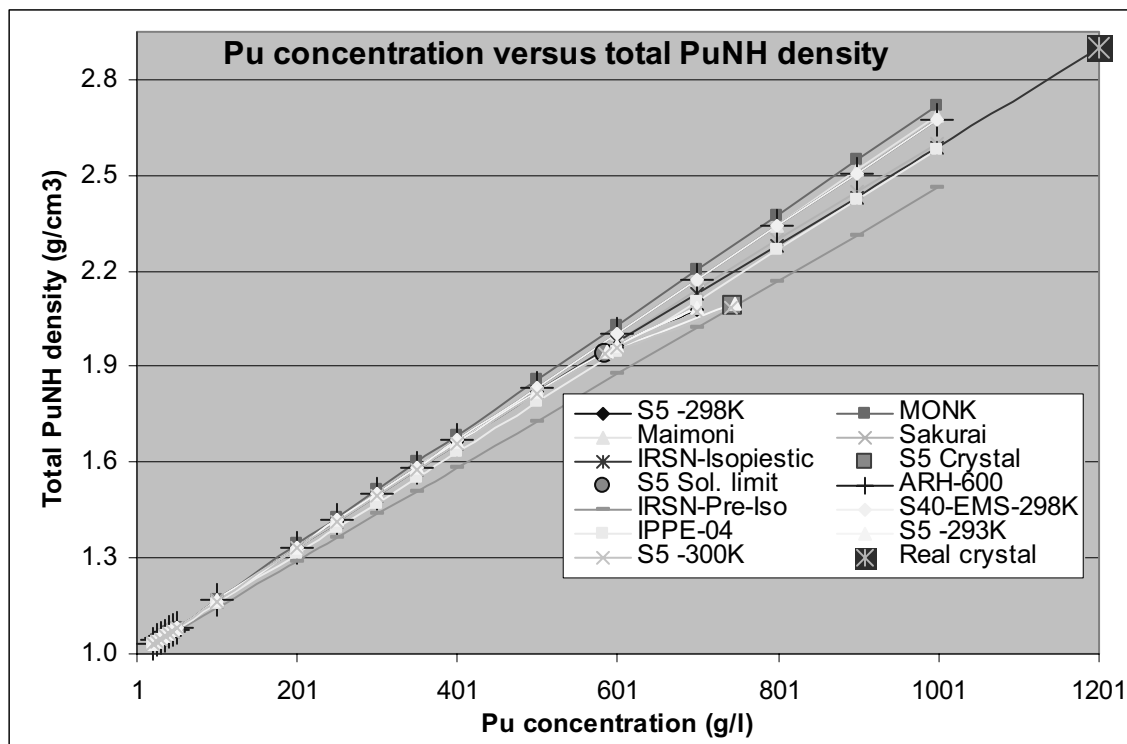


Figure K8. Differences: Total density versus plutonium concentration for PuNH

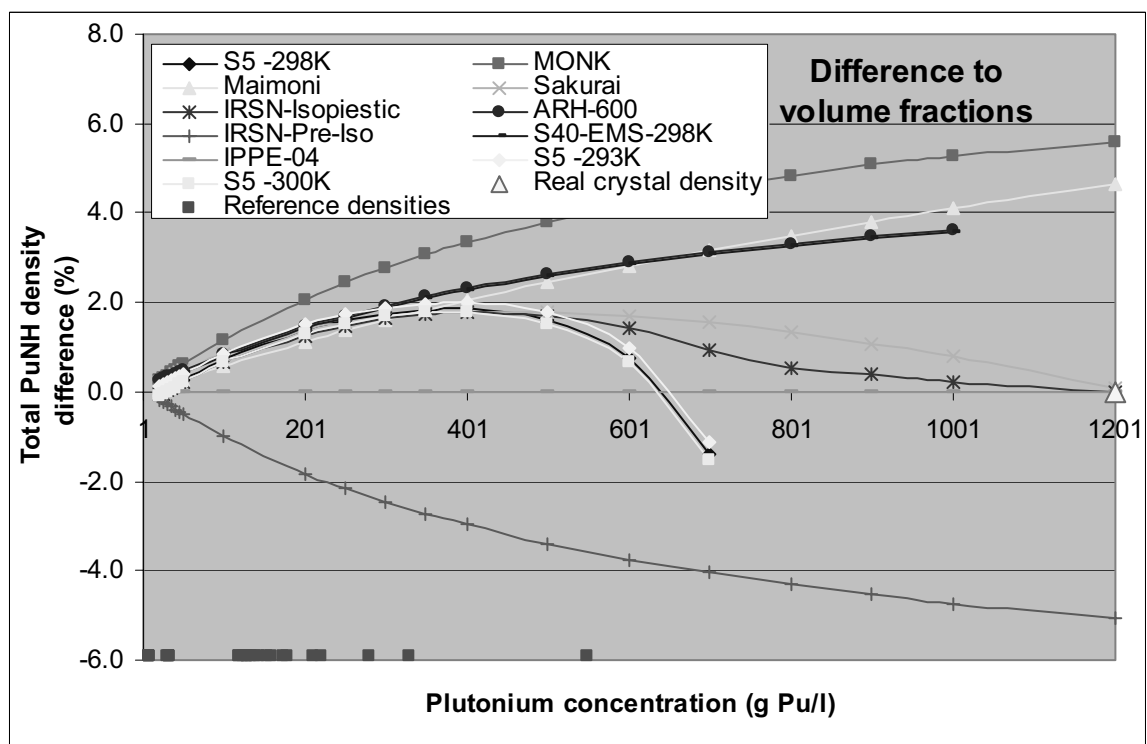


Figure K9. Enlarged differences: H/U versus uranium concentration for UNH

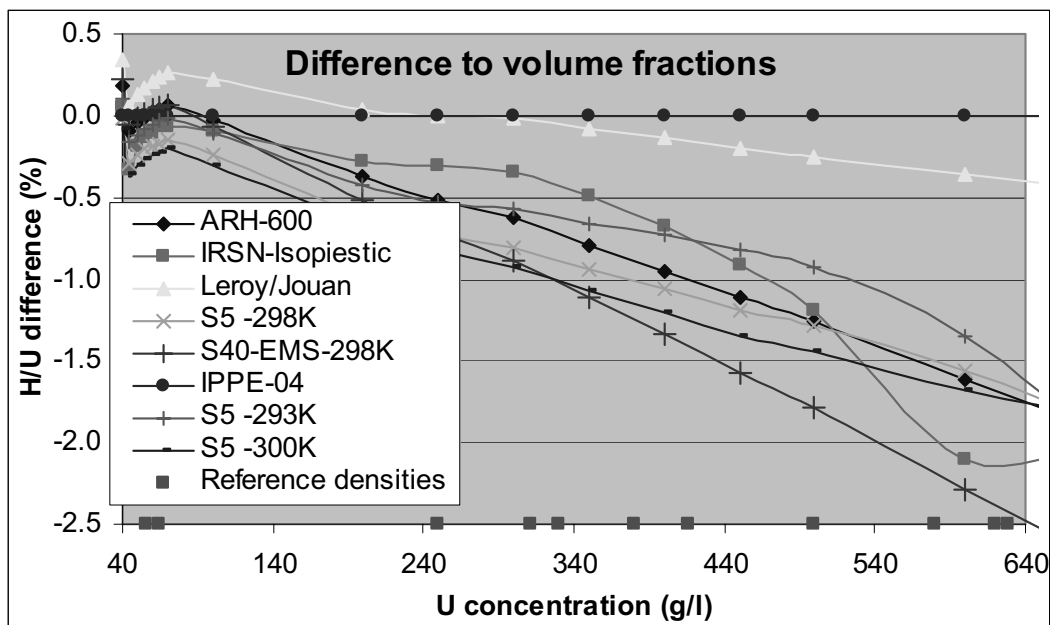


Figure K10. Enlarged differences: UNH density versus uranium concentration

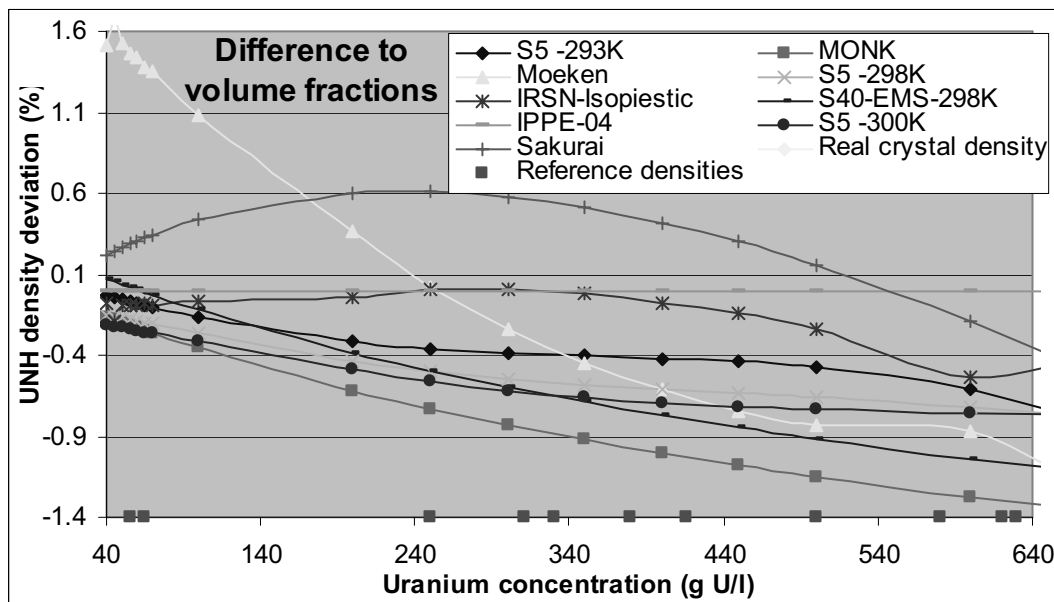


Figure K11. Enlarged differences: H/Pu versus uranium concentration for PuNH

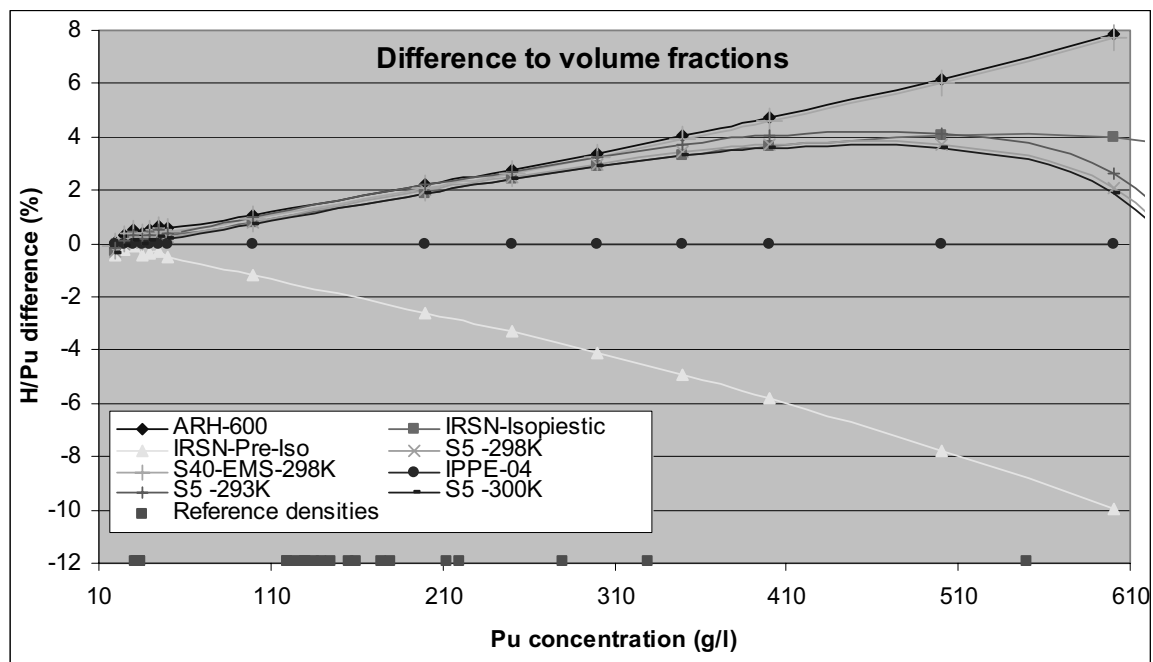
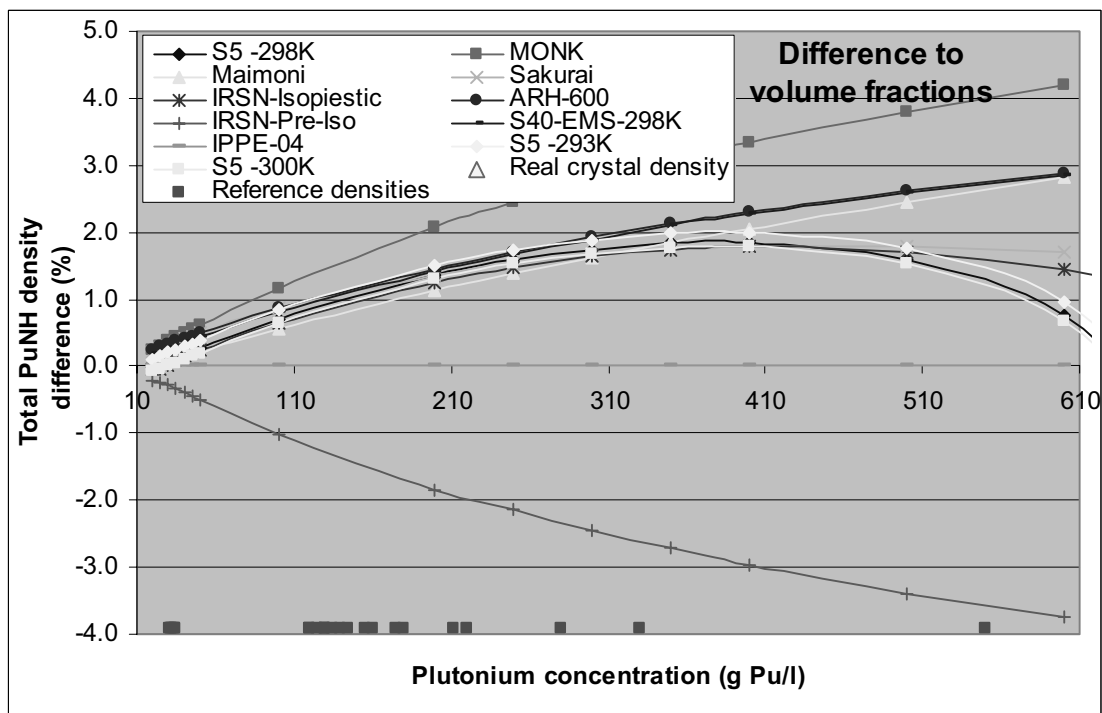


Figure K12. Enlarged differences: PuNH density versus plutonium concentration



Sensitivity of reference values to variations in density methods

The comparison above shows that there are significant differences between different density methods for solutions. Some of the differences are above the solubility limits but even within the soluble range the differences are often significant.

The comparison of best estimate values from different contributors sometimes seems to mirror the differences due to the density methods. IRSN has demonstrated (e.g. [39], [40], [60] and [89]) how large the differences can be for some methods and reference systems. To get more information, some SCALE 5 calculations were made to see the sensitivity to an increase of water content while keeping the actinide density (not concentration!) the same.

The water increase is 1% of the total density (solution, crystal or mixture solution/crystal). This is done in SCALE 5 by adding the 1% as water to create a mixture with the previous solution. The sensitivities calculated are limited to volume systems for all UNH enrichments and for PuNH with the isotope distributions 100 and 71/17/11/1. The temperatures are 300 K for UNH and 293 K for PuNH. A search gives the critical radius.

An exception is made for U(3)NH since the SCALE 5 output shows that the optimum concentration corresponds to a crystal molecule. In this case it would not be adequate to add water (over-moderated when solid). Rather the error in density corresponds to a total density increase in the crystal material.

Critical volume sensitivity to 1 % change in UNH or PuNH density						
Material	“Old” UNH density (g/cm ³)	“New” UNH density (g/cm ³)	Extra H ₂ O (g/cm ³)	Old critical volume (l)	New critical volume (l)	Volume change (%)
U(100)NH	1.4404	1.4404	0.014404	6.830	6.589	-3.53
U(20)NH	1.7761	1.7761	0.017761	16.37	15.60	-4.69
U(5)NH	2.4096	2.4096	0.024096	85.70	80.09	-6.54
U(4)NH	2.5291	2.5291	0.025291	146.2	136.2	-6.82
U(3)NH	2.7264	2.7537	0	412.5	400.3	-2.96
Pu(100)NH	1.4679	1.4679	0.014679	7.550	7.274	-3.65
Pu(71...)NH	1.1999	1.1999	0.011999	15.66	15.18	-3.06

The critical volume for the real crystal density 2.807 g/cm³ is calculated as 378.2 litres. For 293 K, SCALE 5 gives a crystal density at a total density of 2.2285 g/cm³. This is very far from the real density of 2.807 g/cm³. Next version of SCALE 5 will change this information.

It is important to recognise that an over-prediction of the density of a solution at a fixed actinide concentration leads to an over-estimation of k_{eff} for geometry control and probably for mass. For mass it is not obvious since an optimum mass system is over-moderated, the extra water reduces the leakage. For concentration control as measured in g/cm³ or g/l there is no leakage and additional water will increase absorption, leading to an under-estimation of k_{eff} . The limiting value will change. If the concentration is instead measured as the H/X moderation ratio, it will retain the same limiting value.

Some comments to nuclide density comparisons

The most dramatic discrepancies are shown but are not really clear enough in the figures and tables. SCALE 5 tells the user that the crystal density for uranium is very strongly dependent on the temperature and is below 1 000 g U/l for UNH at room temperature and 1 276 g/l for the SCALE default temperature 300K. For plutonium, the temperature dependence is not so strong but the crystal densities are much lower; at 293K it is only 743 g Pu/l for PuNH.

Too low crystal densities could be dangerous in a safety evaluation where crystals are assumed to be mixed with other materials. The IPPE assumption of a mixture of crystals and water is an example. Another would be where the crystals are mixed with water and U_3O_8 that has not been dissolved. The credibility of these arguments has not been considered but it must be recognised that the codes are used to solve problems that are often approximations of real or potential situations.

At zero actinide density and no acidity, the solution should be identical to pure water. The density is about 0.9982, depending on the temperature. The Moeken equation starts with a density of 1.017 g/l which explains the over-estimation of the overall density in the first part of the curve.

The other boundary is the crystal density which is quite well known. It is a very important value that all methods should be able to handle, unless they are explicitly excluded from such applications. The Japanese Handbook [24] clearly limits the range of applicability for the Sakurai equation to far below the saturation limits. Even so it appears to be quite good (compared with the isopiestic law) for plutonium systems all over the concentration range.

The ARH-600 equation and the SCALE 4.0 densities for plutonium are essentially identical. This is no surprise since SCALE 4.0 uses an equation from ARH-600. For uranium, there are differences between the ARH-600 H/U ratio equation results and the SCALE 4.0 H/U ratios. The corresponding densities are identical. A reason may be that the ARH-600 equations are not completely consistent with each other.

The MONK densities appear to be over-estimated for plutonium. However, it is not clear that this corresponds to the calculations. The information about the MONK density calculations is very short and contains errors. Maybe there is an editorial error in the equation (though repeated several times).

There are several other trends and they need to be considered in the overall validation of the reference values. This verification effort is only directed towards non-acid solutions and mixtures. Consideration of acidity, temperature variations and other parameters may change the conclusions about the methods completely.

Appendix L

BEST ESTIMATE REFERENCE VALUES AND COMMENTS

A minor effort is made here to demonstrate the determination of a best estimate reference value for each of the 132 systems and parameters selected by the expert group. The evaluation is subjective and there is no time and no formal expert group left for discussion. This should not be a problem since the study is only at an intermediate state. The evaluated best estimate reference values are for demonstration only and should not even be considered as preliminary.

A calculated result should be considered as having errors, even if the validation shows a zero bias. There is always some remaining uncertainty in every value. The uncertainty value could be smaller than the least significant digit in the reference value but the real error will occasionally be larger than the uncertainty value.

The bias corrected results from the following “major 6” methods were used in APPENDIX I to “automatically” calculate the first level of best estimate reference values: EMS-M5-E7P or -68, EMS-M5-F30, EMS-M5-J33, EMSS5K-238, IPPE-ABBN93 and Serco-Mk8-F22. IPPE’s results using the ABBN93 cross-section library were added late and the validation is not independent but based on the same selection of benchmarks as for the validation of EMS methods. IPPE results are not available for all plutonium isotope distributions, reducing the selection to the “major 5” methods. The bias-corrected MONK results are based on a quite general validation and thus quite “crude”. However, efforts were made to find significant bias trends and to correct for them when found. For this reason the MONK bias-corrected results are included in the automatic best estimate calculation.

CRISTAL is validated and normally gives high-quality results. However, there are known (to IRSN and to the Expert Group) biases in the reference values. Since no attempt was made to correct for them, they are not included in the automatic calculation of best estimate values. However, CRISTAL results normally have low biases and require special consideration when nuclide density effects are evaluated.

JAERI Handbook results are bias-corrected but there is some question about the validity of the biases for best estimate determination rather than for safe values determination. The same is true for the EMS-S4X-238 results. Those evaluations are of particular value since they include results of explicit calculations of positive and negative levels of confidence due to uncertainties. The levels are not symmetric since the relationships between k_{eff} and the reference parameter are not linear.

Other EMS results (older cross-section releases with SCALE 5 and MCNP5) are of value for many purposes but would not improve the quality of the best estimates resulting from the current selection. ORNL results are not bias-corrected even though a reference to a general safety validation (same as used for EMS-S4X-238) is made. Values from other handbooks and standards were perhaps intended as best estimate values at the time given but are not considered so now.

Additional biases are obtained from nuclide density evaluations. Lack of appropriate validation should lead to larger 95% level of confidence uncertainties for some best estimate reference values.

To determine what uncertainties and discrepancies that are large, typical safety factors used in real applications may be considered (but not in this study). The safety factors are usually not the only control. Sometimes there is also a parallel limit on k_{eff} . This seems wise, in particular for large systems. The probability for double-batching (and more!), geometry changes, speed of change (probability of timely discovery), etc. are important.

For mass control where double-batching (and not more) is unlikely but credible, a factor of 0.9 has been used in Germany and many other countries. In France, the safety factor is 0.86.

The volume safety factor applied in Germany and many other countries is 0.8, while the geometry dimension factor is 0.9.

The reference values will be discussed one by one, but many will have common issues. IPPE-84 values are often very different and the reasons are given in the handbook (often compensating errors, sometimes not). IRSN-96 results are given as a range of values, indicating the uncertainty. The source [99] is not a published document; it is used primarily for internal use. Some values are included to demonstrate typical calculation methods of the past.

Various mean (average) values were calculated during the evaluation and some of them are shown in the charts in APPENDIX I. The index “c” in stands for calculation-only while the index “bc” in stands for bias-corrected. Comparisons are made for methods that are used to obtain both calculated-only and bias-corrected values. The purpose is to observe the influences of validation and bias-correction. The EMS-S4X-238 values are not included, partly because the validation is not suitable for best estimate determination and since the method is essentially duplicated (except for nuclide densities), using SCALE 5 instead of SCALE 4.4. CRISTAL and Japanese handbook values are not included in the means either, for reasons given earlier.

The automatic calculation of best averages lead to the mean values and . Using other information, including results from methods that are not automatically included, number density considerations and “reasoned argument”, there will often be additional bias-corrections.

The uncertainties based on statistics on the results are not sufficient. The automatic generation of a total 95% level of confidence is increased from normally two to three standard deviations to cover additional uncertainties. In reality, these statistics are not necessarily related to the real additional uncertainties. Using “argued reasoning”, modifications should be considered to obtain a 95% level of confidence (increase or decrease).

The study is only at a demonstration level. It is better to overestimate the uncertainties than to underestimate them. Contributors and other reviewers should express wishes of changing the proposed biases and uncertainties, preferably but not necessarily by some justification.

The nuclide densities for the 132 reference systems are essential for the determination of biases. Since the bias corrections change the densities related to the best estimate reference values, the following densities are approximations. In particular for uranyl nitrate with low-enriched uranium, the densities (determined with SCALE 5) are not reliable.

The final estimations of best estimate reference values that will be used in the main report follow after the section on reference system densities. To be really credible, all validated results need to be covered either by direct inclusion in the averaging or by given reasons for exceptions. Other results should be understood well enough to explain any deviations from the common best estimate values.

Actinide densities and concentrations of the reference systems

The densities are given in Table L1. For these well-defined reference systems, there is no difference between density and concentration. In safety applications it may be very important to make a clear distinction between the two parameters. The density parameter is a mass to volume ratio while the concentration parameter, as used in criticality safety control, is a mass to mass ratio.

The units may be identical, e.g. g/cm^3 , but the difference in the physics interpretation is there. Sometimes concentration, as measured in e.g. g/l , sounds like a mass per volume unit but it is really not. The litre is a volume unit but here it is used as a short for a litre of a uniquely defined material. In criticality safety, this material must be defined not only by mass but also by other properties. The density for a nuclide, element or compound only informs about its mass per volume. It does not inform about other constituents in the material.

The distinction between density and concentration is also a reason why the moderation ratio H/X (also a concentration) often is a better specification than the concentration in g/l to determine limiting critical values. It directly gives the other relevant mass component to control and it is often not sensitive to temperature, density and other changes.

Table L1. Actinide densities for all applications

Actinide densities for applications (g/cm ³)						
Parameter	Isotopes	Mass	Volume	Cylinder	Slab	Concentration
UO ₂ Uranium density	100	0.0560	9.54 [*]	9.54 ¹	9.54 ¹	0.0122
	20	0.266	1.063	1.121	1.449	0.0636
	5	0.918	1.884	1.932	2.174	0.286
	4	1.063	2.077	1.884	2.271	0.369
	3	1.449	2.319	2.367	2.512	0.521
UNH Uranium density	100	0.056	0.33	0.38	0.50	0.0123
	20	0.250	0.58	0.62	0.70 ^{**}	0.0648
	5	0.77 ²	1.05 ²	1.06 ²	1.10 ²	0.311
	4	0.90 ²	1.14 ²	1.14 ²	1.18 ²	0.416
	3	1.15 ²	1.33 ^{***}	1.33	1.33	0.629 ²
PuO ₂ Plutonium density	100/0/0/0	0.0313	10.107	10.107	10.107	0.00717
	95/5/0/0	0.0323	10.108	10.108	10.108	0.00771
	80/10/10/0	0.0323	10.109	10.109	10.109	0.00800
	90/10/0/0	0.0334	10.108	10.108	10.108	0.00838
	80/15/5/0	0.0344	10.109	10.109	10.109	0.00892
	71/17/11/1	0.0344	10.109	10.109	10.109	0.00908
PuNH Plutonium density	100/0/0/0	0.031	0.28	0.33	0.55	0.00733
	95/5/0/0	0.032	0.14	0.155	0.212	0.00793
	80/10/10/0	0.032	0.13	0.145	0.22	0.00819
	90/10/0/0	0.033	0.125	0.135	0.175	0.00859
	80/15/5/0	0.034	0.12	0.13	0.18	0.00915
	71/17/11/1	0.034	0.12	0.13	0.16	0.00931

* Corrected for UO₂ density 10.84 g/cm³ for 100 % ²³⁵U (10.96 g/cm³ for natural U).

