Reference Values for Nuclear Criticality Safety

Homogeneous and Uniform
UO_2, UNH, PuO_2 and PuNH,
Moderated and Reflected by H_2O

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

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Disclaimer

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}U 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 $UO_2(NO_3)_2$+$6H_2O$), plutonium dioxide (PuO_2) and plutonium nitrate pentahydrate (PuNH or $PuO_2(NO_3)_4$+$5H_2O$).

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 keff 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 systemsare 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 keff 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.

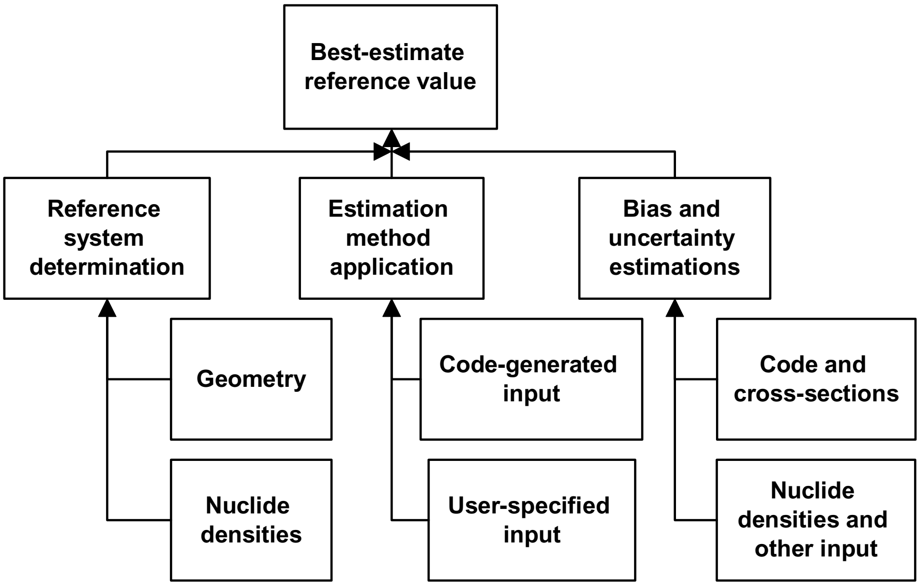
BEST ESTIMATE REFERENCE VALUES

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.

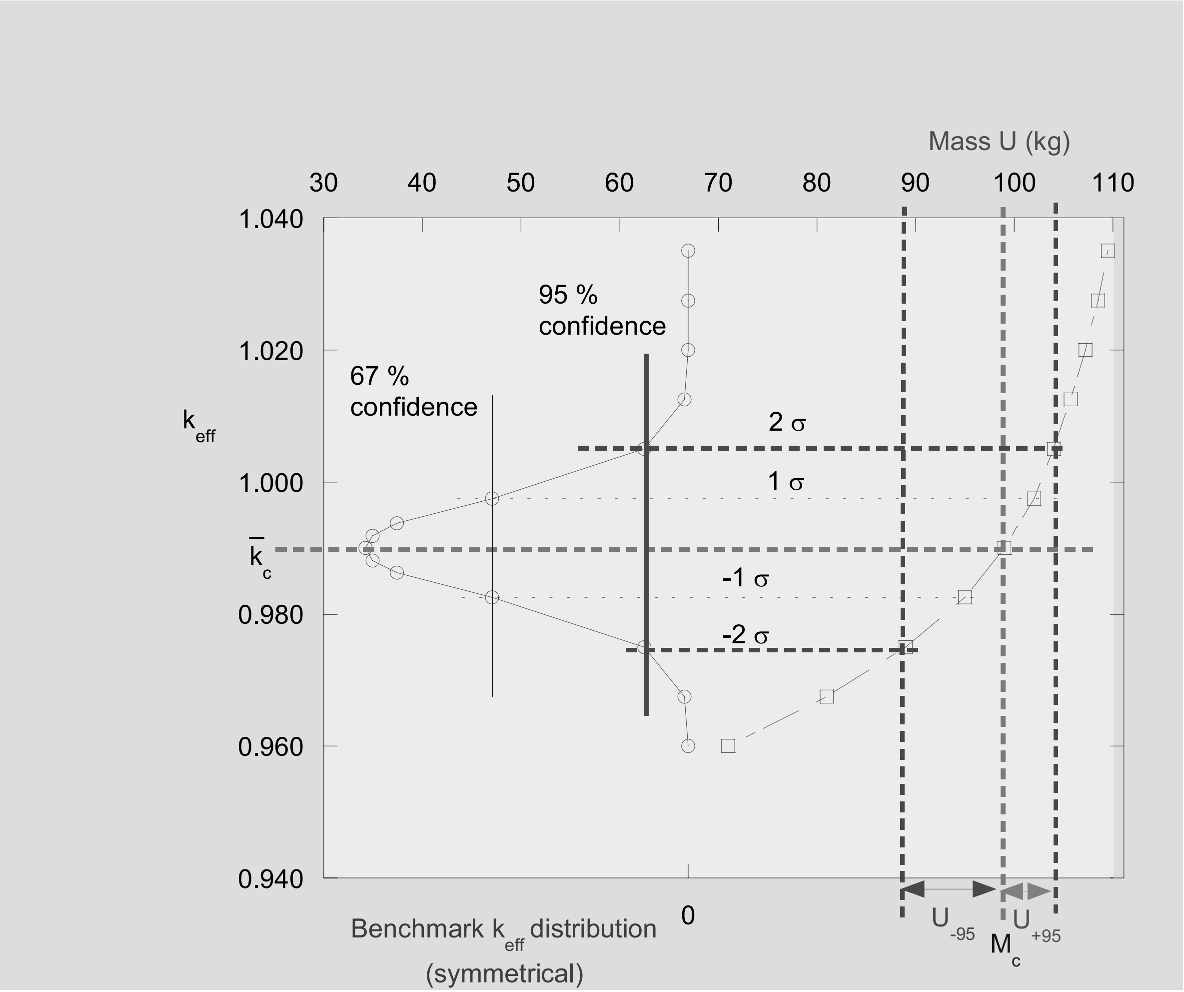
The selection of benchmarks and the evaluation of the results should probably be different for reference value and for safe value determinations. Different weights can be given to each benchmark. Outliers ("odd" results) and complicated systems may be completely left out of the database for reference 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 refernce 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 keff 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 Mc 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}U and the isotope distributions, with each isotope mass percentage of total plutonium given in that order[1], 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 $UO_2(NO_3)_2$+$6H_2O$), plutonium dioxide (PuO_2) and plutonium nitrate pentahydrate (PuNH or $PuO_2(NO_3)_4$+$5H_2O$).