** Above the solubility limit, below the crystal density. A mixture of saturated solution and crystals assumed.

*** Crystal density.

1 ??????????

2 ??????????

Figure L1. Uranium densities for UO₂ reference systems

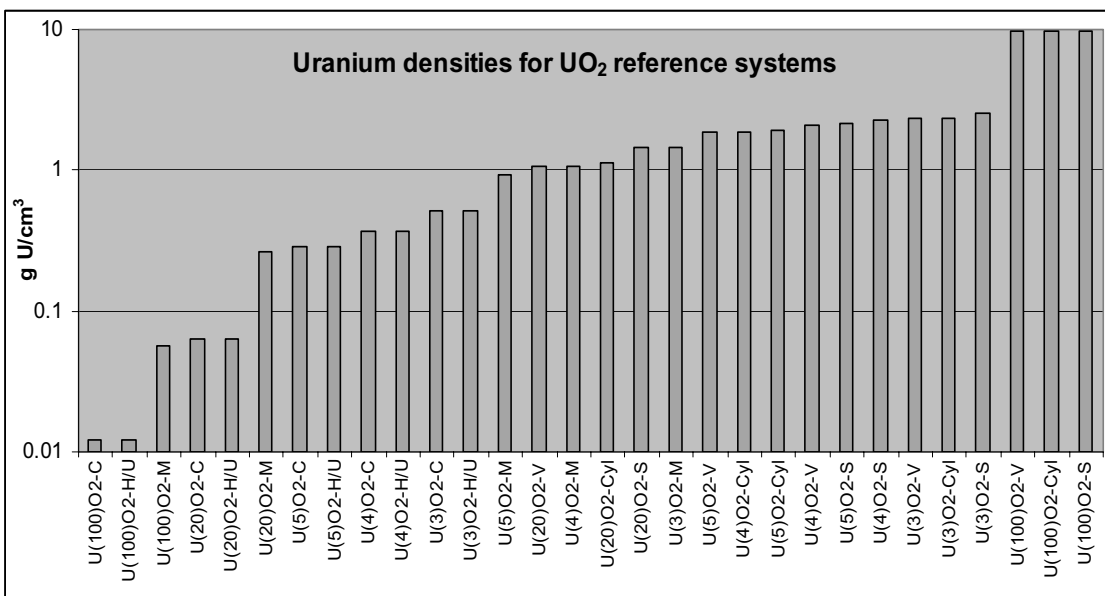


Figure L2. Uranium concentrations for UNH reference systems

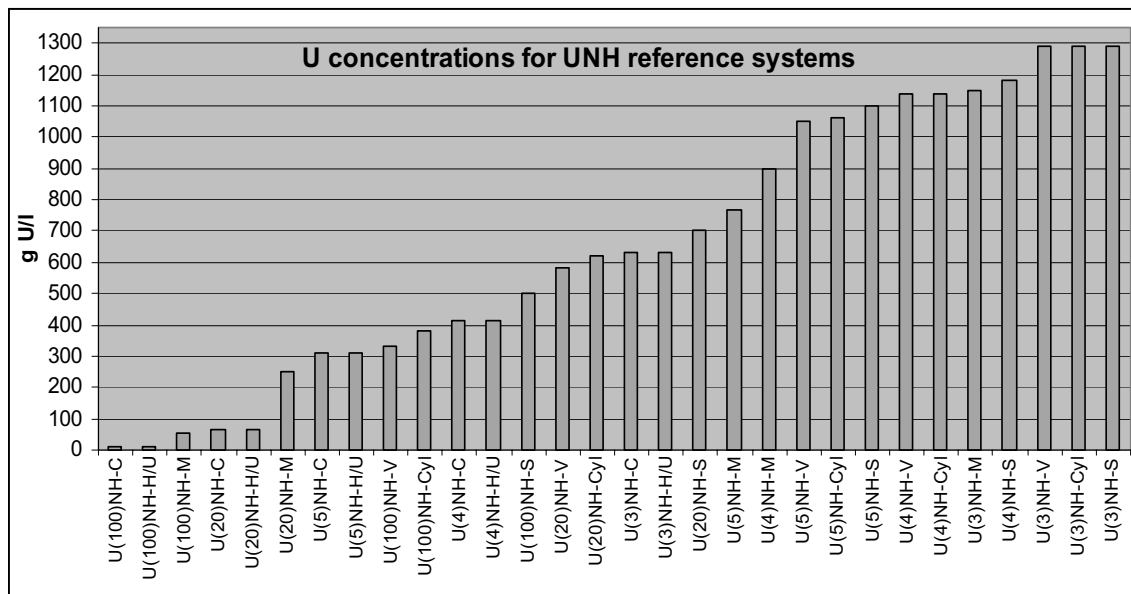


Figure L3. Plutonium densities for PuO₂ reference systems

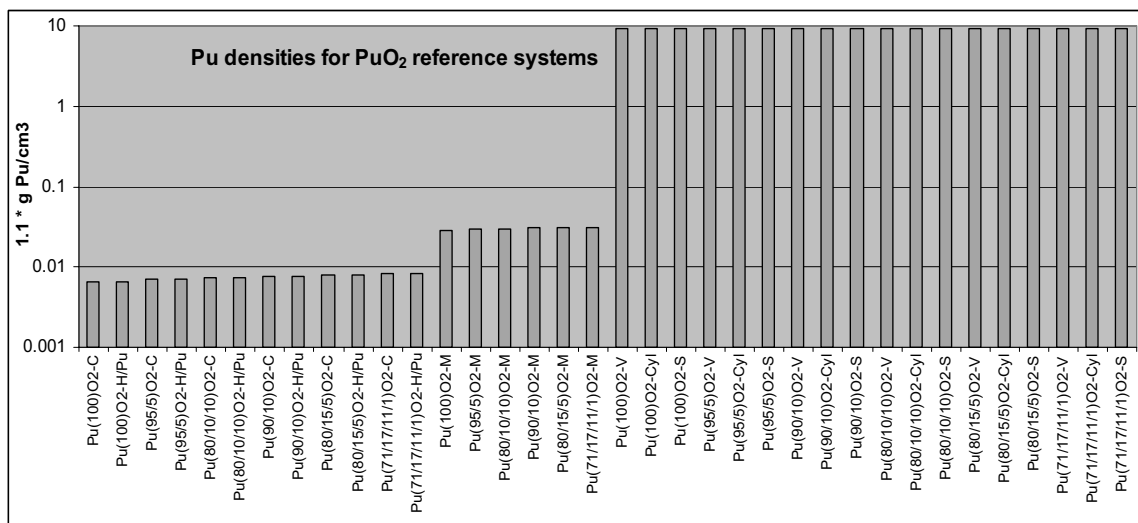
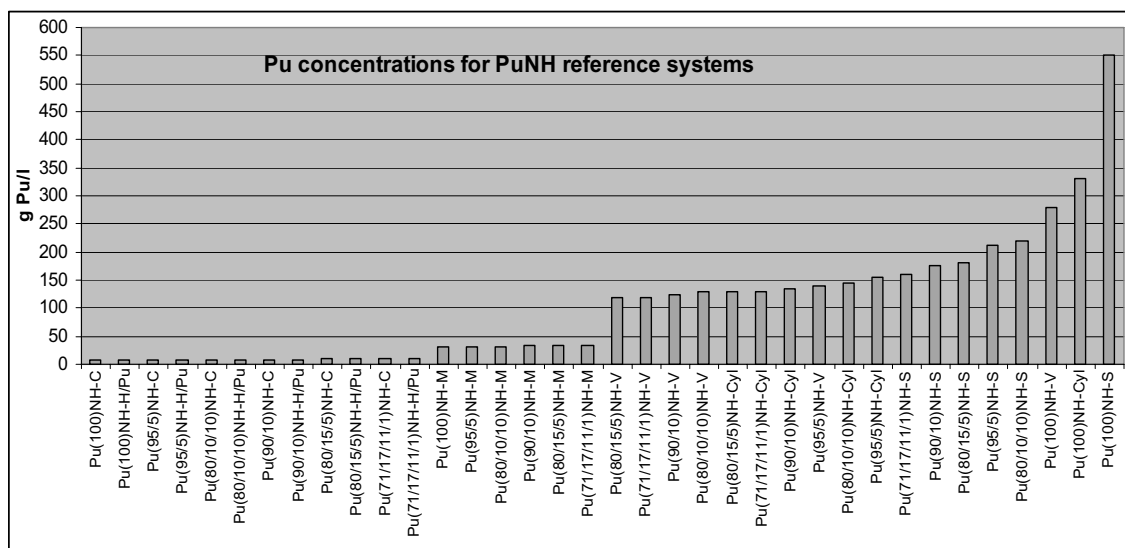


Figure L4. Plutonium concentrations for PuNH reference systems



Uranium dioxide - UO_2

U(100)O₂ - Mass

This system does not seem to be sensitive to the nuclide density issue. The material is well moderated. The geometry is not so sensitive to quadrature and mesh. The mean values $\overline{m}_c$ and $\overline{m}_{bc}$ are not so different, but their standard deviations are. The validation reduces the standard deviation by a factor of three, indicating that it really works.

The CRISTAL value is slightly lower, which is not unexpected (should be slightly conservative). The validated IPPE and Serco results agree well with the EMS results. There are no really large discrepancies. The IRSN-96 results were removed since they appear to concern 93.5 % and not 100 % by mass of ^{235}U and also since they cover a range of values.

The “major 6” average $\overline{m}_{bc6}$ with one standard deviation, is $798 \pm 3 \text{ g } ^{235}\text{U}$. Considering that other uncertainties are expected to be small, the total 95 % level of confidence uncertainty is estimated as $10 \text{ g } ^{235}\text{U}$.

U(20)O₂ - Mass

This system does not seem to be covered as well by benchmarks as that for 100 % ^{235}U . However, the results indicate that the validation works well.

The Japanese Handbook release 2 ([23], [24]) result has now been corrected here but the error needs to be pointed out. Even with a safety factor of 0.70, a system based on the handbook value of 7.43 kg could lead to criticality.

There are no additional biases related to nuclide density determination. There are no large discrepancies besides the already corrected Japanese Handbook release 2 value.

The “major 6” average $\overline{m}_{bc6}$, with one standard deviation, is $5.22 \pm 0.02 \text{ kg}$ of uranium. Considering that other uncertainties are expected to be small, the total 95 % level of confidence uncertainty is estimated as 0.10 kg of uranium.

U(5)O₂ - Mass

The standard deviation of $\overline{m}_{bc}$, is not reduced as much related to that for $\overline{m}_c$ as for the higher enrichments of ^{235}U . This may indicate that the validation is not quite as good and that the system may be more complicated (^{238}U and resonances). However, the validation still seems to work reasonably well. It is also reasonable to expect larger standard deviations for larger systems since the relative sensitivity to k_{eff} changes is smaller.

The Serco MONK value is lower and increases the standard deviation. The deviation is much lower than the uncertainty quoted by Serco.

There are no additional biases related to nuclide density determination. There are no large discrepancies besides the low (conservative for safety application) value in the IPPE-84 handbook, which is already known to have large uncertainties.

The mean $\overline{m}_{bc6}$ with one standard deviation is 37.0 ± 0.3 kg of uranium. The CRISTAL value is lower than the mean. This is important when considering the U(5)NH mass. Considering that other uncertainties are expected to be small, the total 95 % level of confidence uncertainty is estimated as 1.0 kg of uranium.

U(4)O₂ - Mass

The standard deviation of $\overline{m}_{bc}$ is almost reduced by a factor two by validation and this is not bad. The Serco and IPPE validated results are low while the EMS MCNP results with JENDL3.3 and the preliminary ENDF/B-VII library are high. The CRISTAL result is again low, giving a slightly conservative value, as expected.

There are no additional biases related to nuclide density determination. There are no large discrepancies.

The mean $\overline{m}_{bc6}$ with one standard deviation is 55.1 ± 0.4 kg of uranium. Considering that other uncertainties are expected to be small, the total 95 % level of confidence uncertainty is estimated as 1.2 kg of uranium.

U(3)O₂ - Mass

The standard deviation of $\overline{m}_{bc}$ is reduced by a factor two by validation and, again, this is quite good. The EMS MCNP result with JEFF3.0 is low and the preliminary ENDF/B-VII library is high. The CRISTAL result is again low, as expected.

There are no additional biases related to nuclide density determination. There are no large discrepancies. The EMS SCALE result based on ORNL validation is high, indicating that the validation is not focused on this application (this is normal and will not be repeated every time). The bias correction in the ORNL validation is opposite that which is determined from the current EMS validation.

The mean $\overline{m}_{bc6}$ with one standard deviation is 99.0 ± 0.5 kg of uranium. Considering that other uncertainties are expected to be small, the total 95 % level of confidence uncertainty is estimated as 1.5 kg of uranium.

U(100)O₂ - Volume

This system is sensitive to the nuclide density as well as to quadrature and mesh issues for deterministic codes. The nuclide density issue related to the isotopic distribution leads to a reduced theoretical density of UO₂ from 10.96 to 10.84 g/cm³. If the 10.96 density is used, a bias needs to be determined. Using SCALE 5 (XSDRNPM) and the 238 group library, the bias was determined to be 0.13 litres. There is no indication that any of the contributions take the density issue into account. The Japanese Handbooks deal with the issue but don't contain values for this type of material.

This bias correction is significant when comparing calculation results but is probably not so important for safety or economy. Single lumps of such sizes should not be expected in any environment where handbook values or quick calculations are used as a safety evaluation basis. In a distributed system, the problem with lack of moderation may be more complicated to handle.

The mean values $\bar{v}_c$ and $\bar{v}_{bc}$ are not so different, but their standard deviations are. The validation reduces the standard deviation by more than a factor of two, indicating that it works quite well.

There first appeared to be some really large discrepancies. However, the German Handbook [19] gives the critical volume as 5.6 litres and the safe volume as 4.6 litres, **provided that the uranium density is less than 1 g U/cm³**. The curve indicates a critical value around 4 kg for higher uranium densities. This condition was not documented in the tables distributed to the participants (the tables used to collect data on the web site did not allow much explanation).

The ARH-600 handbook value of 6.1 litres is given for uranium, but the reference system is based on UO₂F₂. As can be seen in the German Handbook, the minimum critical volume for UO₂F₂ is close to this value 6.1. The curves stop at a density at 1 g U/cm³ and do not indicate a potential minimum at the theoretical uranium density.

The IRSN-96 result was removed since it appears to concern 93.5 % and not 100 % by mass of ²³⁵U (later all IRSN-96 results were removed).

The SCALE 27- and 44-group cross-section libraries are not designed to cover this type of application. The validation and associated bias corrections improve their results considerably.

The average validated value with one standard deviation, including the IPPE result, is 4.25 ± 0.03 litres. Adding the density-related bias to the best average, the best estimate value becomes 4.38 ± 0.03 litres. Considering that other uncertainties are expected to be small, the total 95 % level of confidence uncertainty is estimated as 0.10 litres. The CRISTAL V1.0 result 4.30 litres includes the isotopic density effect, making the value slightly lower than the best estimate value for this fast system.

U(20)O₂ - Volume

This system is not so sensitive to the nuclide density issue.

The mean value standard deviations are not reduced sufficiently by validation. The IPPEABBN93 value is much lower than the other bias-corrected values and this influences the standard deviations. However, the CRISTAL value is even lower. The IPPE value will be kept since there is no direct evidence of error.

The bias-corrected Japanese Handbook release 2 value of 11.5 litres, as well as the identical IRSN/CEA 1978 handbook value appear too high. The IPPE-84 deviation is large as often is the case. The IRSN-96 result was removed since it is not an estimate but a range of values.

The mean $\bar{v}_{bc6}$ with one standard deviation is 10.78 ± 0.13 litres. The total 95 % level of confidence uncertainty is estimated as 0.40 litres, including effects of other uncertainties.

U(5)O₂ - Volume

This system is not sensitive to the nuclide density issue.

The mean value standard deviations are not reduced sufficiently by validation. The IPPEABBN93 value is much lower than the other bias-corrected values and this influences the standard deviations. However, the CRISTAL value is as low. The IPPE value will be kept since there is no direct evidence of error. However, the bias-correction for IPPE-ABBN93 is large and not very accurate.

The IPPE-84 deviation is large as often is the case. The IRSN-96 result was removed since it is not an estimate but a range of values.

The average validated value with one standard deviation, including the IPPE result, is 27.91 ± 0.32 litres. The total 95 % level of confidence uncertainty is estimated as 1.00 litres, including effects of other uncertainties.

U(4)O₂ - Volume

This system is not sensitive to the nuclide density issue.

The mean value standard deviations are reduced by a factor larger than two by validation. This is better than for the 5 % enrichment ²³⁵U. The IPPEABBN93 value is much lower than the other bias-corrected values and this influences the standard deviations. However, the CRISTAL value is as low. The IPPE value will be kept since there is no direct evidence of error. However, the bias-correction for IPPE-ABBN93 is large and not very accurate.

The IPPE-84 deviation is large as often is the case. The bias-corrected values from the Japanese handbooks are low, in particular the 1988 release.

The best estimate average validated value with one standard deviation, including the IPPE result, is 35.69 ± 0.28 litres. The total 95 % level of confidence uncertainty is estimated as 0.90 litres, including effects of other uncertainties.

U(3)O₂ - Volume

This system is not sensitive to the nuclide density issue.

The mean value standard deviations are reduced by a factor larger than two by bias correction from validation. The IPPEABBN93 value is much lower than the other bias-corrected values and this influences the standard deviations. The CRISTAL value is low but not as low as the IPPE-ABBN93 value. The IPPE value will be kept since there is no direct evidence of error. However, the bias-correction for IPPE-ABBN93 is large and not very accurate.

The IPPE-84 deviation is large as often is the case. The bias-corrected values from the Japanese handbooks are also very low, in particular the 1988 release.

The best estimate average validated value with one standard deviation, including the IPPE result, is 53.49 ± 0.32 litres. The total 95 % level of confidence uncertainty is estimated as 1.00 litres, including effects of other uncertainties.

U(100)O₂ - Cylinder

This system is sensitive to the nuclide density as well as to quadrature and mesh issues for deterministic codes. The nuclide density issue related to the isotopic distribution leads to a reduced theoretical density of UO₂ from 10.96 to 10.84 g/cm³. If the 10.96 density is used, a bias needs to be determined. Using SCALE 5 (XSDRNPM) and the 238 group library, the bias was determined to be 0.12 cm. There is no indication that any of the contributions take the density issue into account. The Japanese Handbooks deal with the issue but don't contain values for this type of material.

The mean values $\bar{\mu}$ and $\bar{\sigma}$ are not so different, but their standard deviations are. The bias correction based on the validation reduces the standard deviation by more than a factor of two, indicating that it works acceptably.

The German Handbook [19] and the ARH-600 Handbook [14] values were removed for the same reason as described under U(100)O₂ volume.

The IRSN-96 result was removed since it appears to concern 93.5 % and not 100 % by mass of ²³⁵U.

The SCALE 27- and 44-group cross-section libraries are not designed to cover this type of application. The validation and associated bias corrections improve their results considerably.

The average validated value with one standard deviation, including the IPPE result, is 12.35 ± 0.02 cm. The CRISTAL result, without consideration of density effects, is a little higher than other values. This situation changes after such consideration. Adding the density-related bias to the best average, the best estimate value becomes 12.47 ± 0.02 cm. Considering that other uncertainties are expected to be small, the total 95 % level of confidence uncertainty is estimated as 0.06 cm.

U(20)O₂ - Cylinder

This system is not so sensitive to the nuclide density issue.

The mean value standard deviations are not reduced so much by bias corrections from validation. The IPPEABBN93 value is much lower than the other bias-corrected values and this influences the standard deviations. The IPPE value will be kept since there is no direct evidence of error. Without the IPPE results, the validation seems to work well with EMS methods. There are no large discrepancies. The IRSN-96 result was removed since it is not an estimate but a range of values.

The average validated value with one standard deviation, including the IPPE result, is 17.97 ± 0.07 cm. The total 95 % level of confidence uncertainty is estimated as 0.20 cm, including effects of other uncertainties.

U(5)O₂ - Cylinder

This system is not so sensitive to the nuclide density issue.

The mean value standard deviations are not reduced much by bias corrections from validation. The IPPEABBN93 value is much lower than the other bias-corrected values and this influences the standard deviations. However, the CRISTAL value is as low. The IPPE value will be kept since there is no direct evidence of error.

The IRSN-96 result was removed since it is not an estimate but a range of values.

The average validated value with one standard deviation, including the IPPE result, is 25.68 ± 0.11 cm. The total 95 % level of confidence uncertainty is estimated as 0.35 cm, including effects of other uncertainties.

U(4)O₂ - Cylinder

This system is not sensitive to the nuclide density issue.

The mean value standard deviations are reduced by a factor less than two by bias correction from validation. The IPPEABBN93 value is much lower than the other bias-corrected values and this influences the standard deviations. However, the CRISTAL value is as low. The IPPE value will be kept since there is no direct evidence of error.

There are no large discrepancies for this reference value.

The best estimate average validated value with one standard deviation, including the IPPE result, is 28.25 ± 0.16 cm. The total 95 % level of confidence uncertainty is estimated as 0.50 cm, including effects of other uncertainties.

U(3)O₂ - Cylinder

This system is not sensitive to the nuclide density issue.

The mean value standard deviations are reduced by a factor less than two by bias correction from validation. The IPPEABBN93 value is much lower than the other bias-corrected values and this influences the standard deviations. The CRISTAL value is low but not as low as the IPPE-ABBN93 value. The IPPE value will be kept since there is no direct evidence of error.

The IPPE-84 deviation is quite large as often is the case. The bias-corrected value from the Japanese handbook release 2 is also a little low.

The best estimate average validated value with one standard deviation, including the IPPE result, is 32.79 ± 0.18 cm. The total 95 % level of confidence uncertainty is estimated as 0.55 cm, including effects of other uncertainties.

U(100)O₂ - Slab

This system is sensitive to the nuclide density as well as to quadrature and mesh issues for deterministic codes. The nuclide density issue related to the isotopic distribution leads to a reduced theoretical density of UO₂ from 10.96 to 10.84 g/cm³. If the 10.96 density is used, a bias needs to be determined. Using SCALE 5 (XSDRNPM) and the 238 group library, the bias was determined to be 0.04 cm. There is no indication that any of the contributions take the density issue into account. The Japanese Handbooks deal with the issue but don't contain values for this type of material.

The mean values $\bar{t}_c$ and $\bar{t}_{bc}$ are not so different, neither are the standard deviations. The bias correction based on the validation reduces the standard deviation by less than a factor of two but, since it is quite small, the validation still works acceptably.

The CRISTAL V1.0 result, with proper consideration of density effects, is a little lower than the best estimate value when the bias for density effects has been considered.

The German Handbook [19] and the ARH-600 Handbook [14] values were removed for the same reason as described under U(100)O₂ volume.

The IRSN-96 results were removed since they appear to concern 93.5 % and not 100 % by mass of ²³⁵U.

The SCALE 27- and 44-group cross-section libraries are not designed to cover this type of application. The validation and associated bias corrections improve their results considerably.

The average validated value with one standard deviation, including the IPPE result, is 3.41 ± 0.03 cm. Adding the density-related bias to the best average, the best estimate value becomes 3.45 ± 0.03 cm. Considering that other uncertainties are expected to be small, the total 95 % level of confidence uncertainty is estimated as 0.10 cm.

U(20)O₂ - Slab

This system is not so sensitive to the nuclide density issue.

The mean value standard deviations are not reduced so much by bias corrections from validation. This time, the Serco MONK value is much higher than the other bias-corrected values and this influences the standard deviations. The Serco value will be kept since there is no direct evidence of error. The validation seems to work well with EMS methods.

There are no large discrepancies. The IRSN-96 result was removed since it is not an estimate but a range of values.

The average validated value with one standard deviation, including the IPPE result, is 7.24 ± 0.10 cm. The total 95 % level of confidence uncertainty is estimated as 0.30 cm, including effects of other uncertainties.

U(5)O₂ - Slab

This system is not so sensitive to the nuclide density issue.

The mean value standard deviations are not reduced much by bias corrections from validation. The Serco MONK value is much higher than the other bias-corrected values and this influences the standard deviations. The Serco value will be kept since there is no direct evidence of error.

The IRSN-96 result was removed since it is not an estimate but a range of values.

The average validated value with one standard deviation, including the IPPE result, is 12.17 ± 0.09 cm. The total 95 % level of confidence uncertainty is estimated as 0.30 cm, including effects of other uncertainties.

U(4)O₂ - Slab

This system is not sensitive to the nuclide density issue.

The mean value standard deviations are reduced by a factor less than two by bias correction from validation. The standard deviation is quite low and there are no large deviations from the average of the six major bias corrected values.

There are no other large discrepancies for this reference value.

The best estimate average validated value with one standard deviation, including the IPPE result, is 13.77 ± 0.07 cm. The total 95 % level of confidence uncertainty is estimated as 0.20 cm, including effects of other uncertainties.

U(3)O₂ - Slab

This system is not sensitive to the nuclide density issue.

The mean value standard deviations are reduced by a factor less than two by bias correction from validation. The IPPEABBN93 value is much lower than the other bias-corrected values and this influences the standard deviations. The CRISTAL value is low but not as low as the IPPE-ABBN93 value. The IPPE value will be kept since there is no direct evidence of error.

The IPPE-84 deviation is quite large and conservative for safety use as often is the case. The bias-corrected value from the Japanese handbook release 2 is also low.

The best estimate average validated value with one standard deviation, including the IPPE result, is 16.69 ± 0.10 cm. The total 95 % level of confidence uncertainty is estimated as 0.30 cm, including effects of other uncertainties.

U(100)O₂ - Concentration

This system is not sensitive to the nuclide density.

The mean values $\bar{c}_c$ and $\bar{c}_{bc}$ are not so different, but the standard deviation increases almost by a factor two due to bias corrections. That means that the validation certainly has not worked at all even though the standard deviation is quite low.

The IRSN-96 result was removed since it appears to concern 93.5 % and not 100 % by mass of ^{235}U .

The average validated value with one standard deviation, including the IPPE result, is $12.18 \pm 0.06 \text{ g/cm}^3$. Considering that other uncertainties are expected to be small, the total 95 % level of confidence uncertainty is estimated as 0.20 g/cm^3 .

U(20)O₂ - Concentration

This system is not sensitive to the nuclide density issue.

The mean values and are not so different, but the standard deviation increases due to bias corrections. That means that the validation has not worked, even though the standard deviation is quite low.

The average validated value with one standard deviation, including the IPPE result, is $64.0 \pm 0.2 \text{ g/cm}^3$. The total 95 % level of confidence uncertainty is estimated as 0.7 g/cm^3 , including effects of other uncertainties.

U(5)O₂ - Concentration

This system is not sensitive to the nuclide density issue.

The mean value standard deviations are not reduced much by bias corrections from validation. However, the standard deviation is small.

The average validated value with one standard deviation, including the IPPE result, is $285.6 \pm 0.7 \text{ g/cm}^3$. The total 95 % level of confidence uncertainty is estimated as 2.0 g/cm^3 , including effects of other uncertainties.

U(4)O₂ - Concentration

This system is not sensitive to the nuclide density issue.

The mean value standard deviation is almost not reduced at all by bias correction from validation. The standard deviation is low and there are no large deviations from the average of the six major bias corrected values.

There are no large discrepancies for this reference value.

The best estimate average validated value with one standard deviation, including the IPPE result, is $369.3 \pm 1.0 \text{ g/cm}^3$. The total 95 % level of confidence uncertainty is estimated as 3.0 g/cm^3 , including effects of other uncertainties.

U(3)O₂ - Concentration

This system is not sensitive to the nuclide density issue.

The mean value standard deviation is slightly increased by bias correction from validation. Since the standard deviation is low, the validation is still considered as successful.

The best estimate average validated value with one standard deviation, including the IPPE result, is $522.0 \pm 1.7 \text{ g/cm}^3$. The total 95 % level of confidence uncertainty is estimated as 5.0 g/cm^3 , including effects of other uncertainties.

U(100)O₂ - Moderation

This system is essentially the same as the concentration system. However, it is not sensitive to the nuclide density laws as the critical concentration is. The moderation parameter for an infinite system is not density dependent. If the different parameter values cover the whole range of moderations, from very dilute to crystal, then a check of corresponding densities obtained by different density laws would be revealing. Thus, since it is less complicated, it makes more sense to start with comparing critical moderations before starting comparing critical concentrations.

At this time, the best estimate of the critical concentration will be used to find the best estimate of the critical moderation. SCALE 5 is used for that. Using that moderation, different density laws can be compared.

The critical moderation corresponding to the best estimate critical concentration (12.18 g/cm^3) is an H/U value of 2137. The total 95 % level of confidence uncertainty is estimated as 34 (corresponds to a density change of 0.20 g/cm^3).

U(20)O₂ - Moderation

Determined in the same way as for U(100)O₂.

The critical moderation corresponding to the best estimate critical concentration (64.0 g/cm^3) is an H/U value of 409. The total 95 % level of confidence uncertainty is estimated as 5 (corresponds to a density change of 0.7 g/cm^3).

U(5)O₂ - Moderation

Determined in the same way as for U(100)O₂.

The critical moderation corresponding to the best estimate critical concentration (285.6 g/cm^3) is an H/U value of 89.63. The total 95 % level of confidence uncertainty is estimated as 0.67 (corresponds to a density change of 2.0 g/cm^3).

U(4)O₂ - Moderation

Determined in the same way as for U(100)O₂.

The critical moderation corresponding to the best estimate critical concentration (369.3 g/cm^3) is

an H/U value of 68.68. The total 95 % level of confidence uncertainty is estimated as 0.58 (corresponds to a density change of 3.0 g/cm³).

U(3)O₂ - Moderation

Determined in the same way as for U(100)O₂.

The critical moderation corresponding to the best estimate critical concentration (522.0 g/cm³) is an H/U value of 47.80. The total 95 % level of confidence uncertainty is estimated as 0.48 (corresponds to a density change of 5.0 g/cm³).

Uranyl nitrate – UNH or UO₂(NO₃)₂ + 6H₂O

U(100)NH - Mass

This system does not seem to be sensitive to the nuclide density issue. The material is well moderated. The geometry is not so sensitive to quadrature and mesh. The mean values and are not so different, but their standard deviations are. The bias correction based on the validation reduces the standard deviation by a factor of more than two, indicating that it really works.

The CRISTAL value is slightly lower, which is not unexpected (should be slightly conservative). The validated IPPE and Serco results agree well with the EMS results. There are no really large discrepancies. The IRSN-96 result was removed since it concerns 93.5 % and not 100 % by mass of ²³⁵U.

The average validated value with one standard deviation, including the IPPE result, is 826 ± 4 g ²³⁵U. Considering that other uncertainties are expected to be small, the total 95 % level of confidence uncertainty is estimated as 12 g ²³⁵U.

U(20)NH - Mass

This system does not seem to be sensitive to the nuclide density issue. The uranium concentration is below the solubility limit. The material is well moderated. The geometry is not so sensitive to quadrature and mesh. The mean values $\bar{m}_c$ and $\bar{m}_{bc}$ are not so different, but their standard deviations are. The bias correction based on the validation reduces the standard deviation by a factor of almost two, indicating that the validation works. The only deviating value is that from IPPE-ABBN93 and that deviation is not so worrying.

The CRISTAL value is slightly lower, which is not unexpected (should be slightly conservative). This was also the case for U(20)O₂ so there is no reason to suspect that the nuclide density laws are causing the differences. The validated IPPE and Serco results agree well with the EMS results.

The average validated value with one standard deviation, including the IPPE result, is 6.13 ± 0.04 kg U. Considering that other uncertainties are expected to be small, the total 95 % level of confidence uncertainty is estimated as 0.12 kg U.

U(5)NH - Mass

This system is sensitive to the nuclide density issue. The density is above the solubility limit. The mean values $\bar{m}_c$ and $\bar{m}_{bc}$ are quite different and so are their standard deviations. The bias correction based on the validation reduces the standard deviation by a factor of more than two, indicating that the validation works well.

The only deviating value in the group of “major six” is that from IPPE-ABBN93 and that deviation is now large. It completely dominates the uncertainty of the best estimate value. This method leads to low values for many other systems involving low-enriched uranium but this is not revealed properly by the validation. It is tempting to remove it from the best estimate evaluation but a justification is required. .

That the validation works really well with all except the IPPE methods is apparent from the very large and successful bias correction for EMS-M5-J32. It goes from a calculated value of 73.8 to a bias corrected value of 78.1 kg uranium.

The CRISTAL value is significantly lower, not expected (until consideration of density effects) since it was identical to the “major 6” mean for U(5)O₂ mass. The validated Serco result agrees quite well with the EMS results but is high before bias correction. It was relatively lower for U(5)O₂ mass. From the comparison of nuclide density methods, it appears that IPPE over-predicts the density (smaller critical mass) while it is under-predicted by Serco (larger critical mass). How much the critical mass would be influenced by these deviations has not been determined, but the deviating results could be explained by this.

The average validated value with one standard deviation, including the IPPE result, is 78.68 ± 1.09 kg U. However, all the major 6 values are rejected because the density methods are not applicable. The IRSN CRISTAL value of 75.4 kg uranium is used as a best estimate, based on indirect validation for the U(5)O₂ mass system. The total 95 % level of confidence uncertainty is estimated as 3.00 kg U.

U(4)NH - Mass

This system is sensitive to the nuclide density issue. The reference system density is now 900 g/l. The mean values $\bar{m}_c$ and $\bar{m}_{bc}$ are not so different but so are their standard deviations. The bias correction based on the validation reduces the standard deviation by a factor of more than two, indicating that the validation works well.

There are two deviating values in the group of “major six”. The value from IPPE-ABBN93 is low and the Serco value is a little high. The IRSN CRISTAL value is close to that from IPPE. These deviations may be explained in a similar way as for the U(5)NH mass system. The IPPE method for density calculations is better for higher uranium densities, the only reasonable method in addition to the new CRISTAL extended isopiestic law.

The cross-section validation works really well with most methods. This is again apparent from the large and successful bias correction for EMS-M5-J32.

The average validated value with one standard deviation, including the IPPE result, is $149.18 \pm$

2.29 kg U. However, all the major 6 values are rejected because the density methods are not applicable. The IRSN CRISTAL value of 144.2 kg uranium is used as a best estimate, based on indirect validation for UO₂ mass systems. It is also well supported by the IPPE value which is credible in this density range. The total 95 % level of confidence uncertainty is estimated as 7.00 kg U.

U(3)NH - Mass

This system is sensitive to the nuclide density issue. The density is 1150 g/l, quite close to the crystal density. The mean values $\bar{m}_c$ and $\bar{m}_{bc}$ are not very different but so are their standard deviations. The bias correction based on the validation reduces the standard deviation by a factor two, indicating that the validation works well.

There is one deviating value in the group of “major six”. The value from IPPE-ABBN93 is low by 5 %. The IRSN CRISTAL value is close to that from IPPE. As is now clear from the evaluation of U(5)NH and U(4)NH mass systems, these are the only credible results.

The cross-section validation works quite well with most methods. See the large but not sufficient bias correction for EMS-M5-J32.

The average validated value with one standard deviation, including the IPPE result, is 495.7 ± 13.4 kg U. All the major 6 values are rejected because the density methods are not applicable. The average of IRSN CRISTAL and IPPE-ABBN93 values of 469 kg uranium is used as a best estimate. The total 95 % level of confidence uncertainty is estimated as 40.0 kg U.

U(100)NH - Volume

This system is sensitive to the nuclide density issue. The density is well below the solubility limit. The mean values $\bar{v}_c$ and $\bar{v}_{bc}$ are not very different, nor are their standard deviations. This indicates that the validation has not worked well.

There is one deviating value in the group of “major six”. The value from IPPE-ABBN93 is low by 3 %. The IRSN CRISTAL value is even lower than that from IPPE. The CRISTAL value was lower also for U(100)O₂ and some of the difference could be because of cross-sections. However, the isopiestic law seems well validated and agrees with the IPPE density method.

The average validated value with one standard deviation, including the IPPE result, is 6.843 ± 0.123 litres. Due to lower values from CRISTAL and from IPPE, a bias-correction of -0.14 litres for the density methods is introduced. The best-estimate value becomes 6.703 litres. The total 95 % level of confidence uncertainty is estimated as 0.400 litres.

U(20)NH - Volume

This system is sensitive to the nuclide density (580 g/l) issue. This is close to the solubility limit. The mean values $\bar{v}_c$ and $\bar{v}_{bc}$ are not very different, nor are their standard deviations. This indicates that the validation has not worked well.

There are two deviating values in the group of “major six”. The value from IPPE-ABBN93 is low

by 4 % and the Serco MONK value is high by 3 %. This appears to be consistent with the comparison of density methods.

The IRSN CRISTAL value is closer to that from IPPE but not as low. It is not unusual for CRISTAL to give slightly conservative results for this type of system.

The average validated value with one standard deviation, including the IPPE result, is 16.46 ± 0.38 litres. Both the Serco MONK and the IPPE results are excluded due to density methods. The CRISTAL result is used to introduce a negative bias correction to a best estimate of 16.3 litres. The total 95 % level of confidence uncertainty is estimated as 1.20 litres.

U(5)NH - Volume

This system is sensitive to the nuclide density (1050 g/l) issue. The mean values $\bar{v}_c$ and $\bar{v}_{bc}$ are not very different, but their standard deviations are, even though they differ by a factor less than two. This indicates that the validation may have worked for some methods.

As in the previous system, there are two deviating values in the group of “major six”. The value from IPPE-ABBN93 is low by 6 % and the Serco MONK value is high by 3 %. The IRSN CRISTAL value is close to that from IPPE. This is consistent with previous results.

The average validated value with one standard deviation, including the IPPE result, is 86.12 ± 2.80 litres. Only the IPPE result of the major 6 is credible. The others are rejected because of the density methods. The IRSN and IPPE values are averaged to get a best estimate of 80.7 litres. The total 95 % level of confidence uncertainty is estimated as 8.00 litres.

U(4)NH - Volume

This system is sensitive to the nuclide density (1140 g/l) issue. The mean values $\bar{v}_c$ and $\bar{v}_{bc}$ are not very different, neither are their standard deviations. This indicates that the validation is not so successful.

As in the previous system, there are two deviating values in the group of “major six”. The value from IPPE-ABBN93 is low by 3.5 % and the Serco MONK value is high by 6 %. The IRSN CRISTAL value is again close to that from IPPE. This is consistent with previous results.

The average validated value with one standard deviation, including the IPPE result, is 142.59 ± 5.11 litres. Only the IPPE-ABBN93 and the IRSN CRISTAL results are credible. Other uncertainties are significant but this is probably covered by the large extra standard deviation. The IRSN and IPPE values are averaged to get a best estimate of 136 litres. The total 95 % level of confidence uncertainty is estimated as 15 litres.

U(3)NH - Volume

This system is very sensitive to the nuclide density issue (crystal density, 1330 g/l). The mean values $\bar{v}_c$ and $\bar{v}_{bc}$ are not very different, but the standard deviation is reduced almost by a factor two by

bias corrections. This indicates that the validation is quite successful for some systems.

There is one strongly deviating value in the group of “major six”. The value from IPPE-ABBN93 is low by 10 %. The IRSN CRISTAL value is very close to that from IPPE. This is consistent with previous results and with the comparison of density methods. These two are the only credible values.

The average “major 6” validated value with one standard deviation, including the IPPE result, is 411.4 ± 16.8 litres. All values, except the IPPE value, are rejected. The IRSN and IPPE values are averaged to get a best estimate of 370 litres. The total 95 % level of confidence uncertainty is estimated as 50.0 litres.

U(100)NH – Cylinder diameter

This system is sensitive to the nuclide density (380 g/l) issue. The mean value $\bar{\Phi}_c$ and $\bar{\Phi}_{bc}$ and their standard deviations are not very different. Considering the large standard deviations, this indicates that the validation is not very successful.

There are two deviating values in the group of “major six”. The value from IPPE-ABBN93 is low by 2 % and the Serco value is 1.3 % high. The IRSN CRISTAL value is very close to that from IPPE. Looking at the comparison of densities, these values are consistent with those results.

The average “major 6” validated value with one standard deviation, including the IPPE result, is 15.10 ± 0.16 cm. The MONK result is rejected due to density biases. The IPPE result is likely to slightly under-predict the diameter due to density biases. A best-estimate value of 14.95 cm appears reasonable. The total 95 % level of confidence uncertainty is estimated as 0.5 cm.

U(20)NH – Cylinder diameter

This system is sensitive to the nuclide density (620 g/l) issue. The mean values $\bar{\Phi}_c$ and $\bar{\Phi}_{bc}$ and their standard deviations are not very different. Considering the large standard deviations, this indicates that the validation is not very successful.

There are two deviating values in the group of “major six”. The value from IPPE-ABBN93 is low by 2 % and the Serco value is 0.6 % high. The IRSN CRISTAL value is close to that from IPPE. According to the density comparisons, the Serco value should be high and the IPPE value low.

The average “major 6” validated value with one standard deviation, including the IPPE result, is 21.09 ± 0.13 cm. The MONK result is rejected. A best-estimate value of 21.0 cm appears reasonable. The total 95 % level of confidence uncertainty is estimated as 0.4 cm.

U(5)NH – Cylinder diameter

This system is sensitive to the nuclide density issue (1060 g/l). The mean values $\bar{\Phi}_c$ and $\bar{\Phi}_{bc}$ and their standard deviations are not very different. Considering the large standard deviations, this indicates that the validation is not very successful.

There are two deviating values in the group of “major six”. The value from IPPE-ABBN93 is low

by 3 % and the Serco value is 1.5 % high. The IRSN CRISTAL value is close to that from IPPE. This is the same experience as before.

The average “major 6” validated value with one standard deviation, including the IPPE result, is 38.96 ± 0.54 cm. All values, except that from IPPE, are rejected. Together with the CRISTAL value a best-estimate value of 37.85 cm based on the average appears reasonable. The total 95 % level of confidence uncertainty is estimated as 1.6 cm.

U(4)NH – Cylinder diameter

This system is sensitive to the nuclide density (1140 g/l) issue. The mean values $\bar{\Phi}_c$ and $\bar{\Phi}_{bc}$ and their standard deviations are not very different. Considering the large standard deviations, this indicates that the validation is not very successful.

There are two deviating values in the group of “major six”. The value from IPPE-ABBN93 is low by 2 % and the Serco value is 1.2 % high. The IRSN CRISTAL value is close to that from IPPE. This is consistent with results for other UNH systems.

The average “major 6” validated value with one standard deviation, including the IPPE result, is 46.66 ± 0.56 cm. All values, except that from IPPE, are rejected. Together with the CRISTAL value a best-estimate value of 45.4 cm based on the average appears reasonable. The total 95 % level of confidence uncertainty is estimated as 1.7 cm.

U(3)NH – Cylinder diameter

This system is very sensitive to the nuclide density (1330 g/l; crystal density) issue. The mean values and their standard deviations are not very different. Considering the large standard deviations, this indicates that the validation is not very successful for some systems. However, sometimes it works quite well. The EMS-M5-J32 value deviation is almost 5 % before bias correction and only 1 % after.

There is one deviating value in the group of “major six”. The value from IPPE-ABBN93 is low by almost 4 %. The IRSN CRISTAL value is close to that from IPPE. The last two values are the only credible.

The average “major 6” validated value with one standard deviation, including the IPPE result, is 67.32 ± 1.18 cm. All “major” values, except that from IPPE, are rejected. Together with the CRISTAL value a best-estimate value of 64.8 cm based on the average appears reasonable. The total 95 % level of confidence uncertainty is estimated as 3.5 cm.

U(100)NH – Slab thickness

This system is sensitive to the nuclide density (500 g/l) issue. The mean values $\bar{t}_c$ and $\bar{t}_{bc}$ are not very different. The standard deviation is reduced significantly (about 30 %) after the bias corrections. This indicates that the validation is not too successful.

There is one deviating group of values within the group of “major six”. The IRSN CRISTAL value is now very close to the best estimate values. The IPPE-ABBN93 value is significantly lower than the best estimate value as well as the CRISTAL value. The IPPE values should be lower due to a bias caused by the density method.

Initially there was a significant difference between SCALE and MCNP results. There was a correlated error in all MCNP results for this slab system; the thermal scattering data (MT card in MCNP) were commented out for the fast UO₂ systems and were not removed for the thermal U(100)NH slabs. This is a typical error when many calculations are carried out in a short time.

The German Handbook value 4.4 cm contributed to the study is low. However, a look at the Handbook figure shows that the proper value should be about 5.35 cm.

The average “major 6” validated value with one standard deviation, including the IPPE result, is 5.443 ± 0.0073 cm. To consider density biases, the IPPE result is rejected and the IRSN CRISTAL value is considered instead. The best-estimate value then becomes 5.457 cm. With such a change the standard deviation due to validation would also be significantly reduced. The total 95 % level of confidence uncertainty is still estimated as 0.35 cm.

U(20)NH – Slab thickness

This system is sensitive to the nuclide density (700 g/l) issue. The mean values $\bar{t}_c$ and $\bar{t}_{bc}$ are not very different. The standard deviation is dominated by the IPPE-ABBN93 value. The validation appears to be successful for the EMS methods.

There is one deviating value within the group of “major six”. The IPPE-ABBN93 value is lower by about 1.7 %. The density method used by IPPE seems to be conservative in this middle density region, the water presence is over-estimated.

The average “major 6” validated value with one standard deviation, including the IPPE result, is 9.289 ± 0.083 cm. The solubility limit is exceeded, but the error due to this is not expected to change the conclusions significantly. Other uncertainties are significant but this is probably covered by the large extra standard deviation. The total 95 % level of confidence uncertainty is estimated as 0.25 cm.

U(5)NH – Slab thickness

This system is sensitive to the nuclide density (1100 g/l) issue. The mean values $\bar{t}_c$ and $\bar{t}_{bc}$ are not very different. The standard deviation is dominated by the IPPE-ABBN93 value. The cross-section validation appears to be successful for the EMS methods.

There are two deviating values within the group of “major six”. The IPPE-ABBN93 value is lower by about 1.9 % and the Serco MONK value is higher by about 1.3 %. The CRISTAL value is close to the IPPE-ABBN93 value. This is similar as for other low-enriched UNH systems.

The average “major 6” validated value with one standard deviation, including the IPPE result, is 20.468 ± 0.221 cm. All “major” values, except that from IPPE, are rejected. Together with the CRISTAL value a best-estimate value of 20.04 cm based on the average appears reasonable. The total

95 % level of confidence uncertainty is estimated as 0.70 cm.

U(4)NH – Slab thickness

This system is sensitive to the nuclide density (1180 g/l) issue. The mean values $\bar{t}_c$ and $\bar{t}_{bc}$ are not very different. The standard deviation is dominated by the IPPE-ABBN93 value. The validation appears to be successful for the EMS methods.

There are two deviating values within the group of “major six”. The IPPE-ABBN93 value is lower by about 2.0 % and the Serco MONK value is higher by about 1.6 %. The CRISTAL value is close to the IPPE-ABBN93 value. This is similar as for other low-enriched UNH systems.

The average “major 6” validated value with one standard deviation, including the IPPE result, is 25.614 ± 0.284 cm. All “major” values, except that from IPPE, are rejected. Together with the CRISTAL value a best-estimate value of 25.05 cm based on the average appears reasonable. The total 95 % level of confidence uncertainty is estimated as 0.85 cm.

U(3)NH – Slab thickness

This system is sensitive to the nuclide density (1330 g/l; crystal density) issue. The mean values $\bar{t}_c$ and $\bar{t}_{bc}$ are quite different and the standard deviation is large. The standard deviation is dominated by the IPPE-ABBN93 value. The validation appears to be successful for the EMS methods.

The IPPE-ABBN93 value is lower by about 3.6 %. The CRISTAL and the Japanese handbook version 2 values are close to the IPPE-ABBN93 value. These values are credible.

The average “major 6” validated value with one standard deviation, including the IPPE result, is 38.962 ± 0.727 cm. All “major” values, except that from IPPE, are rejected. Together with the CRISTAL value a best-estimate value of 37.5 cm based on the average appears reasonable. The total 95 % level of confidence uncertainty is estimated as 2.2 cm.

U(100)NH – Concentration

This system is sensitive to the nuclide density (12.3 g/l) issue. The mean values $\bar{c}_c$ and $\bar{c}_{bc}$ are not so different but the bias corrected standard deviation is reduced to half. This indicates that the validation is successful.

There is one deviating value within the group of “major six”. The Serco value before bias correction is 5.8 % high. After the correction it is only 2.5 % high.

The average “major 6” validated value with one standard deviation, including the IPPE result, is 12.288 ± 0.163 g/cm³. The MONK result is rejected without any other cause that it is not consistent with other results, including MONK results for UO₂. The best estimate value is then reduced to 12.226 g/cm³. Other uncertainties are significant but this is probably covered by the large extra standard deviation. The total 95 % level of confidence uncertainty is estimated as 0.5 g/cm³.

U(20)NH – Concentration

This system is sensitive to the nuclide density (64.8 g/l) issue. The mean values $\bar{c}_c$ and $\bar{c}_{bc}$ are not so different but the bias corrected standard deviation is larger than the uncorrected standard deviation. This indicates that the validation is not adequate. No specific reason has been identified yet.

The average “major 6” validated value with one standard deviation, including the IPPE result, is $64.840 \pm 0.357 \text{ g/cm}^3$. Other uncertainties are significant but this is probably covered by the large extra standard deviation. The total 95 % level of confidence uncertainty is estimated as 1.0 g/cm^3 .

U(5)NH – Concentration

This system is sensitive to the nuclide density (311 g/l) issue. The mean values $\bar{c}_c$ and $\bar{c}_{bc}$ are not so different and this is true for their standard deviations as well. This could indicate that the validation is not adequate but in this case it is also due to small variations.

The average “major 6” validated value with one standard deviation, including the IPPE result, is $311.4 \pm 1.8 \text{ g/cm}^3$. Other uncertainties are significant but this is probably covered by the large extra standard deviation. The total 95 % level of confidence uncertainty is estimated as 5.3 g/cm^3 .

U(4)NH – Concentration

This system is sensitive to the nuclide density (416 g/l) issue. The mean values $\bar{c}_c$ and $\bar{c}_{bc}$ are not so different and this true for their standard deviations as well. This could indicate that the validation is not adequate but in this case it is also due to small variations.

The average “major 6” validated value with one standard deviation, including the IPPE result, is $415.5 \pm 3.2 \text{ g/cm}^3$. Other uncertainties are significant but this is probably covered by the large extra standard deviation. The total 95 % level of confidence uncertainty is estimated as 10.0 g/cm^3 .

U(3)NH – Concentration

This system is sensitive to the nuclide density (629 g/l) issue. The mean values $\bar{c}_c$ and $\bar{c}_{bc}$ are not so different and this is true for their standard deviations as well. This could indicate that the validation is not adequate but in this case it is also due to small variations.

The IPPE-ABBN93 value seems high and the Serco value low. This is opposite to the situation for geometry-limited systems. However, this is consistent from a physics point of view. For those systems additional should reduce the critical value (smaller system). For concentration, more water at a fixed density increases absorption in an over-moderated system. The density trends are thus confirmed.

The average “major 6” validated value with one standard deviation, including the IPPE result, is $628.9 \pm 6.8 \text{ g/cm}^3$. Other uncertainties are significant but this is probably covered by the large extra standard deviation. The total 95 % level of confidence uncertainty is estimated as 20.0 g/cm^3 .

U(100)NH – Moderation

This parameter is essentially the same as the concentration parameter. However, it is not sensitive

to the nuclide density laws as the critical concentration is. The moderation parameter for an infinite system is not density dependent. If the different parameter values cover the whole range of moderations, from very dilute to crystal, then a check of corresponding densities obtained by different density laws would be revealing. Thus, since it is less complicated, it makes more sense to start with comparing critical moderations before starting comparing critical concentrations. This was done by the Expert Group.

Even if the density method is very wrong, the computer code systems should find the correct moderation ratio. This assumes that the H/U ratio is based on what is the actual input to the code and can be verified by the output. An equation or other, separate conversion of concentration to H/U ratio introduces error sources.

At this time, the best estimate of the critical concentration will be used to find the best estimate of the critical moderation. SCALE 5 is used for that. Using that moderation, different density laws can be compared.

The critical moderation corresponding to the best estimate critical concentration (12.288 g/cm^3) is an H/U value of 2109. The total 95 % level of confidence uncertainty is estimated as 83 (corresponds to a density change of 0.50 g/cm^3).

U(20)NH – Moderation

The average “major 6” validated value with one standard deviation, including the IPPE result, is an H/U value of 397.1. The total 95 % level of confidence uncertainty is estimated as 6.2.

U(5)NH – Moderation

The average “major 6” validated value with one standard deviation, including the IPPE result, is an H/U value of 76.22. The total 95 % level of confidence uncertainty is estimated as 1.41.

U(4)NH – Moderation

The average “major 6” validated value with one standard deviation, including the IPPE result, is an H/U value of 55.07. The total 95 % level of confidence uncertainty is estimated as 1.49.

U(3)NH – Moderation

The average “major 6” validated value with one standard deviation, including the IPPE result, is an H/U value of 33.64. The total 95 % level of confidence uncertainty is estimated as 1.28.

Plutonium dioxide – PuO₂

Pu(100)O₂ - Mass

This system does not seem to be sensitive to the nuclide density issue. The material is well moderated. The mean values $\bar{m}_c$ and $\bar{m}_{bc}$ are quite different due to large bias corrections. The standard

deviation is reduced dramatically, by a factor larger than seven, by the corrections. This is what should be expected from high-quality validation but has not been seen so often yet. The standard deviation of the “major 6” bias corrected values is not as small and does not improve by the correction. This means that the larger group is dominated by EMS values and that the different validation input models (IPPE) or even different selection of benchmarks (Serco) are not consistent with those of EMS. This is also seen with most applications of low-enriched uranium.

The IPPE-84 value which is almost always very low (conservative) for uranium systems is now very high (non-conservative); about 12 %. The bias correction for the old EMS SCALE 4 value (based on ORNL validation) is too high, over-estimating the critical mass by 4 %.

The average validated value with one standard deviation, including the IPPE result, is 510 ± 6 g ^{239}Pu . The total 95 % level of confidence uncertainty is estimated as 18 g ^{239}Pu .

Pu(95/5)O₂ - Mass

This system does not seem to be sensitive to the nuclide density issue. The isotopic distribution influence is very small. The material is well moderated. The mean values $\bar{m}_c$ and $\bar{m}_{bc}$ are quite different due to large bias corrections. The standard deviation is reduced significantly, by a factor almost three, by the corrections. This is similar to what was seen for Pu(100)O₂ where the initial spread was larger, giving an even more impressive improvement.

The average validated value with one standard deviation, including the IPPE result, is 621 ± 6 g of Pu. The total 95 % level of confidence uncertainty is estimated as 18 g of Pu.

Pu(80/10/10)O₂ - Mass

This system does not seem to be sensitive to the nuclide density issue. The isotopic distribution influence is small. The material is well moderated. The mean values $\bar{m}_c$ and $\bar{m}_{bc}$ are quite different due to large bias corrections. The standard deviation is reduced by a factor less than two by the corrections. This is less than what was seen for Pu(100)O₂ where the initial spread was larger, and the standard deviation is not as small.

A difference from the uranium evaluations is that the influence of the actinide isotopic distribution was not included in the validation. Another difference is that no IPPE-ABBN93 value was obtained for this system.

The Serco bias correction moves the value from average to about 3 % low.

The average validated value with one standard deviation is 686 ± 12 g of Pu. The total 95 % level of confidence uncertainty is estimated as 36 g of Pu.

Pu(90/10)O₂ - Mass

This system does not seem to be sensitive to the nuclide density issue. The isotopic distribution influence is small. The material is well moderated. The mean values $\bar{m}_c$ and $\bar{m}_{bc}$ are quite different due

to large bias corrections. The standard deviation is reduced by a factor more than two by the corrections.

The Serco bias correction moves the value from average to about 2 % low. The CRISTAL value is a bit lower than the bias corrected average. This appears to be the case for many plutonium systems.

The average validated value with one standard deviation, including the IPPE result, is 754 ± 9 g of Pu. The total 95 % level of confidence uncertainty is estimated as 27 g of Pu.

Pu(80/15/5)O₂ - Mass

This system does not seem to be sensitive to the nuclide density issue. The isotopic distribution influence is small. The material is well moderated. The mean values $\bar{m}_c$ and $\bar{m}_{bc}$ are quite different due to large bias corrections. The standard deviation is reduced by a factor two by the corrections.

There is no IPPE/ABBN93 value for this system. The Serco bias correction moves the value from average to about 2 % low. The CRISTAL value is a bit lower than the corrected average.

The average validated value with one standard deviation is 874 ± 14 g of Pu. The total 95 % level of confidence uncertainty is estimated as 42 g of Pu.

Pu(71/17/11/1)O₂ - Mass

This system does not seem to be sensitive to the nuclide density issue. The isotopic distribution influence is small. The material is well moderated. The mean values $\bar{m}_c$ and $\bar{m}_{bc}$ are quite different due to large bias corrections. The standard deviation is reduced by a factor less than two by the corrections.

There is no IPPE/ABBN93 value for this system. The Serco bias correction moves the value from average to about 2.5 % low.

The average validated value with one standard deviation is 907 ± 17 g of Pu. The total 95 % level of confidence uncertainty is estimated as 50 g of Pu.

Pu(100)O₂ - Volume

This system does not seem to be sensitive to the nuclide density issue. The material is not moderated. The mean values $\bar{m}_c$ and $\bar{m}_{bc}$ are quite similar. The standard deviation is reduced by a factor slightly less than two by the corrections.

The SCALE 27- and 44-group libraries were not developed or intended for this type of fast system. This is probably why the bias corrections are not sufficient.

The average validated value for the “major 6” with one standard deviation is 1.151 ± 0.011 litres. The total 95 % level of confidence uncertainty is estimated as 0.033 litres.

Pu(95/5)O₂ - Volume

This system does not seem to be sensitive to the nuclide density issue. The material is not moderated. The mean values $\bar{m}_c$ and $\bar{m}_{bc}$ are similar. The standard deviation is reduced by a factor less than two by the corrections.

The average validated value with one standard deviation is 1.236 ± 0.013 litres. The total 95 % level of confidence uncertainty is estimated as 0.040 litres.

Pu(80/10/10)O₂ - Volume

This system is somewhat sensitive to the nuclide density issue. The plutonium isotopic distribution reduces the theoretical density very slightly, influencing the leakage. The material is not moderated. The mean values $\bar{m}_c$ and $\bar{m}_{bc}$ are similar. The standard deviation is reduced by a factor less than two by the corrections.

The bias for the plutonium distribution 71/17/11/1 is -0.005. It was not determined for the current distribution but is set to -0.002.

There is no IPPE-ABBN93 value for this system.

The average “major 5” validated value with one standard deviation is 1.286 ± 0.014 litres. This is bias corrected to 1.288 litres, due to the reduced density. The total 95 % level of confidence uncertainty is estimated as 0.042 litres.

Pu(90/10)O₂ - Volume

This system does not seem to be sensitive to the nuclide density issue. The material is not moderated. The mean values $\bar{m}_c$ and $\bar{m}_{bc}$ are similar. The standard deviation is reduced by a factor less than two by the corrections.

The average “major 6” validated value with one standard deviation is 1.307 ± 0.013 litres. The total 95 % level of confidence uncertainty is estimated as 0.040 litres.

Pu(80/15/5)O₂ - Volume

This system is somewhat sensitive to the nuclide density issue. The plutonium isotopic distribution reduces the theoretical density; increasing the leakage. The material is not moderated. The mean values $\bar{m}_c$ and $\bar{m}_{bc}$ are similar. The standard deviation is reduced by a factor less than two by the corrections.

The bias caused by the reduced theoretical density was determined for the distribution 71/17/11/1 using SCALE 5, XSDRNPM and the 238-group library. The result is -0.005 litres. For the current distribution, the bias is smaller. It is set to 0.001 litres.

Similar observations as for the previous system are made. There is no IPPE-ABBN93 value.

The average “major 5” validated value with one standard deviation is 1.366 ± 0.014 litres. The additional bias correction due to the reduced density is 0.001 litres, making the best estimate value 1.367. The total 95 % level of confidence uncertainty is estimated as 0.042 litres.

Pu(71/17/11/1)O₂ - Volume

This system is somewhat sensitive to the nuclide density issue. The plutonium isotopic distribution

reduces the theoretical density; increasing the leakage. The material is not moderated. The mean values $\bar{m}_c$ and $\bar{m}_{bc}$ are similar. The standard deviation is reduced by a factor less than two by the corrections.

The bias caused by the reduced theoretical density was determined using SCALE 5, XSDRNPM and the 238-group library. The result is -0.005 litres.

The same observations as for the previous system are made. There is no IPPE-ABBN93 value.

The average “major 5” validated value with one standard deviation is 1.408 ± 0.018 litres. The additional bias correction due to the reduced density is 0.005, making the best estimate value 1.413. The total 95 % level of confidence uncertainty is estimated as 0.054 litres.

Pu(100)O₂ - Cylinder diameter

This system does not seem to be sensitive to the nuclide density issue. The material is not moderated. The mean values $\bar{m}_c$ and $\bar{m}_{bc}$ are quite similar. The standard deviation is reduced by a factor slightly less than two by the corrections.

Similar conclusions as for the volume can be drawn. The CRISTAL value is slightly higher than the “major 6” average.

The average validated value for the “major 6” with one standard deviation is 7.683 ± 0.031 cm. The total 95 % level of confidence uncertainty is estimated as 0.10 cm.

Pu(95/5)O₂ - Cylinder diameter

This system does not seem to be sensitive to the nuclide density issue. The material is not moderated. The mean values $\bar{m}_c$ and $\bar{m}_{bc}$ are quite similar. The standard deviation is reduced by a factor slightly less than two by the corrections.

Similar conclusions as for the volume can be drawn. The CRISTAL value is again slightly higher than the “major 6” average.

The average validated value for the “major 6” with one standard deviation is 7.948 ± 0.035 cm. The total 95 % level of confidence uncertainty is estimated as 0.11 cm.

Pu(80/10/10)O₂ - Cylinder diameter

This system is somewhat sensitive to the nuclide density issue. The plutonium isotopic distribution reduces the theoretical density very slightly, influencing the leakage. The material is not moderated. The mean values $\bar{m}_c$ and $\bar{m}_{bc}$ are similar. The standard deviation is reduced by a factor less than two by the corrections.

The bias for the plutonium distribution 71/17/11/1 was assumed to be -0.016 cm. It will be smaller for the current distribution. It is set to -0.006 cm.

There is no IPPE-ABBN93 value for this system. Similar conclusions as for the volume can be

drawn. The CRISTAL value is consistently slightly higher than the “major 5” average.

The average “major 5” validated value with one standard deviation is 8.036 ± 0.039 cm. This is bias corrected to 8.042 cm, due to the reduced density. The total 95 % level of confidence uncertainty is estimated as 0.12 cm.

Pu(90/10)O₂ - Cylinder diameter

This system does not seem to be sensitive to the nuclide density issue. The material is not moderated. The mean values $\bar{m}_c$ and $\bar{m}_{bc}$ are similar. The standard deviation is reduced by a factor less than two by the corrections.

Similar conclusions as for the volume can be drawn. The CRISTAL value is slightly (about 1 %) higher than the “major 6” average.

The average “major 6” validated value with one standard deviation is 8.145 ± 0.033 cm. The total 95 % level of confidence uncertainty is estimated as 0.10 cm.

Pu(80/15/5)O₂ - Cylinder diameter

This system is somewhat sensitive to the nuclide density issue. The plutonium isotopic distribution reduces the theoretical density, increasing the leakage. The material is not moderated. The mean values $\bar{m}_c$ and $\bar{m}_{bc}$ are similar. The standard deviation is reduced by a factor less than two by the corrections.

The bias for the plutonium distribution 71/17/11/1 was assumed to be -0.016 cm. It will be smaller for the current distribution. It is set to -0.004 cm.

There is no IPPE-ABBN93 value for this system. Similar conclusions as for the volume can be drawn. The CRISTAL value is slightly higher than the “major 5” average.

The average “major 5” validated value with one standard deviation is 8.266 ± 0.038 cm. The additional bias correction due to the reduced density is 0.004 cm, making the best estimate value 8.270 cm. The total 95 % level of confidence uncertainty is estimated as 0.120 cm.

Pu(71/17/11/1)O₂ - Cylinder diameter

This system is somewhat sensitive to the nuclide density issue. The plutonium isotopic distribution reduces the theoretical density, increasing the leakage. The material is not moderated. The mean values $\bar{m}_c$ and $\bar{m}_{bc}$ are similar. The standard deviation is reduced by a factor less than two by the corrections.

The bias for the plutonium distribution 71/17/11/1 and the volume parameter is -0.005 litres (0.5 %). It was not determined for the current system but is set to 0.2 % (one dimension rather than three as for volume) giving -0.016 cm.

The same observations as for the previous system are made. There is no IPPE-ABBN93 value. The CRISTAL value is slightly higher than the “major 5” average. This is very consistent with previous plutonium cylinder values. The consistency in the differences is positive information.

The results for SCALE with the 27- and 44-group libraries may not be easy to correct for biases since the libraries are not designed to give all the information required for good results with fast systems. The 238-group library seems to be quite good.

The average “major 5” validated value with one standard deviation is 8.350 ± 0.041 cm. The additional bias correction due to the reduced density is 0.016 cm, making the best estimate value 8.366 cm. The total 95 % level of confidence uncertainty is estimated as 0.130 cm.

Pu(100)O₂ - Slab thickness

This system does not seem to be sensitive to the nuclide density issue. The material is not moderated. The mean values $\bar{m}_c$ and $\bar{m}_{bc}$ are quite similar. The standard deviation is reduced by a factor slightly less than two by the corrections.

Similar conclusions as for the volume and cylinder diameter can be drawn. The CRISTAL value is higher (about 3 %) than the “major 6” average. This is within the 95 % level of confidence.

The average validated value for the “major 6” with one standard deviation is 1.721 ± 0.018 cm. The total 95 % level of confidence uncertainty is estimated as 0.060 cm.

Pu(95/5)O₂ - Slab thickness

This system does not seem to be sensitive to the nuclide density issue. The material is not moderated. The mean values $\bar{m}_c$ and $\bar{m}_{bc}$ are quite similar. The standard deviation is reduced by a factor slightly less than two by the corrections.

Similar conclusions as for the volume can be drawn. The CRISTAL value is again about 3 % higher than the “major 6” average.

The average validated value for the “major 6” with one standard deviation is 1.934 ± 0.023 cm. The total 95 % level of confidence uncertainty is estimated as 0.070 cm.

Pu(80/10/10)O₂ - Slab thickness

This system is somewhat sensitive to the nuclide density issue. The plutonium isotopic distribution reduces the theoretical density very slightly, influencing the leakage. The material is not moderated. The mean values $\bar{m}_c$ and $\bar{m}_{bc}$ are similar. The standard deviation is reduced by a factor less than two by the corrections.

The bias for the plutonium distribution 71/17/11/1 was assumed to be -0.004 cm. It will be smaller for the current distribution. It is set to -0.002 cm.

There is no IPPE-ABBN93 value for this system. Similar conclusions as for the volume can be drawn. The CRISTAL value is 2.5 % higher than the “major 5” average.

The average “major 5” validated value with one standard deviation is 1.910 ± 0.023 cm. This is

bias corrected to 1.912 cm, due to the reduced density. The total 95 % level of confidence uncertainty is estimated as 0.070 cm.

Pu(90/10)O₂ - Slab thickness

This system does not seem to be sensitive to the nuclide density issue. The material is not moderated. The mean values $\bar{m}_c$ and $\bar{m}_{bc}$ are similar. The standard deviation is reduced by a factor less than two by the corrections.

Similar conclusions as for the volume can be drawn. The CRISTAL value is about 3 % higher than the “major 6” average.

The average “major 6” validated value with one standard deviation is 2.066 ± 0.025 cm. The total 95 % level of confidence uncertainty is estimated as 0.080 cm.

Pu(80/15/5)O₂ - Slab thickness

This system is somewhat sensitive to the nuclide density issue. The plutonium isotopic distribution reduces the theoretical density, increasing the leakage... The material is not moderated. The mean values $\bar{m}_c$ and $\bar{m}_{bc}$ are similar. The standard deviation is reduced by a factor less than two by the corrections.

The bias for the plutonium distribution 71/17/11/1 was assumed to be -0.004 cm. It will be smaller for the current distribution. It is set to -0.001 cm.

There is no IPPE-ABBN93 value for this system. Similar conclusions as for the volume can be drawn. The CRISTAL value is consistently 3 % higher than the “major 5” average.

The average “major 5” validated value with one standard deviation is 2.095 ± 0.029 cm. The additional bias correction due to the reduced density is 0.001 cm, making the best estimate value 2.096 cm. The total 95 % level of confidence uncertainty is estimated as 0.090 cm.

Pu(71/17/11/1)O₂ - Slab thickness

This system is somewhat sensitive to the nuclide density issue. The plutonium isotopic distribution reduces the theoretical density, increasing the leakage. The material is not moderated. The mean values $\bar{m}_c$ and $\bar{m}_{bc}$ are similar. The standard deviation is reduced by a factor less than two by the corrections.

The bias for the plutonium distribution 71/17/11/1 and the volume parameter is -0.005 litres (0.5 %). It was not determined for the current system but is set to 0.2 % (one dimension rather than three as for volume) giving -0.004 cm.

The same observations as for the previous systems are made. There is no IPPE-ABBN93 value. The CRISTAL value is 3.0 % higher than the “major 5” average.

The average “major 5” validated value with one standard deviation is 2.100 ± 0.026 cm. The additional bias correction due to the reduced density is 0.004 cm, making the best estimate value 2.104

cm. The total 95 % level of confidence uncertainty is estimated as 0.080 cm.

Pu(100)O₂ - Concentration

This system does not seem to be sensitive to the nuclide density issue. However, the criticality is determined by the moderation ratio H/Pu, not by the concentration in g/cm³. If the same concentration leads to different H/Pu ratios, there may be some problem with the nuclide density determination. The material is well moderated. The mean values $\bar{m}_c$ and $\bar{m}_{bc}$ are not so similar. The standard deviation is reduced by a factor three by the corrections, after the removal of the MONK value (see below).

There are quite large differences for this simple system. The EMS methods benefit significantly from the validation procedure. However, the MONK value is 4 % high. The IPPE-ABBN93 is very close to the average.

After looking at the next systems, it became clear that the MONK result was not consistent or credible. The value 7.7 g/cm³ in the 2002 report [55] was the same as for the distribution 95/5 but for 90/10 the value increased to 8.4 g/cm³. The error was confirmed and corrected by Serco in March 2005. Normally this type of editorial mistakes would be corrected during the study and not published.

All contributors to this type of comparison make editorial mistakes occasionally. This report contains so many new values and evaluations that there are bound to be remaining mistakes. The independent review required for safety evaluations is normally not performed by the contributor since a comparison will be made later by the Group. This report will not be as thoroughly checked and this will be indicated in the text (e.g. “for demonstration only”). The experience shows the importance of independent reviews and the value of international comparisons.

The average validated value for the “major 6” (including revised MONK value) with one standard deviation is 7.317 ± 0.061 g/cm³. The CRISTAL V1.0 value of 7.24 g/cm³ has been considered. The total 95 % level of confidence uncertainty is estimated as 0.20 g/cm³.

Pu(95/5)O₂ - Concentration

This system is similar to the previous system. The mean value for calculated only systems $\bar{m}_c$ is significantly lower than the mean value $\bar{m}_{bc}$ for bias corrected results. The standard deviation is not reduced at all by the corrections.

The reason for the lack of success is that the EMS and Serco validations lead to a larger spread in the results. The EMS bias corrections appear to be consistent with each other and leads to a much smaller spread. However, they are strongly correlated, except for cross-sections.

The average validated value for the “major 6” with one standard deviation is 7.882 ± 0.092 g/cm³. The total 95 % level of confidence uncertainty is estimated as 0.300 g/cm³.

Pu(80/10/10)O₂ - Concentration

This system is similar to the previous system. The mean value for calculated only systems $\bar{m}_c$ is

significantly lower than the mean value $\overline{m}_{bc}$ for bias corrected results. The standard deviation is not reduced at all by the corrections. There is no IPPE-ABBN93 value for this system.

The reason for the lack of success is that the EMS and Serco validations lead to a larger spread in the results. The EMS bias corrections appear to be consistent with each other and leads to a much smaller spread.

The average validated value for the “major 5” with one standard deviation is 8.156 ± 0.091 cm. The total 95 % level of confidence uncertainty is estimated as 0.300 cm.

Pu(90/10)O₂ - Concentration

This system is similar to the previous system. The mean value for calculated results $\overline{m}_c$ is significantly lower than the mean value $\overline{m}_{bc}$ for bias corrected results. The standard deviation is reduced somewhat by the corrections.

Similar observations as for the previous plutonium concentration systems are made.

The average validated value for the “major 6” with one standard deviation is 8.561 ± 0.083 cm. The total 95 % level of confidence uncertainty is estimated as 0.250 cm.

Pu(80/15/5)O₂ - Concentration

This system is similar to the previous system. The mean value for calculated results $\overline{m}_c$ is significantly lower than the mean value $\overline{m}_{bc}$ for bias corrected results. The standard deviation is increased somewhat by the corrections. The EMS validation appears to over-compensate for biases. There is no IPPE-ABBN93 value for this system.

Similar observations as for the previous plutonium concentration systems are made.

The average validated value for the “major 5” with one standard deviation is 9.094 ± 0.111 cm. The total 95 % level of confidence uncertainty is estimated as 0.250 cm.

Pu(71/17/11/1)O₂ - Concentration

This system is similar to the previous system. The mean value for calculated results $\overline{m}_c$ is significantly lower than the mean value $\overline{m}_{bc}$ for bias corrected results. The standard deviation is increased somewhat by the corrections. The EMS validation appears to over-compensate for biases. There is no IPPE-ABBN93 value for this system.

Similar observations as for the previous plutonium concentration systems are made.

The average validated value for the “major 5” with one standard deviation is 9.276 ± 0.103 cm. The total 95 % level of confidence uncertainty is estimated as 0.350 cm.

Pu(100)O₂ - Moderation

This system is essentially the same as the concentration system. However, it is not sensitive to the nuclide density laws as the critical concentration is. The moderation parameter for an infinite system is not density dependent. If the different parameter values cover the whole range of moderations, from very dilute to crystal, then a check of corresponding densities obtained by different density laws would be revealing. Thus, since it is less complicated, it makes more sense to start with comparing critical moderations before starting comparing critical concentrations.

At this time, the best estimate of the critical concentration will be used to find the best estimate of the critical moderation. SCALE 5 is used for that. Using that moderation, different density laws can be compared.

The critical moderation corresponding to the best estimate critical concentration (7.283 g/cm^3) is an H/Pu value of 3636. The total 95 % level of confidence uncertainty is estimated as 190 (corresponds to a density change of 0.40 g/cm^3).

Pu(95/5) O_2 -Moderation

The critical moderation corresponding to the best estimate critical concentration (7.882 g/cm^3) is an H/Pu value of 3360. The total 95 % level of confidence uncertainty is estimated as 123 (corresponds to a density change of 0.300 g/cm^3).

Pu(80/10/10) O_2 -Moderation

The critical moderation corresponding to the best estimate critical concentration (8.156 g/cm^3) is an H/Pu value of 3250. The total 95 % level of confidence uncertainty is estimated as 115 (corresponds to a density change of 0.300 g/cm^3).

Pu(90/10) O_2 -Moderation

The critical moderation corresponding to the best estimate critical concentration (8.561 g/cm^3) is an H/Pu value of 3094. The total 95 % level of confidence uncertainty is estimated as 88 (corresponds to a density change of 0.250 g/cm^3).

Pu(80/15/5) O_2 -Moderation

The critical moderation corresponding to the best estimate critical concentration (9.094 g/cm^3) is an H/Pu value of 2914. The total 95 % level of confidence uncertainty is estimated as 78 (corresponds to a density change of 0.250 g/cm^3).

Pu(71/17/11/1) O_2 -Moderation

The critical moderation corresponding to the best estimate critical concentration (9.276 g/cm^3) is an H/Pu value of 2859. The total 95 % level of confidence uncertainty is estimated as 104 (corresponds to a density change of 0.350 g/cm^3).

Plutonium nitrate – PuNH or PuO₂(NO₃)₄ + 5H₂O

Pu(100)NH - Mass

This system is sensitive to the nuclide density (31 g/l) issue. The material is well moderated. The geometry is not so sensitive to quadrature and mesh. The mean $\overline{m}_{bc}$ of bias corrected values is higher than the mean $\overline{m}_c$ without corrections. The standard deviation after bias corrections is reduced to half. This indicates that the validation works.

The old EMS SCALE 4 bias corrected value (4 % high) using ORNL validation is not used in the evaluation since the validation is not focused on this application. A revised method using SCALE 5 and different validation is included.

The CRISTAL value is slightly lower, which is not unexpected (often slightly conservative). An IRSN evaluation of different density laws for this system is of special interest. IRSN used similar methods, except that the density laws used at IRSN during different periods were different. The older ARH-600 method (1968 version, not 1972 revised version of handbook!), the isopiestic law and the combined isopiestic/volume fraction law were used. For this system, the reference values change very little using the three density methods. That was the conclusion of IRSN and remains so in perspective of other differences between contributed values. For geometry limits, the conclusions are different.

The MONK and CRISTAL values are lower than the average (dominated by correlated EMS methods). The IPPE-ABBN93 value is close to the average.

The “major 6” average validated value with one standard deviation, including the IPPE result, is 524 ± 6 g ²³⁵U. Considering additional uncertainties (the density laws appear to have very small uncertainties for this application), the total 95 % level of confidence uncertainty is estimated as 20 g ²³⁵U.

Pu(95/5)NH - Mass

This system is sensitive to the nuclide density (32 g/l) issue. The material is well moderated. The geometry is not so sensitive to quadrature and mesh. The mean $\overline{m}_{bc}$ of bias corrected values is higher than the mean $\overline{m}_c$ without corrections. The standard deviation after bias corrections is reduced to half. This indicates that the validation works.

The conclusions for this system are similar to the previous system.

The “major 6” average validated value with one standard deviation, including the IPPE result, is 639 ± 10 g ²³⁵U. Considering additional uncertainties (the density laws appear to have very small uncertainties for this application), the total 95 % level of confidence uncertainty is estimated as 30 g ²³⁵U.

Pu(80/10/10)NH - Mass

This system is sensitive to the nuclide density (32 g/l) issue. The material is well moderated. The

geometry is not so sensitive to quadrature and mesh. The mean $\overline{m}_{bc}$ of bias corrected values is higher than the mean $\overline{m}_c$ without corrections. The standard deviation before bias corrections is more than 50 % higher. This lower reduction could indicate that the validation works less well than in previous systems but is also the result of the lack of an IPPE-ABBN93 value. The low MONK value increases the uncertainty.

The conclusions for this system are similar to the previous system. However, the IRSN value is close to the average, leaving the low MONK value isolated. On the other hand; the differences are mostly due to different validation and the associated bias corrections. Before the bias corrections, the MONK result is higher than almost all of the EMS values.

The “major 5” (no IPPE value) average validated value with one standard deviation is 707 ± 12 g ^{235}U . Considering additional uncertainties (the density laws appear to have very small uncertainties for this application), the total 95 % level of confidence uncertainty is estimated as 40 g ^{235}U .

Pu(90/10)NH - Mass

This system is sensitive to the nuclide density (33 g/l) issue. The material is well moderated. The geometry is not so sensitive to quadrature and mesh. The mean $\overline{m}_{bc}$ of bias corrected values is higher than the mean $\overline{m}_c$ without corrections. The standard deviation before bias corrections is 100 % higher. This indicates that the validation works

The conclusions for this system are similar to the previous system. The IRSN value is now higher than the bias corrected average, leaving the low MONK value isolated. On the other hand; the differences are mostly due to different validation and the associated bias corrections. Before the bias corrections, the MONK result is right on the average.

The “major 6” average validated value with one standard deviation is 777 ± 13 g ^{235}U . Considering additional uncertainties (the density laws appear to have very small uncertainties for this application), the total 95 % level of confidence uncertainty is estimated as 40 g ^{235}U .

Pu(80/15/5)NH - Mass

This system is sensitive to the nuclide density (34 g/l) issue. The material is well moderated. The geometry is not so sensitive to quadrature and mesh. The mean $\overline{m}_{bc}$ of bias corrected values is much higher than the mean $\overline{m}_c$ without corrections. The standard deviation before bias corrections is more than 100 % higher. The significant reduction of the spread in EMS values (excluding the old EMS SCALE 4 bias corrected result) is easy to see. The validation appears reasonable from that point of view. The low MONK value increases the uncertainty.

The conclusions for this system are similar to the previous system. However, the IRSN value is now closer to the low MONK value. Again; the differences are mostly due to different validation and the associated bias corrections. Before the bias corrections, the MONK result is much higher than almost all of the EMS values.

The “major 5” (no IPPE value) average validated value with one standard deviation is 905 ± 11 g ^{235}U . Considering additional uncertainties (the density laws appear to have very small uncertainties for

this application), the total 95 % level of confidence uncertainty is estimated as 40 g ²³⁵U.

Pu(71/17/11/1)NH - Mass

This system is sensitive to the nuclide density (34 g/l) issue. The material is well moderated. The geometry is not so sensitive to quadrature and mesh. The mean $\overline{m}_{bc}$ of bias corrected values is much higher than the mean $\overline{m}_c$ without corrections. The standard deviation before bias corrections is almost four times higher. The validation appears to be excellent. The bias corrected MONK value is identical to the average.

However, the CRISTAL value is much lower than the average, inconsistent with other PuNH mass results. The very high MONK value before bias correction is not consistent with previous results. Removing the bias corrected MONK value will not change the best estimate. If the MONK value had been consistent with previous results, the average would have been lower. An extra 15 g of uncertainty is added to consider this, the low CRISTAL value and the fact that the IPPE value is missing..

The “major 5” (no IPPE value) average validated value with one standard deviation is 948 ± 8 g ²³⁵U. Considering additional uncertainties (the density laws appear to have very small uncertainties for this application), the total 95 % level of confidence uncertainty is estimated as 40 g ²³⁵U.

Pu(100)NH - Volume

This system is sensitive to the nuclide density (280 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean $\overline{m}_{bc}$ of bias corrected values is lower than the mean $\overline{m}_c$ without corrections. This is a change from the mass system results. The standard deviation after bias corrections is reduced a little. This indicates problems with validation.

The CRISTAL value is about 3 % higher than the average for the “major 6” bias corrected value. This is different than for plutonium oxide systems. An IRSN evaluation of different density laws for this system is of special interest. IRSN used similar methods, except that the density laws used at IRSN during different periods were different. The older ARH-600 method (ARH-600 from 1968, not revised from 1972) and the new combined isopiestic/volume fraction law were used. For this system, the reference values change dramatically when using the two density methods. The ARH-600 “law” gives highly non-conservative values. That was the conclusion of IRSN but has been shown to be valid only for the density equation in the 1968 edition. It does not apply to the 1972 revision and to implementations in SCALE 4.

Results that could be too high due to inappropriate nuclide density methods include the original ARH-600 handbook (8.25 litres), the DIN standard (8.1 litres) and the German Handbook (8.3 litres). The IRSN/CEA 1978 Handbook refers to an H/U equation which gives better results. Both of the Japanese Handbook releases (single evaluation?) give very high values and this appears to be known to JAERI (Moeken equation problem) and corrected in a future Data Collection release 2.

SCALE 4 uses the ARH-600 method, but the results appear to be reasonable, often conservative. The reason is that it uses the 1972 revised equations of ARH-600..

The old EMS SCALE 4 bias corrected value (9 % high) using ORNL validation is not used in the evaluation since the validation is not focused on this application. A revised method using SCALE 5 and different validation is included. The large bias correction due to the old validation is not related to the density issue. It should also be recognized that the stated uncertainty in the associated validation is large and covers the best estimate value (a general conclusion of this validation from ORNL).

The MONK and IPPE-ABBN93 bias corrected values are lower than the average (dominated by correlated EMS methods). The density equation for MONK should give conservative deviations from the IRSN CRISTAL densities, see Figure K8. The IPPE method should give opposite trends, an over-estimation of the volume.

The “major 6” average validated value with one standard deviation, including the IPPE result, is 7.361 ± 0.131 litres. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95 % level of confidence uncertainty is estimated as 0.5 litres.

Pu(95/5)NH - Volume

This system is sensitive to the nuclide density (140 g/l) issue. The material is well moderated, though not as well as for mass systems and not as well as for the previous system with 100 % ^{239}Pu . The geometry is not so sensitive to quadrature and mesh. The mean $\bar{m}_{bc}$ of bias corrected values is lower than the mean $\bar{m}_c$ without corrections. This is a change from the mass system results. The standard deviation after bias corrections is reduced to less than half. This indicates a successful validation.

The conclusions are similar as for the previous system, that for Pu(100)NH. The CRISTAL value is now just slightly lower than the average. The IPPE-ABBN93 values are very high, which is unexpected compared with the previous Pu(100)NH system value, but consistent with the comparison of density methods..

The “major 6” average validated value with one standard deviation, including the IPPE result, is 10.782 ± 0.129 litres. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95 % level of confidence uncertainty is estimated as 0.5 litres.

Pu(80/10/10)NH - Volume

This system is sensitive to the nuclide density (130 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean $\bar{m}_{bc}$ of bias corrected values is slightly lower than the mean $\bar{m}_c$ without corrections. The standard deviation after bias corrections is reduced to less than a third. This indicates a very successful validation.

The conclusions are similar as for the previous system. The CRISTAL value is now slightly lower than the average.

The methods that resulted in high values due to the density issue for the previous system are absent for this system. This includes IPPE-ABBN93.

The “major 5” (IPPE missing) average validated value with one standard deviation, including the IPPE result, is 12.176 ± 0.097 litres. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95 % level of confidence uncertainty is estimated as 0.5 litres.

Pu(90/10)NH - Volume

This system is sensitive to the nuclide density (125 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean $\overline{m}_{bc}$ of bias corrected values is slightly higher than the mean $\overline{m}_c$ without corrections. The standard deviation after bias corrections is reduced to less than half. This indicates a successful validation.

The conclusions are similar as for a previous system, that for Pu(95/5)NH. The CRISTAL value is lower than the average.

The “major 6” average validated value with one standard deviation, including the IPPE result, is 13.415 ± 0.157 litres. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95 % level of confidence uncertainty is estimated as 0.5 litres.

Pu(80/15/5)NH - Volume

This system is sensitive to the nuclide density (120 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean $\overline{m}_{bc}$ of bias corrected values is higher than the mean $\overline{m}_c$ without corrections. The standard deviation after bias corrections is reduced to less than a third. This indicates a successful validation even though the lack of a bias corrected IPPE value makes the basis weaker.

The conclusions are similar as for the previous systems. The CRISTAL value is lower than the average.

The “major 5” (no IPPE value) average validated value with one standard deviation, including the IPPE result, is 15.424 ± 0.120 litres. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95 % level of confidence uncertainty is estimated as 0.5 litres.

Pu(71/17/11/1)NH - Volume

This system is sensitive to the nuclide density (120 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean $\overline{m}_{bc}$ of bias corrected values is higher than the mean $\overline{m}_c$ without corrections. The standard deviation after bias corrections is reduced to a quarter. This indicates a successful validation even though the lack of a bias corrected IPPE value makes the basis weaker.

The conclusions are similar as for the previous systems. The CRISTAL value is again lower than the average. The MONK bias corrected values have consistently resulted in values close to the best

estimate average for the last systems.

The “major 5” (no IPPE value) average validated value with one standard deviation, including the IPPE result, is 15.830 ± 0.085 litres. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95 % level of confidence uncertainty is estimated as 0.5 litres.

Pu(100)NH – Cylinder diameter

This system is sensitive to the nuclide density (330 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean $\overline{m}_{bc}$ of bias corrected values is lower than the mean $\overline{m}_c$ without corrections. This is similar to the volume system results but a change from the mass system results. The standard deviation after bias corrections is reduced to a half. This indicates a successful validation.

The conclusions are similar as for the volume system, see Pu(100)NH. The IRSN demonstrations of influences of density laws apply to the cylinder diameter as well as to the volume parameter. The CRISTAL value is now higher than the average. This is similar as for Pu(100)NH mass. The IPPE-ABBN93 value is high, which is similar to values from volume systems except for Pu(100). The Serco value before bias correction is the same as the bias corrected average but after bias correction it is lower.

The “major 6” average validated value with one standard deviation, including the IPPE result, is 15.555 ± 0.116 cm. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95 % level of confidence uncertainty is estimated as 0.4 cm.

Pu(95/5)NH – Cylinder diameter

This system is sensitive to the nuclide density (155 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean $\overline{m}_{bc}$ of bias corrected values is the same as the mean $\overline{m}_c$ without corrections. The standard deviation after bias corrections is reduced to less than a half. This indicates a successful validation.

The conclusions are similar as for the Pu(100)NH cylinder diameter system. The CRISTAL value is now identical to the bias corrected best estimate average. The IPPE-ABBN93 value is still high, but the bias correction helps.

The “major 6” average validated value with one standard deviation, including the IPPE result, is 17.942 ± 0.097 cm. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95 % level of confidence uncertainty is estimated as 0.4 cm.

Pu(80/10/10)NH – Cylinder diameter

This system is sensitive to the nuclide density (145 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The

mean $\overline{m}_{bc}$ of bias corrected values is about the same as the mean $\overline{m}_c$ without corrections. The standard deviation after bias corrections is reduced to a half. This indicates a successful validation.

The conclusions are similar as for the previous PuNH cylinder diameter system. The CRISTAL value is again identical to the bias corrected best estimate average. The bias corrected MONK value is just slightly lower.

The “major 5” average (no IPPE-ABBN93 value) validated value with one standard deviation is 18.740 ± 0.120 cm. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95 % level of confidence uncertainty is estimated as 0.4 cm.

Pu(90/10)NH – Cylinder diameter

This system is sensitive to the nuclide density (135 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean $\overline{m}_{bc}$ of bias corrected values is the same as the mean $\overline{m}_c$ without corrections. The standard deviation after bias corrections is reduced to a third. This indicates a successful validation.

The conclusions are similar as for the Pu(100)NH cylinder diameter system. The MONK and CRISTAL values are now almost identical to the bias corrected best estimate average. The IPPE-ABBN93 value is still high, but the bias correction helps.

The “major 6” average validated value with one standard deviation, including the IPPE result, is 19.475 ± 0.082 cm. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95 % level of confidence uncertainty is estimated as 0.4 cm.

Pu(80/15/5)NH – Cylinder diameter

This system is sensitive to the nuclide density (130 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean $\overline{m}_{bc}$ of bias corrected values is about the same as the mean $\overline{m}_c$ without corrections. The standard deviation after bias corrections is reduced to a quarter. This indicates a successful validation even though the IPPE-ABBN93 value is missing.

The conclusions are similar as for the previous PuNH cylinder diameter systems. The CRISTAL value is slightly lower than the bias corrected best estimate average. The bias corrected MONK value is slightly higher.

The “major 5” average (no IPPE-ABBN93 value) validated value with one standard deviation is 20.542 ± 0.052 cm. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95 % level of confidence uncertainty is estimated as 0.4 cm.

Pu(71/17/11/1)NH – Cylinder diameter

This system is sensitive to the nuclide density (130 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean $\overline{m}_{bc}$ of bias corrected values is about the same as the mean $\overline{m}_c$ without corrections. The standard deviation after bias corrections is reduced to less than a half. This indicates a successful validation even though the IPPE-ABBN93 value is missing.

The conclusions are similar as for the previous PuNH cylinder diameter systems. The CRISTAL value is slightly lower than the bias corrected best estimate average. The bias corrected MONK value is close to the CRISTAL value.

The “major 5” average (no IPPE-ABBN93 value) validated value with one standard deviation is 20.718 ± 0.087 cm. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95 % level of confidence uncertainty is estimated as 0.4 cm.

Pu(100)NH – Slab thickness

This system is sensitive to the nuclide density (550 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean $\overline{m}_{bc}$ of bias corrected values is lower than the mean $\overline{m}_c$ without corrections. The standard deviation after bias corrections is slightly reduced. This indicates a not so successful overall validation. The EMS methods seem to benefit from the bias corrections.

The conclusions are similar as for the Pu(100)NH volume and cylinder systems. The IRSN demonstrations of influences of density laws apply. The CRISTAL value is again, like for the volume and cylinder systems higher than the average (for isotopic distribution 100 % ^{239}Pu only). The bias corrected IPPE-ABBN93 value is close the bias corrected average. The MONK value after bias correction is lower.

The “major 6” average validated value with one standard deviation, including the IPPE result, is 5.668 ± 0.088 cm. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95 % level of confidence uncertainty is estimated as 0.3 cm.

Pu(95/5)NH – Slab thickness

This system is sensitive to the nuclide density (212 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean $\overline{m}_{bc}$ of bias corrected values is almost the same as the mean $\overline{m}_c$ without corrections. The standard deviation after bias corrections is reduced to less than half. This indicates a successful overall validation.

The conclusions are similar as for other PuNH volume and cylinder systems. However, the variations between bias corrected values (excluding as always the EMS SCALE 4 and the JAERI handbook values) all seem to be limited. Also the CRISTAL value is within this limited range of values.

The “major 6” average validated value with one standard deviation, including the IPPE result, is 7.176 ± 0.063 cm. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95 % level of confidence uncertainty is estimated as 0.3 cm.

Pu(80/10/10)NH – Slab thickness

This system is sensitive to the nuclide density (220 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean $\overline{m}_{bc}$ of bias corrected values is lower than the mean $\overline{m}_c$ without corrections. The standard deviation after bias corrections is reduced to about 65 %. This may indicate some problem with the overall validation.

The conclusions are similar as for other PuNH volume and cylinder systems. The CRISTAL value is higher than the best estimate while the bias corrected MONK value is lower.

The “major 5” average validated value with one standard deviation, including the IPPE result, is 7.612 ± 0.094 cm. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95 % level of confidence uncertainty is estimated as 0.3 cm.

Pu(90/10)NH – Slab thickness

This system is sensitive to the nuclide density (175 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean $\overline{m}_{bc}$ of bias corrected values is the same as the mean $\overline{m}_c$ without corrections. The standard deviation after bias corrections is reduced to about 40 %. This indicates a successful overall validation.

The conclusions are similar as for other PuNH volume and cylinder systems. The CRISTAL value and the IPPE-ABBN93 bias corrected value are higher than the best estimate while the bias corrected MONK value is lower.

The “major 6” average validated value with one standard deviation, including the IPPE result, is 8.108 ± 0.054 cm. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95 % level of confidence uncertainty is estimated as 0.3 cm.

Pu(80/15/5)NH – Slab thickness

This system is sensitive to the nuclide density (180 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean $\overline{m}_{bc}$ of bias corrected values is the same as the mean $\overline{m}_c$ without corrections. The standard deviation after bias corrections is reduced to less than 50 %. This indicates a successful overall validation.

The conclusions are similar as for other PuNH volume and cylinder systems. The CRISTAL value is higher than the best estimate while the bias corrected MONK value is lower. The EMS SCALE bias

corrected values are lower while the EMS MCNP bias corrected values are higher than the best estimate value. The spread of results is small.

The “major 5” average validated value with one standard deviation, including the IPPE result, is 8.750 ± 0.060 cm. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95 % level of confidence uncertainty is estimated as 0.3 cm.

Pu(71/17/17/1)NH – Slab thickness

This system is sensitive to the nuclide density (160 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean $\bar{m}_{bc}$ of bias corrected values is the same as the mean $\bar{m}_c$ without corrections. The standard deviation after bias corrections is reduced to less than 50 %. This indicates a successful overall validation.

The conclusions are similar as for other PuNH volume and cylinder systems. The CRISTAL value is close to the best estimate while the bias corrected MONK value is lower. The EMS SCALE bias corrected values are lower than the best estimate value. The spread of results is small.

It appears so far as if the MONK densities are not as bad as indicated by the comparison in APPENDIX K.

The “major 5” average validated value with one standard deviation, including the IPPE result, is 8.886 ± 0.084 cm. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95 % level of confidence uncertainty is estimated as 0.3 cm.

Pu(100)NH – Concentration

This system does not seem to be sensitive to the nuclide density (7.33 g/l) issue. However, the criticality is determined by the moderation ratio H/Pu, not by the concentration in g/cm^3 . If the same concentration leads to different H/Pu ratios, there may be some problem with the nuclide density determination. The material is well moderated. The mean value $\bar{m}_c$ is higher than $\bar{m}_{bc}$. The standard deviation is reduced to about 40 % by the corrections, after the removal of the MONK value (see below). This is quite good.

There are quite large differences for this simple system. The EMS methods appear to benefit from the validation procedure. The MONK value reported to the Group [55] was 6 % high. It was clearly some editorial mistake and this was confirmed and corrected by Serco in March 2005. The IPPE-ABBN93 value is above the best estimate, the CRISTAL value is below.

The average validated value for the “major 6” (including revised MONK value) with one standard deviation is 7.328 ± 0.026 g/cm^3 . The total 95 % level of confidence uncertainty is estimated as 0.20 g/cm^3 .

Pu(95/5)NH – Concentration

This system does not seem to be sensitive to the nuclide density (7.93 g/l) issue. The mean value $\bar{m}_c$ is lower than $\bar{m}_{bc}$. The standard deviation is reduced to about a third by the corrections. This indicates that the bias corrections work well.

The spread of the bias corrected values is quite small, except for the MONK value.

The average validated value for the “major 6” with one standard deviation is 7.929 ± 0.066 g/cm³. The total 95 % level of confidence uncertainty is estimated as 0.20 g/cm³.

Pu(80/10/10)NH – Concentration

This system does not seem to be sensitive to the nuclide density (8.19 g/l) issue. The mean value $\bar{m}_c$ is lower than $\bar{m}_{bc}$. The standard deviation is increased by the corrections. This indicates that there is a problem with the overall validation. The spread of the EMS is reduced significantly. However, the MONK value is bias corrected in the other direction, causing a large difference.

There is no IPPE value. The CRISTAL value is between the MONK bias corrected value and the best estimate value.

The average validated value for the “major 5” with one standard deviation is 8.194 ± 0.111 g/cm³. The total 95 % level of confidence uncertainty is estimated as 0.20 g/cm³.

Pu(90/10)NH – Concentration

This system does not seem to be sensitive to the nuclide density (8.59 g/l) issue. The mean value $\bar{m}_c$ is lower than $\bar{m}_{bc}$. The standard deviation is not reduced at all. This indicates a problem with the overall validation.

The spread of the bias corrected values is quite small, except for the MONK value. However, the MONK values are close to the EMS values before bias correction.

The average validated value for the “major 6” with one standard deviation is 8.594 ± 0.099 g/cm³. The total 95 % level of confidence uncertainty is estimated as 0.20 g/cm³.

Pu(80/15/5)NH – Concentration

This system does not seem to be sensitive to the nuclide density (9.15 g/l) issue. The mean value $\bar{m}_c$ is lower than $\bar{m}_{bc}$. The standard deviation is unchanged by the corrections. This indicates that there is a problem with the overall validation. The spread of the EMS is reduced significantly. However, the MONK value, being higher than any of the EMS values before bias corrections, is reduced by the bias correction while the EMS values are increased.

There is no IPPE value. The CRISTAL value is between the MONK bias corrected value and the best estimate value.

The average validated value for the “major 5” with one standard deviation is 9.154 ± 0.090 g/cm³. The total 95 % level of confidence uncertainty is estimated as 0.20 g/cm³.

Pu(71/17/11/1)NH – Concentration

This system does not seem to be sensitive to the nuclide density (9.31 g/l) issue. The mean value $\bar{m}_c$ is lower than $\bar{m}_{bc}$. The standard deviation is increased by the corrections. This indicates that there is a problem with the overall validation. The spread of the EMS is reduced significantly. However, the MONK value, being similar to the EMS values before bias corrections, is reduced by the bias correction while the EMS values are increased.

There is no IPPE value. The CRISTAL value is between the MONK bias corrected value and the best estimate value.

The average validated value for the “major 5” with one standard deviation is 9.314 ± 0.124 g/cm³. The total 95 % level of confidence uncertainty is estimated as 0.25 g/cm³.

Pu(100)NH – Moderation

This system is essentially the same as the concentration system. However, it is not sensitive to the nuclide density laws as the critical concentration is. The moderation parameter for an infinite system is not density dependent. If the different parameter values cover the whole range of moderations, from very dilute to crystal, then a check of corresponding densities obtained by different density laws would be revealing. Thus, since it is less complicated, it makes more sense to start with comparing critical moderations before starting comparing critical concentrations.

At this time, the best estimate of the critical concentration will be used to find the best estimate of the critical moderation. SCALE 5 is used for that. Using that moderation, different density laws can be compared.

The critical moderation corresponding to the best estimate critical concentration (7.328 g/cm³) is an H/Pu value of 3598. The total 95 % level of confidence uncertainty is estimated as 96 (corresponds to a density change of 0.20 g/cm³).

Pu(95/5)NH – Moderation

The critical moderation corresponding to the best estimate critical concentration (7.929 g/cm³) is an H/Pu value of 3325. The total 95 % level of confidence uncertainty is estimated as 82 (corresponds to a density change of 0.20 g/cm³).

Pu(80/10/10)NH – Moderation

The critical moderation corresponding to the best estimate critical concentration (8.194 g/cm³) is an H/Pu value of 3221. The total 95 % level of confidence uncertainty is estimated as 97 (corresponds to a density change of 0.20 g/cm³).

Pu(90/10)NH – Moderation

The critical moderation corresponding to the best estimate critical concentration (8.594 g/cm^3) is an H/Pu value of 3068. The total 95 % level of confidence uncertainty is estimated as 70 (corresponds to a density change of 0.20 g/cm^3).

Pu(80/15/5)NH – Moderation

The critical moderation corresponding to the best estimate critical concentration (9.154 g/cm^3) is an H/Pu value of 2881. The total 95 % level of confidence uncertainty is estimated as 62 (corresponds to a density change of 0.20 g/cm^3).

Pu(71/17/11/1)NH – Moderation

The critical moderation corresponding to the best estimate critical concentration (9.314 g/cm^3) is an H/Pu value of 2833. The total 95 % level of confidence uncertainty is estimated as 74 (corresponds to a density change of 0.25 g/cm^3).

Preliminary summary of accuracies of different methods

Since the best-estimate reference values are not known very accurately for some systems, it is difficult to correctly express the accuracies of individual methods. The benchmarks only cover cross-sections and codes, not nuclide density determinations. These are important for the nitrate systems. All the EMS MCNP5 and SCALE 5 methods for each system are based on a single nuclide density determination (CSAS in SCALE 5).

The concept “conservative” is used here to mean an over-prediction of k_{eff} . It is normally used as a safety concept, but here it is rather used for simplicity. K_{eff} increases with an increase in most of the reference parameters but for the moderation ratio the relationship is reversed. A conservative method thus means that the critical mass, geometry and concentration (with the density unit g/cm^3) values are under-predicted and the H/U ratio is over-predicted.

ARH-600 handbook

Some of the contributed ARH-600 values were not intended for the associated reference systems. Some were for uranium with 93 % by mass of ^{235}U , other were for UO_2F_2 rather than for UO_2 . Most of the values are for PuNH and they are usually non-conservative. It seems likely that the inaccurate density equation used by IRSN until recently was also used to derive many of the values and curves in the ARH-600 handbook. A revised page from October 1968 still contains an inaccurate density equation. In the 1972 revision, a better equation was quoted, but it was probably not used to revise the curves. The equations used in SCALE before version 5 were based on the 1972 revised equations of the ARH-600 handbook.

DIN standards

For UO_2 , all values seem to be slightly conservative or close to the best-estimate values. The similar is true for UNH (only 100 % enrichment ^{235}U available). For PuO_2 , there could be some non-conservatory values for cylinder and in particular slab geometry. There seems to be a trend, similar to that for IRSN CRISTAL calculations, but much weaker. For PuNH there are serious over-predictions (non-conservative) of the minimum critical geometry values. A likely cause is the density method used. Many of the values are similar to those given in ARH-600. The water fraction of the solution appears to be under-estimated. This explains why the concentration limits are conservative. This is based on speculation, looking at the results, not on an investigation of the method.

EMS: MCNP5 with ENDF/B-V cross-sections

There are two methods for plutonium systems, one with an early cross-section set for ^{239}Pu (.50c) and the other with a final version (.55c). The difference is dramatic for fast systems but not for thermal, something that is probably familiar to frequent users of this library. For UO_2 , all values seem to be slightly conservative. For UNH, the cross-sections give the same trend but the density method makes a comparison of the overall methods complicated. The densities were determined using density relationships in SCALE 5 at 293K. For PuO_2 , both sets are conservative for mass systems while the final version seems quite accurate on fast systems (the early set is conservative). For PuNH (also at 293 K), the behaviour should be similar as for thermal PuO_2 . The two sets do seem to be very similar for all PuNH systems. However, the density issues for solutions make it more complicated to find weak trends.

EMS: MCNP5 with ENDF/B-VI.2 cross-sections

The results for UO_2 systems are very consistent. There is a strong trend with the ^{235}U enrichment or rather with the presence of ^{238}U . Without this nuclide, for $\text{U}(100)\text{O}_2$ systems, the results appear very accurate. For low enrichments, the reference values are highly non-conservative. The same trend is seen for the UNH systems. If the best-estimate values for PuO_2 are correct, this method is consistently very accurate. This conclusion is supported by the small bias-corrections as well. For PuNH systems, the accuracy is good for mass systems (over-moderated) while giving consistent over-predictions for geometry-controlled systems (near optimum infinite system moderation). For both nitrate systems (U and Pu) the quality of the values depends on the nuclide density methods. The densities were taken from SCALE 5 calculations at 293K.

EMS: MCNP5 with ENDF/B-VI.6 cross-sections

The ^{238}U trend from the previous release VI.2 cross-section library is absent; all uranium systems are calculated with consistency and good accuracy. Errors due to nuclide densities are not considered in this conclusion. The plutonium systems, good results were obtained, similar to those for ENDF/B-VI.2 cross-sections. The over-predictions for some thermal Pu systems are lower than for release VI.2.

EMS: MCNP5 with ENDF/B-VI.8 cross-sections

The changes from release VI.6 seems to be small. Both the uranium and the plutonium values are close for almost all systems.

EMS: MCNP5 with ENDF/B-VII.P cross-sections

For uranium with 100 or 20 % by mass of ^{235}U , there is a clear trend for some over-estimation of the reference values. For low-enriched uranium the values are good and similar to the releases VI.6 and VI.8. The only plutonium isotope, ^{239}Pu does not seem to change much compared with release VI.8.

EMS: MCNP5 with JEF 2.2 cross-sections

The uranium values are consistently near the best-estimate, excluding density effects. The behaviour seems similar to ENDF/B-VI.6 but with a negative trend (conservative) for slab, cylinder and maybe volume control. For plutonium systems there is a consistent and very strong under-prediction (conservative) of the PuO_2 mass and all limited PuNH system values. This under-prediction is found by the validation and corrected for. The concentration values seem to be slightly high, while the fast systems are close to the best-estimate (excluding density effects).

EMS: MCNP5 with JEFF 3.0 cross-sections

For uranium systems, the behaviour is quite similar to JEF 2.2. There appears to be spectrum-related trends with slightly higher (less conservative) values for JEFF 3.0 for near optimum moderated leakage systems (geometry control) and lower for over-moderated leakage systems (mass). For plutonium there is a drastic improvement for moderated leakage systems while retaining the good qualities of JEF 2.2 for other systems. This is also detected by the validation process, leading to small biases for JEFF 3.0.

EMS: MCNP5 with JENDL 3.2 cross-sections

There is a very strong conservative bias for all uranium systems. Moderated PuO₂ and PuNH system values show the same trend. Fast plutonium systems are calculated about the average.

EMS: MCNP5 with JENDL 3.3 cross-sections

The uranium systems are now calculated with what appears to be small biases. The improvement from JENDL-3.2 is significant. The moderated PuO₂ and PuNH system values show the same trend as for JENDL-3.2, a conservative bias. Fast plutonium systems are also similar to JENDL-3.2; about the average.

EMS: SCALE 1 and KENO V with 27 group cross-sections from SCALE 3

The calculations of UO₂ mass reference systems with this method all resulted in high over-predictions of the critical mass (non-conservative). This was expected from earlier experience but is not consistent with SCALE 5 and the same (or very similar) cross-section library. The reason for the differences is not known.

EMS: SCALE 4.4, XSDRNPM with 238 group cross-sections

The SCALE 4 default values for convergence, mesh and angular quadrature in XSDRNPM calculations were used in 2000 and 2001. Already at that time it was understood that this may not be sufficient for fast systems. Further, the validation was based on a too wide selection of benchmarks. The biases are not reliable. The calculated UO₂ values all appear quite good, with small deviations from the best-estimate values. The UNH and PuNH values reflect the nuclide density methods. SCALE 4 results don't seem very different to SCALE 5 results. The validation indicates conservative cross-section biases for Pu systems.

EMS: SCALE 5, XSDRNPM and KENO V with 238-group cross-sections

Better default values and improving them for some systems (in particular fast systems) lead to some changes in reference values compared with SCALE 4 and the same cross sections. The new density method in SCALE 5 does not seem to change the reference values much. Overall, the 238-group library holds very well for all systems and the validation seems to work well.

EMS: SCALE 5, XSDRNPM and KENO V with 27-group cross-sections

In spite of the statistical fluctuations, the Monte Carlo Code KENO V is in practice more reliable and often more accurate than the deterministic code XSDRNPM. Reasons are that it is easier to validate the KENO V method (more benchmarks) and that the cost of high precision (many neutron histories) has been reduced significantly during the years. Comparison of early XSDRNPM calculations of reference values with KENO V calculations showed that there were several cases of insufficient convergence, mesh and/or angular quadrature in the XSDRNPM calculations. Improving such input has led to almost identical results.

The 27 group library has been used in Sweden since 1978 when the specifications and the 218-group library that it is collapsed from were published. It is not the most accurate library today but the

limitations are quite well understood and predictable. Many safety reports and licenses have been issued based on calculations with this library. For this reason it will remain to be important. As is shown in the study, different combinations of codes and different versions of the 27-group library may result in quite different reference values. The results reported here may not be representative of older calculations.

For high-enriched uranium systems (both thermal and fast), the results are clearly conservative. For low-enriched uranium the results appear quite accurate with no strong trends. This is contradictory to experience from the 1980's, when the results were often non-conservative for low-enriched uranium. Changes in the structure and in the NITAWL resonance processing code may have improved the situation.

All calculations of plutonium systems lead to very conservative results, at least as far as the cross-sections are concerned. The validation reveals this behaviour but the fast systems are not corrected sufficiently. A reason may be that the 27-group library was never designed or intended for fast systems. If the physics of such systems are not simulated well enough, it is not easy to correct for the deviations through bias corrections. For thermal systems, it is surprising to see how well the bias corrections correct for the errors in the plutonium cross-sections.

EMS: SCALE 5, XSDRNPM and KENOv with 44-group cross-sections

The 44-group library has not been used as much in Sweden as the 27- and 238-group libraries. However, it is used widely internationally in transport safety reports and in publications. Information on its behaviour is useful. It is important to note that the 44-group library is not a collapsed sub-set of the 238-group library.

For high-enriched uranium systems, the results are conservative, though not as much as for the 27-group library. For low-enriched uranium systems the accuracy is better. Compared with the 44-group library, the 27-group library leads to less conservative, sometimes non-conservative results for the low-enriched uranium. This is also seen in the validation results.

For plutonium, the thermal system results are very conservative, though not as much as the for the 27-group library. For fast systems, the group-structure was not designed or intended for such simulations. The results are conservative but the validation cannot correct for it appropriately. For PuNH systems, the density effect makes it more complicated to evaluate the cross-section influence.

GRS: The German criticality safety handbook

The first (1970's) version of this handbook has been the most popular in Sweden since it covers many of the solutions common in fuel fabrication (wet UF₆ conversion process and recovery of scrap). There have been some revisions in the mid 1980's and in 1998. The methods used to derive the values are described but the density determination methods are not always clear.

The tables and curves in the handbook don't always agree with each other. This can be confusing.

The handbook is, like most other safety handbooks, intended to be used together with validation and other steps to assure that the application is safe. The purpose has never been to give exact values.

The handbook does not cover all reference systems. The high-enriched (20, 100 % ^{235}U) uranium system results seem to be scattered around the best-estimate values. The low-enriched UO_2 results are consistently non-conservative. The low-enriched UNH results are even more consistent, though in the opposite, conservative direction. The table and the curves give different values for the same system.

For UNH with the enrichments 3, 4 and 5 % by mass of uranium, there is another peculiarity. The U(5)NH mass parameter (485 kg U) that was given in the tables on the NAIS web page and distributed to participants during meetings is based on an editorial error in the 1985 version of the handbook. This was corrected to 445 kg U in the 1998 release of the handbook. Of the 12 mass and geometry values for these systems, the corrected U(5)NH mass value is the only one that is different from the IRSN Standard de Criticité from 1978. The GRS results were obtained with GAMTEC/DTF-IV calculations while the IRSN results were obtained with a combination of literature search and calculations with DTF/IV, MORET and APOLLO. The values seem to have a common origin but it is not easy to find.

There are not so many values for plutonium systems, but it is apparent that the PuNH values are highly non-conservative. The density method could be a reason.

IPPE-84: Russian handbook from 1984

As seen from the description of the methods used, these values involve many large errors and uncertainties. Sometimes, they cancel out, sometimes not. The users of this handbook were informed about the uncertainties.

IPPE-ABBN93

This method is based on the ABBN93a cross section library used with either KENOv or XSDRNPM/S. It has been used in several publications as well as in the generation of data in ICSBEP Handbook. In a very short period in late 2004, IPPE carried out reference value calculations for most systems and also reported validation results for the benchmarks listed in the report.

The simple density method for solutions used by IPPE for this project is not accurate for all densities but it seems more appropriate than other methods, except the IRSN isopiestic method. It is accurate for low and high densities, including the crystal form of the material.

The validation reported here for this method is based on the EMS selection of benchmarks. IPPE has published other validation studies that may have different conclusions.

The UO_2 results are either very close to the best-estimate average or a little bit conservative.

The UNH systems for medium and low-enriched uranium are much more conservative than the average values. They are often close to the IRSN extended isopiestic method. This is not a coincidence; the IRSN extended and the IPPE simple mixing methods are the only methods that consider the real crystal densities. For some densities, the IPPE method appears to be more conservative than the IRSN isopiestic method. This could be explained by the additional water present due to the IPPE mixing method compared with the solutions methods.

The PuO_2 results are very close to the best-estimate values and the bias-corrected EMS MCNP

results, both for fast and thermal systems. This is a sign that the selection and evaluation of benchmarks have been successful for these applications.

For PuNH systems, the IPPE results often appear a little non-conservative. This appears to be contradictory to the experience from evaluation of UNH results. However, a look at the comparison of density methods (APPENDIX K) shows that the IPPE mixing gives underestimation of the water presence in PuNH while the opposite was true for UNH. Since the validation of density methods have not been reported very well, some care must be made in drawing conclusions.

IRSN –Standard de Criticité 1978

This handbook (issued by CEA which at that time included the current IRSN) has been published and is a valuable information source for criticality safety specialists. The H/X ratio to actinide density and other density relations for nitrate solutions from ARH-600 are quoted. It is not easy to find the origin of the values since they seem to be selected conservatively from a number of sources, including literature and APOLLO, DTF/IV and MORET calculations. See also the discussion above on the many identical UNH values in the German Handbook and this IRSN Standard.

An internal IRSN review of this Guide was carried out until 1996. The source [99] is not published and was not given to the Expert Group. During the final evaluation a copy was reviewed but there is no clear information on what methods were applied to obtain the values. The reported values were removed unless they can be found in the Standard, since the methods were not described very well and the results quoted in different contributions were often different.

It is not easy to directly see any trend for the UO_2 values. Some appear very conservative, other very non-conservative and some quite good. This could be related to their potentially different sources.

For UNH with low-enriched uranium, most values are identical to the German Handbook values.

For the plutonium systems that are covered, there is a wide spread of results; some are very conservative others are very non-conservative.

IRSN Pre-Isopiestic – CRISTAL and other methods using a replaced ARH-600 density relation

These values for nitrates are based on an option in CRISTAL where the older density methods based on Leroy-Jouan (UNH) and ARH-600 (PuNH) are tested against the new extended isopiestic density law. However, the ARH-600 equation comes from the 1968 ARH-600 version that was replaced in 1972. It has been used in IRSN long after that since the 1972 ARH-600 version did not correspond to the IRSN concerns and since a method simulating the real behaviour of solutions of high actinide concentrations and high acidity was not yet available.

The only values given are for Pu(100)NH mass and volume systems. The mass values are similar while the minimum critical volume is overestimated significantly by the old method. The reason is apparent from the comparison of density methods in APPENDIX K.

IRSN Current methods – CRISTAL using the extended isopiestic density law

The CRISTAL system with the CIGALES graphical interface pre-processor is validated with consideration of density issues related to isotope distributions as well as to solubility and mixing of solutions and salts (crystal form). The calculated reference values are not bias-corrected and uncertainties based on validation are not given. However, the results are either more credible (density issues) or quite close to best estimate reference values for systems where density issues are not complicating comparisons. An exception is plutonium dioxide slab systems for which IRSN reference values are a few percent higher than for other systems. The differences are within the expected uncertainty range and it is not yet obvious which values are more correct than others.

JAERI: The Japanese Handbooks, release 1 and 2

The Japanese handbooks contain a lot of useful information. However, the benchmarks are old, from the 1980's and earlier. This means that their biases and uncertainties were not as well documented as in the ICSBEP Handbook. The bias-corrections do not consider biases in the benchmarks themselves. Further, the existence of k_{eff} biases in the handbooks could probably have been used to derive the calculated values during the evaluation. Time did not allow this.

The evaluations used to determine values in release 2 of the handbook are very often identical to those for the first release. Sometimes only one value is given; it may be given for release 2 even if the first release has an identical value.

There are not many values for high-enriched uranium. For low-enriched uranium in UO_2 , Handbook 1 gives conservative results. The situation is more mixed for Handbook 2 though also that handbook sometimes gives very conservative results. For UNH systems, the release 2 sometimes gives non-conservative deviations. The discrepancies from average values are often large. This is similar to the EMS SCALE 4 calculations that were bias-corrected using general ORNL safety validation.

There are not many values for plutonium systems. For PuNH volume, cylinder and slabs, values are given and they appear to be identical in both releases. The values are severely overestimated (non-conservative). This could be a density effect.

As mentioned elsewhere in the report, the minimum critical mass for $\text{U}(20)\text{O}_2$ is overestimated by 40 %. This is more of an editorial error than an evaluation error but it is still very serious.

ORNL: SCALE 4.3, XSDRNPM/S and the 238 group library

This method is essentially identical to the EMS method with SCALE 4.4 and the same library. Differences could be caused by better convergence criteria used by ORNL and better interpolation in finding the optimum densities by EMS.

ORNL refers to the same validation report used by EMS in 2001 and that has been rejected by EMS for this study. It is a validation report intended for general safety application and with very large uncertainties. A more focused evaluation is preferable when a best-estimate value is requested.

ORNL also makes comments on the question of solubility limits for nitrate densities. The reported values include densities below real crystal density but with crystal density composition as well as lower densities using the same solution equation as in ARH-600 (revised 1972).

The same conclusions apply as to the EMS methods based on this cross-section library.

SERCO: MONK 8A and 8B with JEF 2.2 continuous energy cross-sections

For UO_2 systems, the values are quite close to the best-estimates and the bias-corrections based on Serco validation are small. Some slab values appear to be non-conservative.

For UNH systems, many values appear to be strongly non-conservative. The density methods are questionable (as for many other contributors) and it is difficult to see any cross-section related trends.

For PuO_2 thermal systems, the trends are interesting. The bias-corrections are opposite to those for EMS methods and reverse the trends for “raw” data results. It is not easy to say which validation works best. The IRSN isopiestic method is more often closer to the EMS values but not always.

For PuNH the cross-section motivated bias corrections are large. However, the density methods seem to be just as important. Until such validation is carried out, it is difficult to evaluate other trends.

APPENDIX M NUMERICAL AND STATISTICAL CONSIDERATIONS

This appendix collects a number of issues related to precision, accuracy, convergence, interpolation, extrapolation, etc. that determine the quality of the results.

Precision of reference values

A reasonable target for the numerical and statistical values obtained from deterministic and Monte Carlo codes is a k_{eff} with a precision of 0.001. Better precision is achievable but may not be meaningful at this stage. This k_{eff} target is translated into units of reference values by taking the logarithm of the reference value unit to changes in k_{eff} (APPENDIX D). This is how the least significant figure before (positive logarithmic value) or after the decimal point (negative logarithmic value) is obtained. The precision in the reference value will thus correspond to between 0.0001 and 0.001 in k_{eff} .

The useful precision in biases and uncertainties depends on the application and whether systematic effects are to be evaluated. As proposed in [69], at least two significant digits are motivated in each standard deviation. However, the recommendation that a measured value should have the same precision is not clear. Systematic effects could motivate much better precision in the standard deviation than in the measured value. A coverage factor larger than one may require a higher precision of the standard deviation.

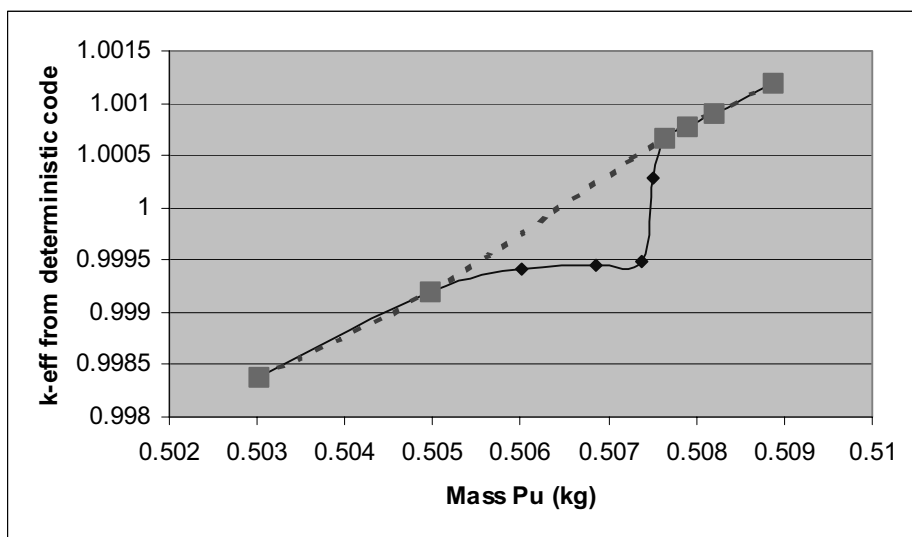
Accuracy of reference values

Unlike the precision, a requested accuracy may be difficult to achieve. It depends on many error sources. The availability and quality of adequate benchmarks (for cross-sections, nuclide densities and other data) are of particular importance.

Numerical convergence

During the evaluation of reference values using SCALE 4 in 2000, it became apparent that there was a problem with convergence, see [29].

Figure M1. Convergence deviation



The straight line with the blue diamond markers correspond to actual calculation results with XSDRNPM using the default convergence criterion of 10^{-4} . The dotted line and the purple squares correspond to the correct values. The calculations and the figure were made to demonstrate a problem to the code developers at ORNL. Their conclusion was that it was a convergence problem. Sure enough, increasing the convergence criterion to 10^{-5} solved the problem. SCALE 5 now has that as a default criterion.

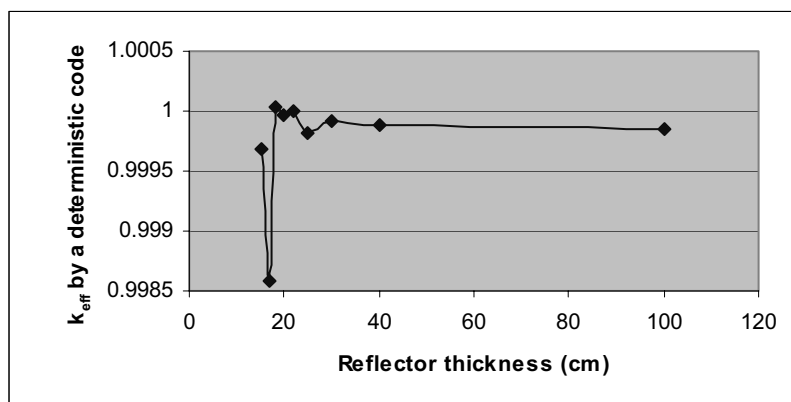
It is easy to see what types of serious mistakes that could be made if unconverged results had been used to determine sensitivities, reactivities, etc.

Geometry mesh

Modern computer codes are built into packages that simplify the work for the user in different ways. One way is to determine default parameters that are adequate for typical user problems. The mesh distribution for deterministic codes is important for the accuracy of the result but also for the calculation time. A balance between these objectives is determined by the code developers. It is the user's responsibility to make sure that the automatically generated mesh is sufficient for the problem being solved.

In SCALE 4, the mesh distributions in the fissile material centre and in the reflector are calculated by default. The user can change them by a size factor (SZF) in the calculation sequence CSAS1X or by running the XSDRNPM code separately, with full control of all input. The difference of a reflector and a moderator between heterogeneously distributed fissile "lumps" is clear to the user but may not be so easy to make when the default mesh strategy is made. During evaluations of graphite and other reflectors, a peculiar consequence of inadequate default mesh distributions was discovered, see Figure M2. Increasing the reflector thickness, it was found that k_{eff} went through a sequence of variations, with an optimum at some thickness. The figure was generated for water but the behaviour was more dramatic for graphite. From a physics point of view there is nothing to explain the behaviour; there is only a water reflector and nothing else outside this water.

Figure M2. Optimum reflection



The default mesh was sufficient for a lattice of fuel rods or similar problems. For a thick reflector, it was not sufficient. Similar conclusions can be made for several of the systems covered by the study reported here. In particular for thin (neutronically) slabs such as solid $\text{U}(100)\text{O}_2$ and all plutonium isotope distributions in PuO_2 , the mesh distribution had to be tightened to get good results. This was demonstrated by comparison of XSDRNPM and KENOVA calculations with the same cross-section libraries. The very high CRISTAL values contributed for these systems indicate a mesh inadequacy.

Angular quadrature

During the comparison of XSDRNPM and KENOVA calculations using the same cross-section libraries, it was found that the default angular quadrature of 8 in SCALE is not sufficient for fast systems. It was particularly important to increase the quadrature for volumes, less important for cylinder diameters and least for slabs. The example inputs for ICSBEP Handbook benchmarks give examples of an angular quadrature of 64. This was found to be necessary also for fast spheres in the current study. For cylinder and slabs the quadrature used for fast systems was 32. The values obtained from using a too low quadrature order seem to be conservative.

Source convergence and initial transients in Monte Carlo calculations

The systems involved in the reference value calculations are simple and no difficulty is expected concerning source convergence. The benchmarks used to validate the reference values are not very complicated either. However, to reduce the uncertainty due to source convergence and initial transients (insufficient number of initial neutrons skipped), the total number of generations were often increased compared with sample inputs and the number of skipped neutrons were also increased. Similar statistics were also applied to the calculation of reference values with the Monte Carlo codes KENOVA (SCALE 5) and MCNP5.

Error sources, uncertainties, systematic and random effects

Various error and uncertainty terms have been described in APPENDIX B. In general they seem to comply with the recommendations in the U.S. standard [94] and in the ICSBEP Handbook [68].

Examples of these terms can be taken from the validation of reference values in this study. The average deviation between calculation results and benchmarks is a combined bias of many error

sources. The remaining statistical uncertainty, obtained from making the average determination, is often assumed to be normally (Gaussian) distributed. The uncertainty gives a random effect for a single application but a systematic effect for a group of applications. The safety and economic effects of the uncertainty, as applied to many systems or operations, are systematic.

Combination of uncertainties

This issue seems to be controversial but has direct support in the U.S. standard [94] and in a ICSBEP Guide [69]. Before the discussion on combined uncertainties, an example follows.

Consider the neutron absorption rate A in a plate. Two equations are used to demonstrate the determination of the combined (total) uncertainty. The first equation is a simple sum of the absorptions A_1 , A_2 and A_3 in the present nuclides 1, 2 and 3.

$$A = A_1 + A_2 + A_3 \quad (1)$$

The other equation is related to the three input parameters neutron flux F in the plate, to the total absorption cross section S_a of the plate material and to the thickness T of the plate. The constant c is used to obtain the following relation:

$$A = c * F * S_a * T \quad (2)$$

How do the uncertainties in the individual input parameters influence the total uncertainty in A ?

The following equation is taken from the ICSBEP Guide [69]:

$$u_c^2(k_{eff}) = \sum_{i=1}^N (\Delta k_i)^2 + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N (\Delta k_i)(\Delta k_j) r_{i,j} \quad (3)$$

The input parameters are indicated by “i” and “j”. The equation is used to combine uncertainties in k_{eff} to a combined uncertainty. Standards, guides and handbooks often refer to this equation or the same principle. A necessary requirement is that all relations (sensitivities) are linear, also when the uncertainties are combined. If all uncertainties are independent, the second summation term vanishes. Can Dk values in the same system at the same time be independent?

Criticality safety specialists often answer: “Yes, if the input parameters are independent, then the uncertainties are also independent”.

Now, to consider the input parameters, let’s look at a more general source for combination of uncertainties, the U.S. standard [94]:

$$u_c^2(y) = \sum_{i=1}^N \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i) + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N \frac{\partial f}{\partial x_i} \frac{\partial f}{\partial x_j} v(x_i, x_j) \quad (4)$$

Here $y = f(x_1, x_2 \dots x_N)$. The equation (4), often referred to as the *law of propagation of uncertainty*, contains input uncertainties $u^2(x_i)$ and input covariances $v(x_i, x_j)$. An important factor now

is the partial derivative $\partial f / \partial x_i$. It is sometimes referred to as a sensitivity coefficient. Does that make it a constant? Certainly not, as will be seen by the continuation of the example started in the beginning of this section. The equation is based on a first order Taylor expansion of the function y . This is probably not sufficient for many criticality safety evaluations with crude approximations and associated uncertainties.

Going from equation (4) to (3) means that the neutron flux has to be considered as a parameter within the range “i” of parameters. This will not be easy to do. The flux uncertainty is a function of every other parameter uncertainty. The sensitivity of k_{eff} to a flux uncertainty (a probability distribution) is a very complex problem to solve. The covariances between the flux and other uncertainties will not be zero.

If equation (1) includes only independent uncertainties, each partial derivative becomes one and the equation becomes a summary of the variances (square of standard deviations).

$$u_c^2(A)_{\text{total}} = \sum_{i=1}^N u^2(A_i) \quad (5)$$

Are the uncertainties independent? The three terms in equation (1) are essentially based on equation (2) for each nuclide.

If the input parameters in equation (2) are independent, the partial derivatives becomes $c \cdot S_a \cdot T$, $c \cdot F \cdot T$ and $c \cdot F \cdot S_a$ respectively. The independence of the input parameters makes **their** correlation term vanish. However, the uncertainty terms are correlated to the input parameters through the partial derivatives (all but one term) or the input parameter uncertainty (the remaining term). The terms in the sum are correlated through their common dependence on each input parameter.

$$u_c^2(A)_{\text{total}} = (c \sum_a T)^2 u^2(A_1) + (c \Phi T)^2 u^2(A_2) + (c \sum_a \Phi)^2 u^2(A_3) \quad (6)$$

There is a simpler way of writing this relationship using relative uncertainties. It applies to functions that depend on products of parameters (covers division since it is a product of the inverse parameter). It is easy to derive by dividing the equation with the square of the function (A or $c \cdot F \cdot S_a \cdot T$).

$$\frac{u_c^2(A)_{\text{total}}}{A^2} = \frac{u^2(A_1)}{A_1^2} + \frac{u^2(A_2)}{A_2^2} + \frac{u^2(A_3)}{A_3^2} \quad (7)$$

The ratios are relative variances. The relationship still requires independence between the input parameters. It must not be more complicated than a product of two or more parameters.

Of the three input parameters F , S_a and T , there is one that is influenced by the others. It is of course the neutron flux F . Even if the beam from some neutron source will not be influenced by the other two input parameters, S_a and T , the neutron flux in the plate will be. Self-shielding related to resonance absorption is familiar to criticality safety specialists. The neutron energy spectrum will be depleted by strong absorption in the plate. Each absorber nuclide will change the spectrum for the other nuclides. Moderation and reflection will do the same. This is dependence.

In a critical system, the situation is much more complex. The relationship of k_{eff} to the transport equation is not a simple product of independent parameters. Unlike the neutron beam in the previous paragraph, the neutron source is very strongly dependent on the changes in the system. A reduction of the plate thickness or removal of strong neutron absorbers from the plate may actually increase the neutron absorption in the plate. The reason would be that the removal of the absorber nuclides causes the fundamental mode to change to give a very strong neutron flux in the plate (an increase of the neutron flux by ten orders of magnitude and more is possible).

The neutron flux correlation is a missing link. Rather than rewriting this section to propose a solution, a separate APPENDIX S is added.

Interpolation

The different contributors have approached the issue of moderation optimisation differently. Similarly, the issue of interpolation to obtain critical values from values near criticality has been treated differently. An important issue is how close the calculation points are. Significant interpolation errors have been observed.

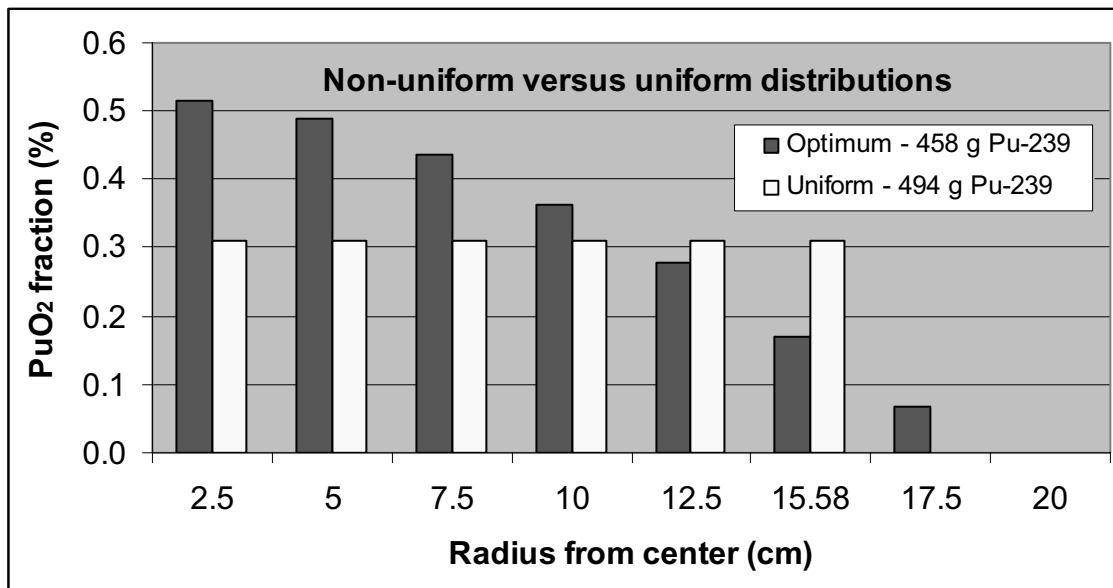
In the EMS contribution from 2001, an effort had been made to determine a reasonable precision of the requested values. This is the same logarithmic method as used in this report, APPENDIX D. Optimisation and interpolation were made to allow such precision. A comparison with other contributions shows that they sometimes are not as precise. Large spacings between parameter values without adequate curve-fitting lead to quite large errors in a few cases.

APPENDIX N MINIMUM AND OTHER REFERENCE VALUES

The minimum critical values are not always minimum. As pointed out before, the limiting moderation ratios H/X of interest can be either minimum or maximum, as shown in some IRSN reports. Heterogeneous arrays of fuel rods can reduce the “minimum” critical mass. The SMORES sequence [85] in SCALE 5 can be used to calculate optimum non-uniform distributions. The Japanese Handbook 2 [24] contains such information.

The result of using SMORES on a $\text{Pu}(100)\text{O}_2$ mixture with water to determine the minimum critical mass is shown in Figure N1.

Figure N1. Minimum critical mass of $\text{Pu}(100)\text{O}_2$ in uniform and non-uniform distributions



The minimum critical mass for a uniform distribution is 494 g ^{239}Pu and the radius is 15.58 cm. For a non-uniform distribution, SMORES finds a critical mass of 458 g ^{239}Pu and the radius is now increased to 17.5 cm. A slightly smaller mass may be possible with more geometry regions. SMORES is a new tool and it is quite complicated to get convergence. It would be useful to create a few benchmarks for non-uniform distributions. The result was obtained with the 44-group cross-section library. It was confirmed using a direct XSDRNPM/S calculation using the 238-group library.

Comparisons of simple k_{inf} calculations can provide important information. Examples are the problem with ^{241}Am in JENDL-3.3 (now revised to solve the problem) and problems with the MONK DICE library. Both of these problems were found (EMS and Serco respectively) during comparisons of k_{∞} calculation results for actinide nuclides.

In the determination and use of the concept of “minimum critical concentration”, it is very important to understand its meaning. It is not a minimum critical density, even though the units may be identical (e.g. g/cm^3). The concentration is for the fissile material and pure water only and there must not be any voids within the material. A powder particle, with lower than theoretical density, must be completely “flooded” internally with water to fulfil the specifications. The sum of the fractions of theoretical densities must be one. With voids or low-absorbing nuclides present, the minimum critical concentration, if measured in grams per total volume (e.g. g/cm^3), will be lower. To avoid potentially

dangerous situations, it may be better to specify the concentration limits as atomic number density ratios (e.g. H/U) or mass ratios (e.g. mass of fissile nuclides per mass of hydrogen).

Another reference value is that which corresponds to criticality for a soluble material at theoretical density. In this study, such reference values for UNH and PuNH crystal density materials would be valuable.

An issue that has been discussed, in particular in the development of transport safety regulations, is the significance of natural and depleted uranium for criticality safety. Addition of natural or depleted uranium to the approved contents of a package can cause criticality if it is not accounted for as a fissile material. Some authorities are aware of this and express it in the certificate to avoid confusion or mistakes. Other authorities are not as aware of the criticality safety significance of natural and depleted uranium. Multilateral approval requirements reduce the remaining risk but it is still there. For packages or materials that don't require criticality safety licensing, the exception criteria are clearly not based on exclusion of fissile nuclides in natural and depleted uranium.

The minimum concentrations (or maximum H/X ratio) that can support criticality were requested for this study and have been evaluated. Very similar values are used to define the exception criteria in the IAEA Transport Regulations. The concentrations are exactly critical in infinite amounts. Will the addition of natural or depleted uranium increase or reduce k_{eff} ?

Pu(100)O₂ in water at the limiting plutonium concentration was evaluated first. Using MCNP5 and the JENDL 3.3 rev.1 cross-section library, k_{∞} for just the plutonium/water mixture was calculated as 0.9991 ± 0.0002 . An infinite slab geometry with alternate 4.0 cm thick slabs of the Pu(100)O₂/water mixture and 1.0 cm thick slabs of natural uranium was then calculated using the same method. The resulting k_{∞} is 1.1002 ± 0.0003 . A similar system with U(100)O₂ in water at the limiting uranium concentration, except that the natural uranium slabs were 1.2 cm thick, resulted in a k_{∞} of 1.0925 ± 0.0004 . A system with U(3)O₂ in water at the limiting uranium concentration, with the uranium/water mixture 2.0 cm thick and the natural uranium slabs 0.4 cm thick, resulted in a k_{∞} of 1.0441 ± 0.0004 .

The systems are not quite optimised but sufficiently clear to demonstrate that not only natural but also depleted (to some level) uranium can cause super-criticality in a system that is safe without the natural or depleted uranium. See also [102] concerning the influence of natural uranium on a sub-critical assembly.

APPENDIX O REFLECTION

The scope and objectives refer to reflection. Both IRSN and EMS have studied and reported influences of different reflecting materials, alone or in combination. There are also many ICSBEP Handbook benchmarks with different reflectors. Some notes on this will be added before the report is final.

The EMS results [30] and [95] have been obtained for all fissionable nuclides. The purpose was to find the most efficient reflector combination for each nuclide. The combinations were water alone, steel alone, lead alone, 1.5 cm water plus lead and 1.5 cm water plus steel. In addition, natural uranium alone and 3 cm water plus natural uranium replacing the reflector material were calculated (natural uranium is a fissile material, not a reflector). It was found that a thin layer of water, usually together with steel but sometimes with lead, reduced the minimum critical values for fissile nuclides. For non-fissile nuclides, only steel or only lead were more efficient. It was also found that lead became a better reflector than steel for large units and for arrays while steel was more efficient for small units. This was also found in an independent study by IRSN.

The IRSN results [41] for nitrates are directly of interest for this study since they cover some of the fissionable materials and the same reference parameters as the study. The corresponding reference values are also included in [59]. IRSN found a similar optimum as EMS for a water-layer of about 1.5 cm between the fissile material and a lead reflector, figures A.38 and A.39 in [41]. There are benchmarks based on critical experiments that can be used to verify the combined effect of a thin water layer between fissile material and lead.

The influence of concrete and lead on the reference parameters are shown in Table O1 and Table O2. Note that the composition of concrete can vary a lot.

The values are not interpolated; the nearest calculation value was selected. In particular for spheres (mass and volume parameters), the interpolation may be difficult. The Rombough equation [96] is very useful for interpolation of these parameters, see APPENDIX Q.

The general importance of considering other reflector materials than water is evident from preliminary IRSN and EMS evaluations. The effect of moderation in the reflector (concrete) can be seen for the non-moderated systems. In these cases concrete is a better reflector than lead. However, the combination of a thin water layer and lead, as discussed in some IRSN and EMS reports and has been familiar to criticality safety specialists at least for 40 years, would give even smaller critical parameter values. This is different than the combination of lead and outside water reflection often used in France.

Table O1. CRISTAL - UNH with different reflector materials

CRISTAL - Reference values for different reflector materials						
System	Isotopes	Mass (kg)	Volume (l)	Cylinder (cm)	Slab (cm)	Conc. (g/cm ³)
UNH + 20 cm water	100	0.81	6.54	14.88	5.4	12
	20	5.92	16.03	20.92	9.18	65
	5	75.38	80.48	37.82	20.04	137
	4	144.2	134.92	45.18	24.98	415
	3	464.9	365.5	64.62	37.4	624
UNH+ 60 cm concrete	100	0.71	5.77	13.1	2.7	
	20	5.17	13.82	18.58	5.74	
	5	64.09	67.38	34.04	15.08	
	4	122.69	113.23	41.2	19.58	
	3	399.88	312.15	59.56	31.42	
UNH + 25 cm Pb + 20 cm water	100	0.58	5.09	11.98	2.3	
	20	4.17	11.56	16.54	4.14	
	5	49.97	53.25	29.64	10.46	
	4	95.37	88.61	35.88	13.8	
	3	313.2	244.1	52.28	23.32	

Table O2. CRISTAL - PuNH with different reflector materials

CRISTAL - Reference values for different reflector materials						
System	Isotopes	Mass (kg)	Volume (l)	Cylinder (cm)	Slab (cm)	Conc (g/cm ³)
PuNH + 20 cm water	100/0/0/0	0.51	7.57	15.66	5.84	7.2
	95/5/0/0	0.63	10.74	17.94	7.24	7.8
	80/10/10/0	0.71	12.06	18.74	7.7	8.07
	90/10/0/0	0.77	13.29	19.46	8.18	8.47
	80/15/5/0	0.89	15.24	20.48	8.83	9.1
	71/17/11/1	0.92	15.6	20.66	8.9	9.2
PuNH+ 60 cm concrete	100/0/0/0	0.45	6.42	13.6	2.96	
	71/17/11/1	0.78	13	18.02	5.16	
PuNH + 25 cm Pb 20 cm H ₂ O	100/0/0/0	0.36	5.6	12.32	2.35	
	71/17/11/1	0.62	10.73	15.9	3.68	

APPENDIX P HUMAN ERROR

Human error (APPENDIX B) during input preparation, during derivation of the best estimate critical values or during documentation cannot be excluded. It is easy to suspect human error whenever outliers are encountered, but this must be done with great caution. Agreement between results may involve common input data errors (nuclear data, density data, etc.).

Admitting to the existence of human error is a fundamental basis for quality and for safety. Like for systematic effects, the probability distribution of human error effects can be estimated. Also like for systematic effects, the influence of human error can be reduced with additional resources and some of its effects can be corrected for. The corrections may be very different for accuracy and for safety applications. This study focuses on accuracy (physical constants are requested).

Statistically, a benchmark with an uncertainty of 0.001 is worth as much as ten benchmarks with uncertainties of 0.003. The ten benchmarks need to be completely uncorrelated (experimental configuration, manufacturing, measurement system, chemical analysis, etc.). Otherwise only the random effect of the uncertainty will be reduced, not the systematic effect.

From a human error point of view, the set of ten uncorrelated benchmarks has an advantage: some single mistakes or omissions do not so easily influence all benchmarks.

APPENDIX Q EXPERT GROUP INFORMATION

Participants

The participation has varied slightly during the years. The participation can be separated into different types: meeting participation, reference value contribution and to sponsoring. All have been important but the list here will follow the most active participants from each contributing country.

- France
 - IRSN
 - Jacques Anno
 - Veronique Rouyer
- Germany
 - BfS -
 - H. Schweer
 - GRS - Gesellschaft für Reaktor und Sicherheit
 - Wolf Weber (coordinator, chairman)
 - Bernhard Gmal
- Japan
 - JAERI
 - Hiroshi Okuno
 - NAIS
 - Yoshitako Naito
 - NUPEC
 - Susumu Mitake
- Russia
 - IPPE
 - Anatoliy Tsiboulia
 - Eugeni Roshikhin
- Sweden
 - EMS
 - Dennis Mennerdahl
- United Kingdom
 - DfT
 - Nicholas Barton
 - HSE NII
 - David Simister
 - Serco
 - Dave Hanlon
- United States
 - ANL
 - Ed Fujita

- INEL
 - Blair Briggs
- LANL
 - R. E. Anderson
- ORNL
 - Calvin Hopper
 - Cecil Parks
 - Mike Westfall
- PNL
 - Mikey Brady-Raap
- OECD/NEA
 - Ali Nouri

IPPE and Serco have not participated in so many meetings but have been active in contributing reference values. Other participants not mentioned here have contributed to the discussion at meetings.

Meetings and some significant communication

The expert group was discussed during the previous Working Party meeting in 1998, but it was formally started after that. W. Weber (GRS) was the coordinator of the Expert Group and the chairman during most meetings.

- 1st meeting, 15 September 1999.
 - Chaired by B. Gmal, in the absence of the expert group chairman W. Weber.
 - Some previously existing data were reported from Japan, France, Germany, Russia and USA.
 - ISO and ANS 8.15 standards development was discussed.
 - Best estimate values were proposed by R.M. Westfall (ORNL). The group agreed but there was no common understanding on how to obtain those values.
 - J. Anno (IRSN) presented several French efforts in compiling criticality safety data. The importance of chemical and engineering data for criticality calculations was pointed out. Study of a fissile solution with a density gradient was proposed. A very useful compilation of density laws was included in a table. Another table demonstrated the limitations of the IRSN law used at the time (DILAPO, called PreIso in this report).
 - H. Okuno (JAERI) proposed simple geometry systems.
 - B. Gmal (GRS) reported on a recent revision of the German Criticality Handbook. Further, new SCALE-4.3 and MCNP-4A critical values obtained by W. Weber were reported.
 - Y. Naito (NAIS) reported on a web site that had been started to support the collection of critical values.
 - Recommendations:
 - Data to be collected by Y. Naito for introduction on the NAIS web page
 - The data needed at first were values for basic systems of U-233, U-235, Pu-239 metal and oxide water mixtures.
 - If possible estimates of uncertainties of the values should be provided
 - Preliminary deadline is 31st January 2000
- September 7, 2000. E-mail from Y. Naito concerning the current status of the web site. Many

important suggestions and conclusions were given. Some quotes follow below:

- Data not registered: $\text{UO}_2 + \text{H}_2\text{O}$ and $\text{UO}_2\text{F}_2 + \text{H}_2\text{O}$ without reflectors, systems with Pb reflection, fuel lattices, U-Pu systems, minor actinide (MA) data, ^{233}U data. This shows how very wide the scope still was.
 - “We must establish the criterion to select the data which should be registered”. The issue of different qualities of the data was clearly pointed out at this time.
 - “My idea is that we accept every data which are supplied by WG members if they think the data are the best of minimum critical data”.
 - “We have not much information about MA critical data. In such a case, we must accept pure calculation results.”
- 2nd meeting, 12 September 2000.
 - The final scope and objectives were defined.
 - Recommended values will not be given to avoid difficulties in countries where licenses are based on minimum critical values.
 - A limitation to two or three fissile systems was determined for an intermediate compilation. Various proposals were given but no specification was made.
 - Report the intermediate compilation to the Working Party by end of February 2001.
- 4th WPNCS Meeting, September 15, 2000
 - The Weber report to the WP expressed the opinion that only existing data were to be compiled, re-calculations were not intended. The aim was to present the range of values existing in different countries. [This is not what the scope and objectives state. It is not what some of the participants expected. See also new calculation results from ORNL, EMS, Serco, IRSN, IPPE/Editorial comment 2005]. Consensus on recommended values was not needed. This was agreed for the first part of the study. The web-site was slightly awkward. Exchange of Excel files was recommended.
- 3rd meeting, 5 December 2001.
 - The chemical compounds were limited to UO_2 , UNH, PuO_2 and PuNH during 2001.
 - France, Sweden, UK and USA presented new contributions.
 - J. Anno presented the new isopiestic method for nuclide densities in solutions.
 - Preparations to create an Intermediate Compilation report were made. The idea was to let the contributors compile their methods and data. After that reviewers were supposed to evaluate differences in the results. The report was planned for the middle of 2002.
- Questionnaires in Microsoft Excel format were prepared by the coordinator W. Weber and distributed during 2002. Contributors were requested to fill in information on methods and input for the calculations. IRSN and some Serco information was distributed. EMS prepared all information, but it may never have been distributed.
- 4th meeting, 10 September 2002.
 - There were now 570 entries on the NAIS web page, an increase by 140 from the previous meeting.
 - A proposal for contents of a report was presented by W. Weber.
 - There was considerable discussion on the criteria for evaluation and the quality of the data.
 - Plans for completing the report were drawn.
 - Y. Naito added a hand-written summary of conclusions and recommendations. Agreed to by D. Mennerdahl. The data are best-estimate values. It was not necessary to agree on recommended or standard values (at this time). It was also pointed out that the plutonium vector 71/17/11/1 had been added by the Expert Group. This was not clear to all participants until 2002.

- 6th meeting of the WPNCS, Paris, 12 September 2002
 - The Expert Group members discussed an outline of the report which will assemble the minimum critical values collected so far. The document will also describe the methods used for the derivation of these data. The discrepancies between the compiled data will be assessed and an attempt will be made to explain the most important reason(s) for the discrepancies. [Comparing discrepancies between non-validated values would be essentially useless, Editorial comment 2005]
 - On new programs of work: The Expert Group participants will mainly concentrate on the completion of the compilation report for the selected fissile media. **A year or two would be needed in order to finalise this effort.** After that, new media can be also studied.
- Unofficial meeting hosted by S. Mitake, Tokyo 16 October 2003.
 - W. Weber presented a summary of results and the spread of the results related to their age.
 - There were long discussions on the benefits of determining best-estimate values.
- 7th WPNCS meeting in Tokyo, October 17, 2003.
 - Wolf Weber proposed the following time schedule for the assembly and publication of the final report:
 - November 2003 - January 2004: Assembly of the report.
 - February 2003 - March 2004: Peer-review
 - April 2004: Publication of the report
 - The proposal was accepted.
 - For the continuation of this activity beyond the publication of the aforementioned report, the Expert Group on Minimum Critical Values needs to submit to the WPNCS for approval of a detailed programme of work including the intended deliverables and corresponding time schedules.
- 5th meeting, 31 August 2004.
 - Chaired by D. Mennerdahl. The expert group formally did not exist anymore. The primary purpose of the meeting was to arrange a documentation of the study in a report.
 - The structure of a draft report, essentially from 2002, by W. Weber was discussed.
 - A revised structure, added and revised results, as well as some extensions to the W. Weber draft report was presented by D. Mennerdahl.
 - D. Mennerdahl was asked to prepare a final draft report for Christmas (2004). He accepted. This was later accepted by the Working Party (meeting on 3 September 2004).
 - A list of issues [13] was prepared by D. Mennerdahl during and after the meeting on the morning of August 31. During the time between the meeting and the Working Party Meeting on September 3, very constructive responses were obtained from almost all participants that were asked, including some by email from absent participants.
 - JAERI presented the coming Data Collection 2 related to the Japanese Handbook. The validation will be significantly improved by the availability of the ICSBEP Handbook. In the previous validation, the experimental biases were not considered. The Moeken equation for low-enriched uranium gave considerable errors in the first Data Collection. The background of the very high minimum critical value for U(20)O₂ in the first Data Collection was given (the minimum was not properly searched). The incorrect value was given to the Expert Group and had not been corrected before this meeting.

- Work on final draft after the 5th meeting.
 - A first version of a terminology appendix was distributed.
 - Due to other commitments, the work on the final draft started seriously in mid-October 2004.
 - The TSUNAMI sequences and modules in SCALE 5 were used to generate similarity indices for a number of benchmarks with the applications.
 - The SMORES sequence in SCALE 5 was used to see the influence of non-uniform distributions.
 - Thousands of calculations of reference values and benchmarks from the ICSBEP Handbook were calculated with MCNP5 and many cross-section libraries as well as with SCALE 5/XSDRNPM and SCALE 5/KENOVA and several cross-section libraries.
 - IPPE supplied results for benchmarks and reference values.
 - Results were documented in tables. Charts were generated.
 - Several discrepancies were discovered and discussed with contributors.
 - A comparison of methods used to determine nuclide densities was made and distributed to the contributors (not to all participants) in early March 2005.
 - Extensive communication on nuclide density methods during first 3 weeks of March.
 - March 26 (Easter). The last words on the final draft completed and it was distributed.
 - April 1. IRSN informs about the withdrawal of preliminary results for UO₂ and PuO₂.
 - April 17. Appendix S; “The missing link” involving correlations through the neutron flux is added.
 - May 4. IRSN contributes approved values for uranium and plutonium dioxides.

APPENDIX R FUTURE CONSIDERATIONS

The study carried out so far is valuable for several purposes. It fits very well with other OECD/NEA activities and not only those related to criticality safety:

- It provides an excellent opportunity for demonstrating how validation based on the ICSBEP Handbook works.
- The comparisons of results from many sources are valuable to licensing authorities, particularly in the international transport area, but also to any criticality safety specialist who needs independent verification or needs to understand differences between results from different methods.
- The results and the information about methods are valuable for development of standards, handbooks, guides and safety recommendations.
- The reference values can be made more accurate than most benchmarks based on individual critical experiments. This makes them valuable for validation of methods, in particular for deterministic methods for which benchmarks based on critical experiments are few.
- Discrepancies between reference values in published handbooks, standards and guides have been clearly demonstrated and several of them explained. Some of the standards may be old but they are still used, in particular in older safety assessments that are still applied.
- The importance of including nuclide density determination and other input preparation methods in the validation has been pointed out.

Future phases of the study could include some of the following issues:

- Improvement of the current results. New methods and data for validation, neutron transport and nuclide density determination can be taken advantage of. Uncertainties need to be evaluated.
- New methods for evaluation of similarities between benchmarks and applications, for finding significant trending parameters and values, correlations between benchmarks, etc., with the focus on reference value determination.
- Additional fissionable nuclides and elements, including mixtures of elements. Several participants contributed values for other ^{235}U enrichments and plutonium isotopic distributions than the ones the study was finally limited to.
- Other chemical compounds and solutions. Several participants contributed values for other compounds than the four that the study was finally limited to. In particular UO_2F_2 generated significant interest and response.
- Heterogeneous and non-uniform materials.
- Comparisons of k_∞ for nuclides, elements, compounds, solutions and mixtures with water. A very simple calculation that is also very informative. See discussion below.
- Other reflector materials than water. Already included in the current scope.
- Theoretical densities for nuclides, elements, compounds, solutions and mixtures of these are essential for criticality safety evaluation. There are also other relations and data that can be

compared for the benefit of the criticality safety community. Best estimates of such data can be compiled.

- Evaluation and demonstration of empirical methods for curve-fitting of k_{eff} to reference parameters. The equation and method proposed by Rombough [96] for displaying the relationship between k_{eff} and the fissionable material spherical radius is a good example. The parameters a, b and c need to be determined using curve-fitting techniques (e.g. non-linear regression).

$$k_{\text{eff}} = k_{\infty} * (1 - e^{-R/a})^b * R^c$$

- Use of h (eta) in the evaluation of criticality properties of different nuclides, elements, compounds and mixtures. The OECD/NEA code JANIS [71] can be used to display h and other properties.

Demonstration of usefulness of k_{∞} comparisons

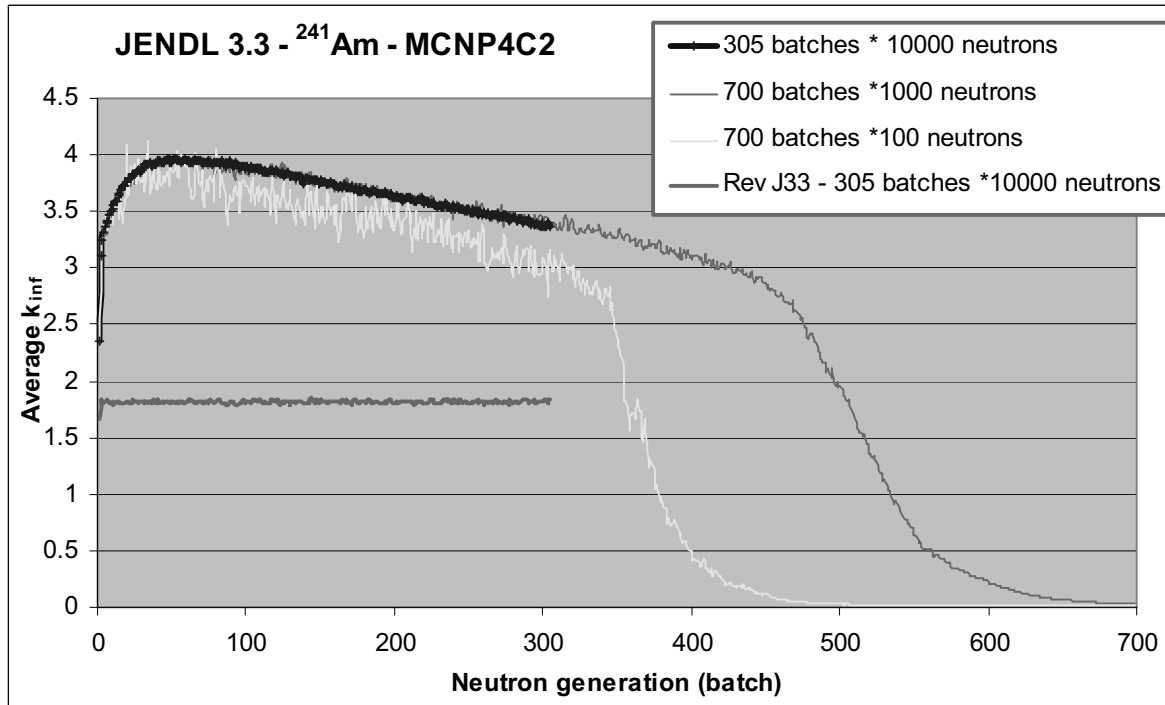
During a recent European Commission (EC) study [95] of criticality properties of all fissionable nuclides, involving several of the participants (IRSN, DfT, Serco and EMS), a comparison of k_{∞} values turned out to be very productive.

An unpublished ACE cross-section library (for use with MCNP), based on JENDL-3.3 and processed by KAERI (South Korea), showed an extremely strange k_{∞} behaviour for ^{241}Am , see Figure R1. This nuclide is important in many studies, e.g. in actinide transmutation and is also present and significant in some benchmarks (decays from ^{241}Pu).

The figure shows that k_{∞} calculated with MCNP4C2 and JENDL-3.3 rev. 0 cross-sections depends strongly on the number of batches, almost independent of the number of neutrons per batch. In the first part of the calculation, k_{∞} increases from less than 2 to about 4 and after that it keeps falling to below 0.01. KAERI was informed, but since their ACE library was not an official product, JAERI was not informed until an official ACE library from them was released, almost a year later. The problem remained. There was a combination of errors and omissions in the basic JENDL-3.3 library causing the problem. Revision 1 of JENDL-3.3 solves the problem.

A lesson to be learned from this is that simple k_{∞} comparisons can quickly reveal serious deficiencies in cross-section libraries. Not until 18 months after the release of JENDL-3.3, at the ICNC 2003 conference in Tokai-Mura, Japan [59], the problem was made aware to the JENDL-3.3 developers. This delay appears unnecessary.

Figure R1. Extreme behaviour of original JENDL-3.3 ²⁴¹Am cross-section



Another example of k_{∞} discrepancies from the EC study [95] involved differences between MONK and MCNP calculation results even when cross-section libraries based on the same basic ENDF/B-VI library were used. Serco noted the differences and decided to look at the issue. They had already discovered a problem with use of the DICE library for certain applications.

Serco has been involved in the study reported here, in the EC study and in development of a revision of the ANS 8.15 standard for many fissionable nuclides. During the evaluation of the minimum critical mass for ²⁴¹Am, Serco was doing the calculations. The problem with the DICE library, noticed during the EC project, turned out to be significant for the ²⁴¹Am critical mass determination [59].

Since Serco has been involved in the current study, it is assumed that there is no significant influence of this problem on the MONK-8A and -8B reference values. The cause of the problem was also related to a lack of interpolation of less accurate data for minor actinides. It would not be noticeable for the current uranium and plutonium nuclides.

Another lesson, to be learned from the EC project, is that international studies can serve as sources for information on difficulties, discrepancies and other problems with currently used methods in nuclear criticality safety.

K_{∞} and other reference values with different reflector materials

A typical structure for compilation of reference values including k_{∞} and critical masses for different reflectors is shown in Table R1. Uncertainties should also be added. Influence of water moderation can be displayed in Table R2.

Table R1. Reference values for different reflector materials

Fission- able nuclide	Theor. density (g/cm ³)	k _∞	M _{cr, b} Bare spher e (kg)	M _{cr, h2o} Sphere + 20 cm H2O (kg)	M _{cr, ss} Sphere + 30 cm steel (kg)	M _{cr, pb} Sphere + 25 cm lead (kg)	M _{cr, nu} Sphere +25 cm U _{nat} (kg)	M _{cr, hss} Sphere + 1.5 cm H2O +30 cm steel (kg)	M _{cr, hpb} Sphere + 1.5 cm H2O +25 cm lead (kg)	M _{cr, hnu} Sphere + 3.0 cm H2O + 25 cm U _{nat} (kg)
²²⁹ Th	11.575									
²³¹ Pa	15.336									
²³² U	18.681									
²³³ U	18.762									
²³⁴ U	18.842									
²³⁵ U	18.923									
²³⁵ Np	20.303									
²³⁶ Np	20.389									
²³⁷ Np	20.476									
²³⁶ Pu	19.601									
²³⁷ Pu	19.685									
²³⁸ Pu	19.768									
²³⁹ Pu	19.851									
²⁴⁰ Pu	19.934									
²⁴¹ Pu	20.017									
²⁴² Pu	20.101									
²⁴⁴ Pu	20.267									
²⁴¹ Am	13.660									
^{242m} Am	13.717									
²⁴³ Am	13.774									
²⁴² Cm	13.407									
²⁴³ Cm	13.463									
²⁴⁴ Cm	13.518									
²⁴⁵ Cm	13.574									
²⁴⁶ Cm	13.629									
²⁴⁷ Cm	13.685									
²⁴⁸ Cm	13.740									
²⁵⁰ Cm	13.851									
²⁴⁷ Bk	14.671									
²⁴⁸ Bk	14.731									
²⁴⁹ Bk	14.790									
²⁴⁸ Cf	15.050									
²⁴⁹ Cf	15.110									
²⁵⁰ Cf	15.171									
²⁵¹ Cf	15.232									
²⁵² Cf	15.292									
²⁵⁴ Cf	15.412									
²⁵² Es										
²⁵⁴ Es										
²⁵⁷ Fm										
²⁵⁸ Md										
²⁶¹ Md										
²⁶⁵ Md										
²⁷⁰ No										
²⁷⁸ Sg										
²⁸² Hs										
²⁸⁷ 110										
²⁸⁸ 110										
Others										

Table R2. Influences of water moderation

Fissionable nuclide	k_{∞} H/X									Fissile? (Y/N)
	0.01	0.1	1	10	100	1000	10000	100000	1000000	
²²⁹ Th										N
²³¹ Pa										N
²³² U										Y
²³³ U										Y
²³⁴ U										N
²³⁵ U										Y
²³⁵ Np										N
²³⁶ Np										Y
²³⁷ Np										N
²³⁶ Pu										Y
²³⁷ Pu										Y
²³⁸ Pu										N
²³⁹ Pu										Y
²⁴⁰ Pu										N
²⁴¹ Pu										Y
²⁴² Pu										N
²⁴⁴ Pu										N
²⁴¹ Am										N
^{242m} Am										Y
²⁴³ Am										N
²⁴² Cm										N
²⁴³ Cm										Y
²⁴⁴ Cm										N
²⁴⁵ Cm										Y
²⁴⁶ Cm										N
²⁴⁷ Cm										Y
²⁴⁸ Cm										N
²⁵⁰ Cm										N
²⁴⁷ Bk										Y
²⁴⁸ Bk										Y
²⁴⁹ Bk										N
²⁴⁸ Cf										N
²⁴⁹ Cf										Y
²⁵⁰ Cf										N
²⁵¹ Cf										Y
²⁵² Cf										Y
²⁵⁴ Cf										N
²⁵² Es										Y
²⁵⁴ Es										Y
²⁵⁷ Fm										Y
²⁵⁸ Md										Y
²⁶¹ Md										N
²⁶⁵ Md										N
²⁷⁰ No										N
²⁷⁸ Sg										N
²⁸² Hs										N
²⁸⁷ ₁₁₀										Y
²⁸⁸ ₁₁₀										N
Others										?

During the EC project [95] it became clear how useful the Java-based code JANIS could be for displaying actinide nuclide properties. The reasons why certain nuclides behave in a certain way, or rather why the cross-sections indicate such behaviour, can be understood by looking at the charts generated by JANIS. A few examples taken from [72] are shown here.

The minimum critical mass for ^{242}Cm was found to be a factor more than 30 higher using ENDF/B-VI.8 (and earlier) rather than JENDL-3.3 (and 3.2 as well as JEFF-3.0) cross-sections. The h values for JENDL 3.3 and ENDF/B-VI.8 are shown in Figure R2. and Figure R3.

Figure R2. JENDL-3.3 η (eta) for ^{242}Cm

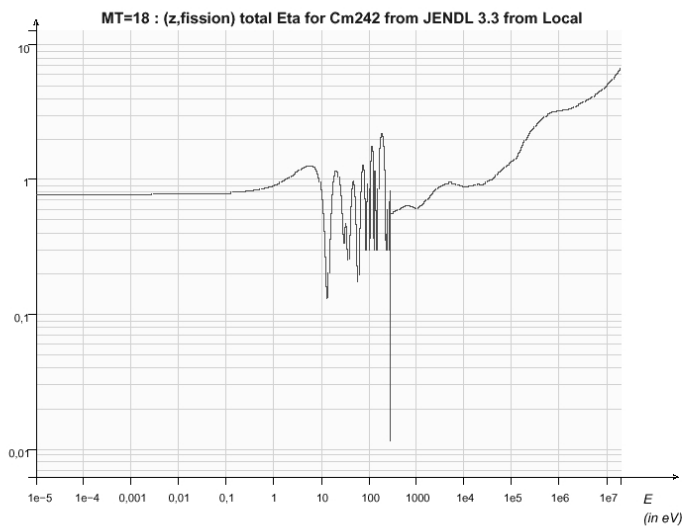
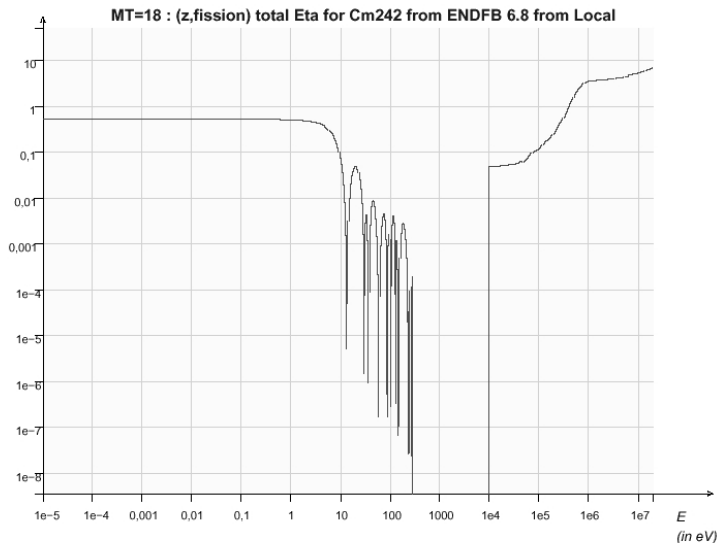


Figure R3. ENDF/B-VI.8 η (eta) for ^{242}Cm



It is not difficult to see why the critical mass based on ENDF/B-VI.8 is high. The logarithmic scale does not show the low η (eta) value in the intermediate energy range from a few hundred to 10 000 eV. It is zero over this range. JANIS supports display of overlaid charts, see Figure R4.

It is also easy to see that natural uranium is a fissile element,

Figure R4. ENDF/B-VI.8 and JENDL-3.3 (η) for ^{242}Cm

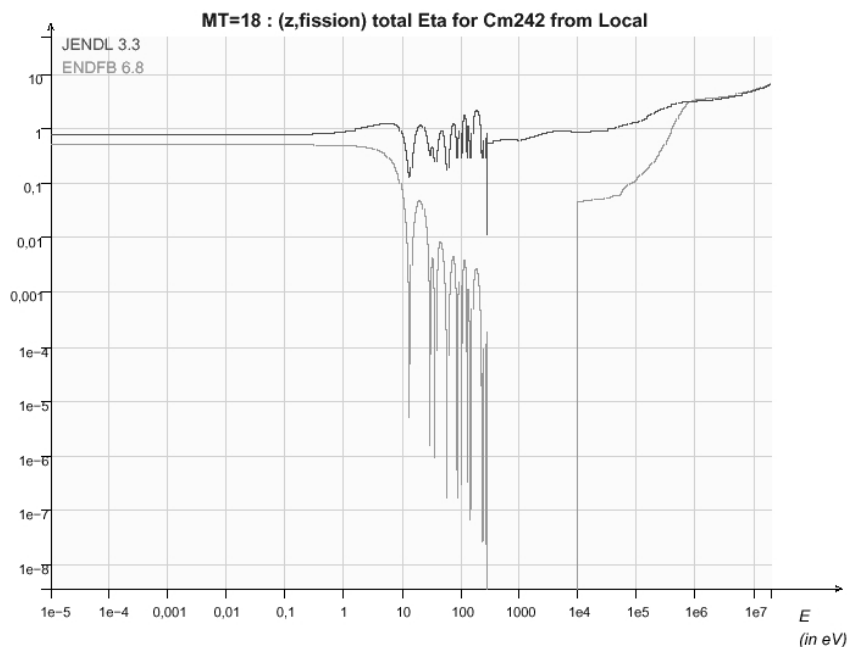
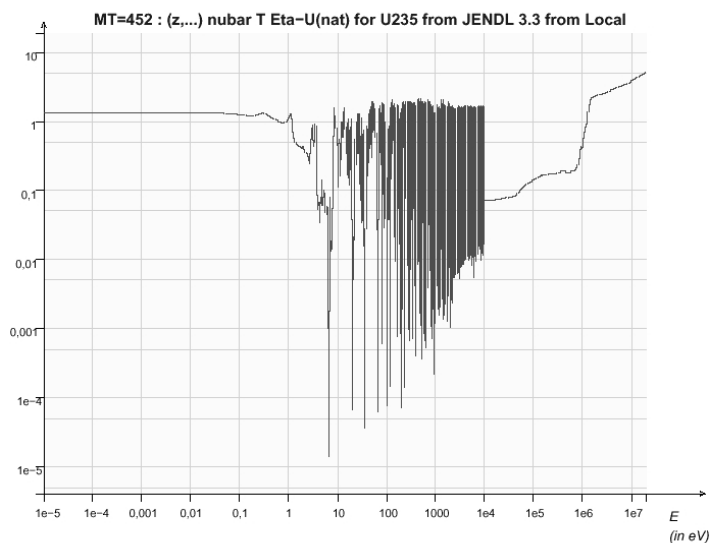


Figure R5. JENDL-3.3 (η) for natural uranium



APPENDIX S COMBINED UNCERTAINTY - THE MISSING LINK

Evaluation of criticality safety variations and incidents as well as of k_{eff} uncertainties requires a good model of neutron physics. The combined uncertainty in k_{eff} due to various parameter uncertainties needs to be determined in benchmark, reference value and criticality safety evaluations.

In this appendix, some terms and notations that may be different from definitions in other applications will be used. This is not intentional; the purpose is to describe the physics of the system in simple terms. Neutron removal refers to the fraction and energies of neutrons that are removed from the system or a system region through absorption (capture, fission, etc.). The neutron production properties refer to the probabilities for neutron-atom interactions that produce new neutrons and to other information that determines the result of the neutron removal.

From a physics point of view, k_{eff} is defined as the ratio between chain-reaction-induced neutrons (excluding spontaneous fission and other fixed neutron sources) divided by removed (lost) neutrons. Not only fission but also other neutron producing reactions such as n-2n are covered. The removed neutrons refer to neutrons that were produced in the previous generation. Each generation corresponds to a converged process, meaning that a new generation only differs from the previous generation in the number of neutrons produced, not in their spatial or energy distributions.

A simplified and commonly misunderstood k_{eff} model

A model that is commonly used to determine the combined k_{eff} uncertainty leads to the conclusion that individual k_{eff} uncertainties in the same system can be independent. Such conclusions seem to be based on the relationships between the probabilities for the input parameter uncertainties. Something is missing in such a model; the global uncertainty caused by a local uncertainty in a material property. The global uncertainty is related to the neutron flux and not to a k_{eff} value.

The combined uncertainty is given in an ICSBEP guide [69] (a factor 2 is missing in [92]).

$$u_c^2(k_{\text{eff}}) = \sum_{i=1}^N (\Delta k_i)^2 + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N (\Delta k_i)(\Delta k_j) r_{i,j}$$

This equation is a form of the general “law of propagation of uncertainties” in [94] and given below in equation (3). In equation (1), $D k_i$ and $D k_j$ correspond to the products of partial derivatives (sensitivity coefficients) and uncertainties as used in [94]. The correlation coefficient $r_{i,j}$ is the ratio between the covariance and the product of the uncertainties. It is always between -1 and +1. Linearity in the sensitivity of k_{eff} to each input parameter and in particular to correlations is essential.

If one of the partial derivatives is zero, the correlation always becomes zero, independent of the other derivative, correlation coefficient and system changes. Correct application of reactivity equivalence covering the uncertainty range gives such a case if the linearity requirement is complied with also when the uncertainties are combined.

A simplified but realistic k_{eff} model

A way of describing k_{eff} is as a function $F(\mathbf{S})$ where $\mathbf{S}$ or rather $\mathbf{S}(V, E)$ is a variable standing for system or material (equivalent when the material positions are specified) properties covering all volume positions (V) and all neutron energies (E). The dependences on V and E will not be specified for each

variable and parameter but they must be considered. $\mathbf{S}$ contains all parameters required to determine the k_{eff} related physics of the system. $\mathbf{S}$ is a global variable. If it is divided into components (volume and/or energy region), each component is dependent on other components. This is easy to realize, e.g. by exchanging the locations of fissile material with reflector material components.

The function $F(\mathbf{S})$ can be written as $\mathbf{R}_r(\mathbf{S}) \cdot \mathbf{S}_p$, where $\mathbf{R}_r(\mathbf{S})$ stands for the neutron removal distribution. This distribution consists of neutrons removed from a converged chain-reaction-induced neutron source (fission, n-2n, etc.) generation that is normalised to one neutron. Leaked neutrons are included as captured neutrons in an outer, non-fissionable region. $\mathbf{S}_p$ contains all sub-parameters needed to determine the number and properties of produced neutrons from information on each neutron removal, but not to determine the interaction relations between different regions. This distinction makes $\mathbf{S}$ very different to $\mathbf{S}$. $\mathbf{R}_r(\mathbf{S}) \cdot \mathbf{S}_p$ determines the neutron production.

$$k_{\text{eff}} = F(\mathbf{S}) = F(\mathbf{R}_r, \mathbf{S}_p) = \mathbf{R}_r(\mathbf{S}) \cdot \mathbf{S}_p = \sum_{i=1}^N (R_{r,i}(\mathbf{S}) * \Sigma_{p,i}) = \sum_{i=1}^N k_{\text{eff},i} \quad (2)$$

The equation is first written as a function F , then as a vector product which is then described by the sum of products and finally translated into a sum of k_{eff} contributions. The large $\mathbf{S}$ is a summation symbol, not to be confused with the parameter $\mathbf{S}$. The dimension N of both vectors ($1 \times N$ and $N \times 1$) is determined by the number of regions. The vector product gives the normalised sum of produced neutrons in each region. This is equivalent to a numerical k_{eff} contribution from this region (not to be confused with a reactivity value of the region). The corresponding equations using integrals are not needed here. A region may be related both to volume and to energy properties of the material (making N equal to the product of volume and energy regions).

A local change in a material specification not only changes the k_{eff} contribution from the associated regions but also all other k_{eff} contributions. This is already obvious from a physics point of view and the equation (2) shows the connections. The missing link is that every $R_{r,i}$ is correlated, not only to every $\Sigma_{p,j}$, but to other $R_{r,j}$.

The combined variance of k_{eff} due to combined uncertainties in $\mathbf{R}_r$ and $\mathbf{S}_p$ and where $v(\mathbf{R}_r, \mathbf{S}_p)$ is the covariance can be expressed [94] as

$$u_c^2(k) = \left(\frac{\partial F}{\partial \Sigma_p} \right)^2 u^2(\Sigma_p) + \left(\frac{\partial F}{\partial R_r} \right)^2 u^2(R_r) + 2 \frac{\partial F}{\partial \Sigma_p} \frac{\partial F}{\partial R_r} v(R_r, \Sigma_p) \quad (3)$$

This is a first order Taylor series expansion of the variance, assuming linearity in the relations. The linearity of the sensitivity coefficients (the partial derivatives) need to be preserved not only for the single variance terms but also for the correlated term which should mirror the physics effect of the combination. Linearity when only one parameter at a time is changed is not sufficient. Correlations between only two uncertainties at a time are not sufficient when there are more uncertainties. The linearity compliance may be realistic for measurements but not for many criticality safety evaluations.

A more practical solution is found if the system is divided into the N regions mentioned above. An uncertainty in S_i in the system region i may lead to an uncertainty in $\Sigma_{p,i}$ and in $\Sigma_{p,j}$ in other regions j (zero in a non-fissionable region and in many other cases) but always leads to uncertainties in $R_{r,j}$ in every region j . The uncertainties in $R_{r,j}$ and $\Sigma_{p,i}$ are always correlated (the covariance is not zero) if the $\Sigma_{p,i}$ uncertainty is not zero. Uncertainties in $R_{r,i}$ and $R_{r,j}$ are always correlated.

$R_{r,j}$ for each region j is a function of the global system parameter $\mathbf{S}$. $\Sigma_{p,i}$ is a function of the local system parameter S_i . Uncertainties in S_i in the same or in different regions are correlated through $\mathbf{R}_r$.

Since the function F can be given as the product $\mathbf{R}_r(\mathbf{S})\mathbf{S}_p$, the variance equation above can be simplified by referring to relative uncertainties. The partial derivatives are easy to calculate ($\mathbf{S}_p$ and $\mathbf{R}_r(\mathbf{S})$ respectively) and after division by $\mathbf{R}_r(\mathbf{S})\mathbf{S}_p$ (to create relative uncertainties) and introducing the coefficient r to indicate correlation between the uncertainties, the equation can be transformed to

$$\left(\frac{u_c(k)}{k}\right)^2 = \left(\frac{u^2(\Sigma_p)}{\Sigma_p}\right)^2 + \left(\frac{u^2(R_r)}{R_r}\right)^2 + 2r \frac{u(\Sigma_p)}{\Sigma_p} \frac{u(R_r)}{R_r} \quad (4)$$

An uncertainty in a material parameter X_j in a system is equivalent to uncertainties in the system variable $\mathbf{S}$ (always in $\mathbf{R}_r(\mathbf{S})$ and sometimes in $\mathbf{S}_p$). The parameter X_j can be divided into the N regions referred to above. Each regional parameter is referred to as $X_{j,i}$.

If the parameters $X_{j,i}$ for each region i are combined into the regional parameter S_i , the equations can be simplified, without losing any information. The correlations between different X_j parameters need to be observed when the region variables S_i and associated uncertainties and covariances are determined.

$$S_i = \sum_{j=1}^M X_{j,i} \quad (5)$$

Each change in a system influences the global parameter $\mathbf{S}$ and thus $\mathbf{R}_r(\mathbf{S})$. The uncertainty $u_c(\mathbf{S}_p)$ due to uncertainties in S_i in each region i of the system can be determined as

$$u_c^2(\Sigma_p) = \sum_{i=1}^N \left(\frac{\partial \Sigma_{p,i}}{\partial S_i} \right)^2 u^2(S_i) + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N \frac{\partial \Sigma_{p,i}}{\partial S_i} \frac{\partial \Sigma_{p,j}}{\partial S_j} v(S_i, S_j) \quad (6)$$

$\mathbf{S}_{p,i}$ represents the neutron production related information for each region i , while S_i represents the total system information for region i . An example of correlated uncertainties is the uncertainties in temperatures of different volume regions. Another example of correlation is the neutron flux.

The variance $u_c^2(\mathbf{R}_r)$ due to uncertainties in S_i in each region i of the system is determined as

$$u_c^2(R_r) = \sum_{i=1}^N \left(\frac{\partial R_{r,i}}{\partial S_i} \right)^2 u^2(S_i) + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N \frac{\partial R_{r,i}}{\partial S_i} \frac{\partial R_{r,j}}{\partial S_j} v(S_i, S_j) \quad (7)$$

It is repeated that S does not only represent the material structure and geometry but all system properties, including neutron physics. In general, the “sensitivity coefficients” (partial derivatives) for the neutron removals are more significant than for the material neutron production properties of the materials, making the correlations in equation (7) stronger than in equation (6).

The conclusion is that if there is an uncertainty in the system, whether it is an uncertainty in the material properties or in the configuration of the materials, the system response to other uncertainties will become different. The effect of a combination of uncertainties cannot be determined from the individual uncertainties, the correlations must be considered.

Reality checks

It is easy to find cases where non-linearity applies. Essentially all relations between k_{eff} and an input parameter are non-linear. Only for small uncertainties, the linearity applies. A linear relation could be valid for a parameter that is designed for that purpose. In the case of combined and significant uncertainties, it would be difficult to maintain the linearity.

An example of combined uncertainties is taken from the reactivity worth of control rods in a nuclear reactor at zero power level. Assume that all uncertainties in k_{eff} due to the control rod axial position are identical, follow a linear relationship with k_{eff} and that the events causing the uncertainties are independent. The combined effect of two simultaneous uncertainties is requested. The system is assumed to be maintained just critical using a global parameter (boron concentration or water level).

Some people would now say that there is no correlation between the uncertainties. The combined effect of two uncertainties are said to be identical, independent of the horizontal locations of the control rods in the reactor. It makes no difference whether they are adjacent or in opposite “corners”.

In reality, a partial insertion of a control rod would reduce the effect of an adjacent cluster since the neutron flux would be depressed in this part of the reactor. The opposite would be true for a partial removal of the control rod. The correlation effects are relatively strong in both cases. On the other hand, a partial insertion or removal of one control rod may not significantly change the effect of a control rod in the opposite “corner” of the reactor. The correlation effect is relatively weak.

It is very likely that the case of a combined uncertainty of two adjacent control rods will violate the linearity requirement of the sensitivity coefficients.

A proper model of physics is needed to evaluate critical experiments leading to a close simulation of the experiment. It may be even more important when simplified benchmarks are designed and when a benchmark is applied in computer code input preparation.

Examples of the various variables and parameters are useful to test and understand the model. The thickness of a steel plate in water between fissile materials is a parameter X_1 . The thicknesses of the water regions on either side of the plate can be represented by the additional parameters X_2 and X_3 . The

total thickness of the three regions is a fourth parameter X_4 . The dimensions are correlated. The uncertainties are correlated. Correlations to uncertainties in other dimensions (e.g. the fissile material) are not significant. The local neutron flux is changed by a change in water moderation. The global neutron flux is changed since the changed moderation changes the fission distribution. The absorption fractions in the steel and in the water are changed.

The variable S1 may represent the steel plate and the first energy group. All the uncertainties in X_{l_1} - X_4 contribute to the uncertainty in S_l through the uncertainty in the neutron flux. There is no neutron production in the region 1 so the parameter $S_{p,1}$ remains zero. However, the uncertainty in the global neutron removal distribution $Rr(S)$ is influenced, including $R_{r,1}$.

³ Trailing zeros are sometimes skipped, e.g. 100 instead of 100/0/0/0, 90/10 rather than 90/10/0/0, etc.

⁴ The formal "Scope and objectives" as published on the OECD/NEA/NSC www page