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.

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[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-78	[21]	Handbook	DTF-IV, literature?	
IRSN-DTF-96	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]

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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 ^{239}Pu. "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 KENOVa 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 I1.

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 UO_2

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	

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

[2] A correction has been made since the theoretical density for $U(100)O_2$ is 10.84 and not 10.96 g/cm^3.

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	

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

Table 4. Demonstration reference values for PuO_2

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	

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

[2] Includes a correction. The theoretical density for PuO_2 with this isotope distribution is not 11.46 g/cm^3.

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	

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[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

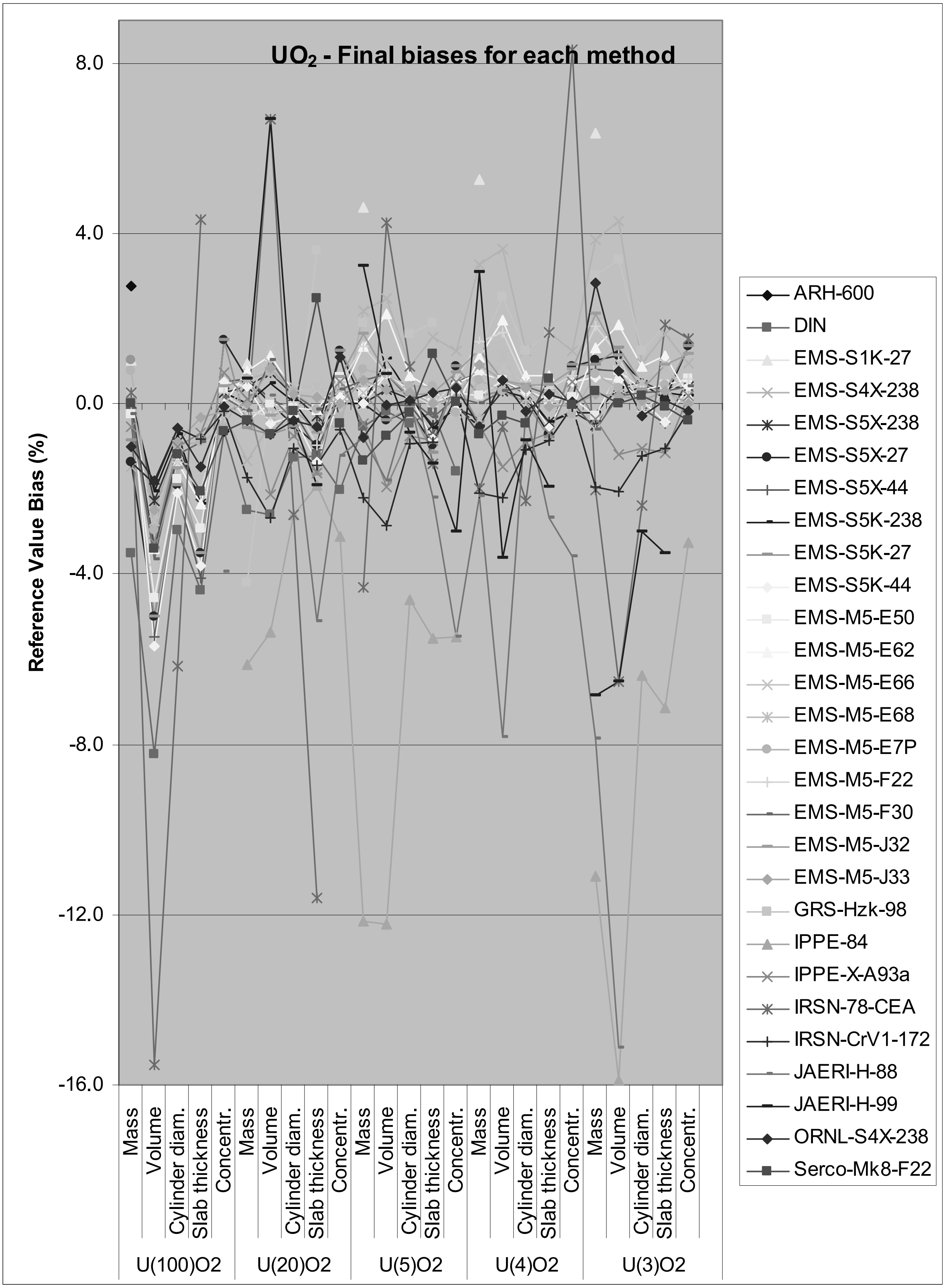


Figure 4. UO_2 reference values – Estimated total biases for each method (enlarged)

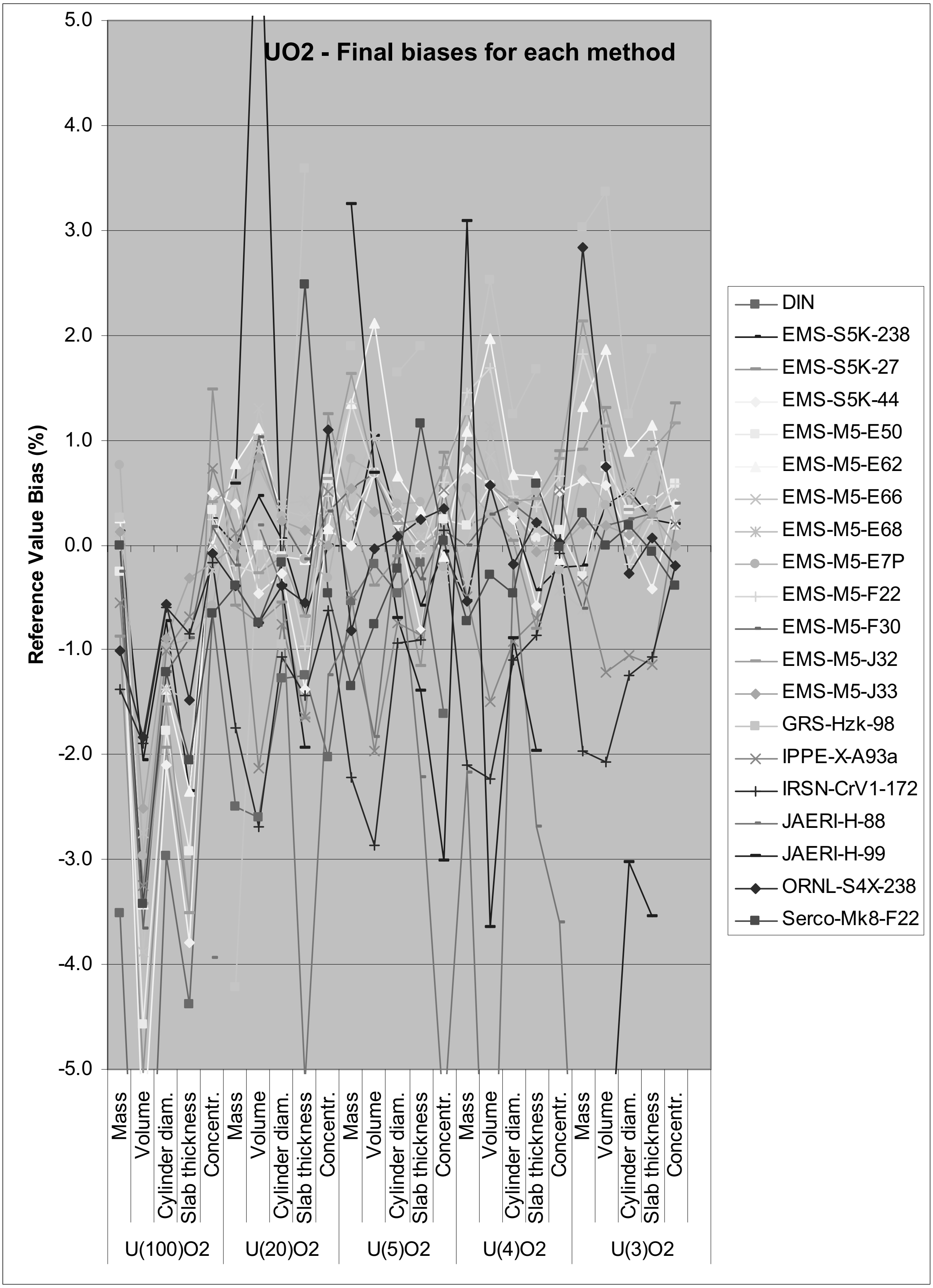


Figure 5. UO_2 reference values – Estimated total biases for “modern” method (enlarged)

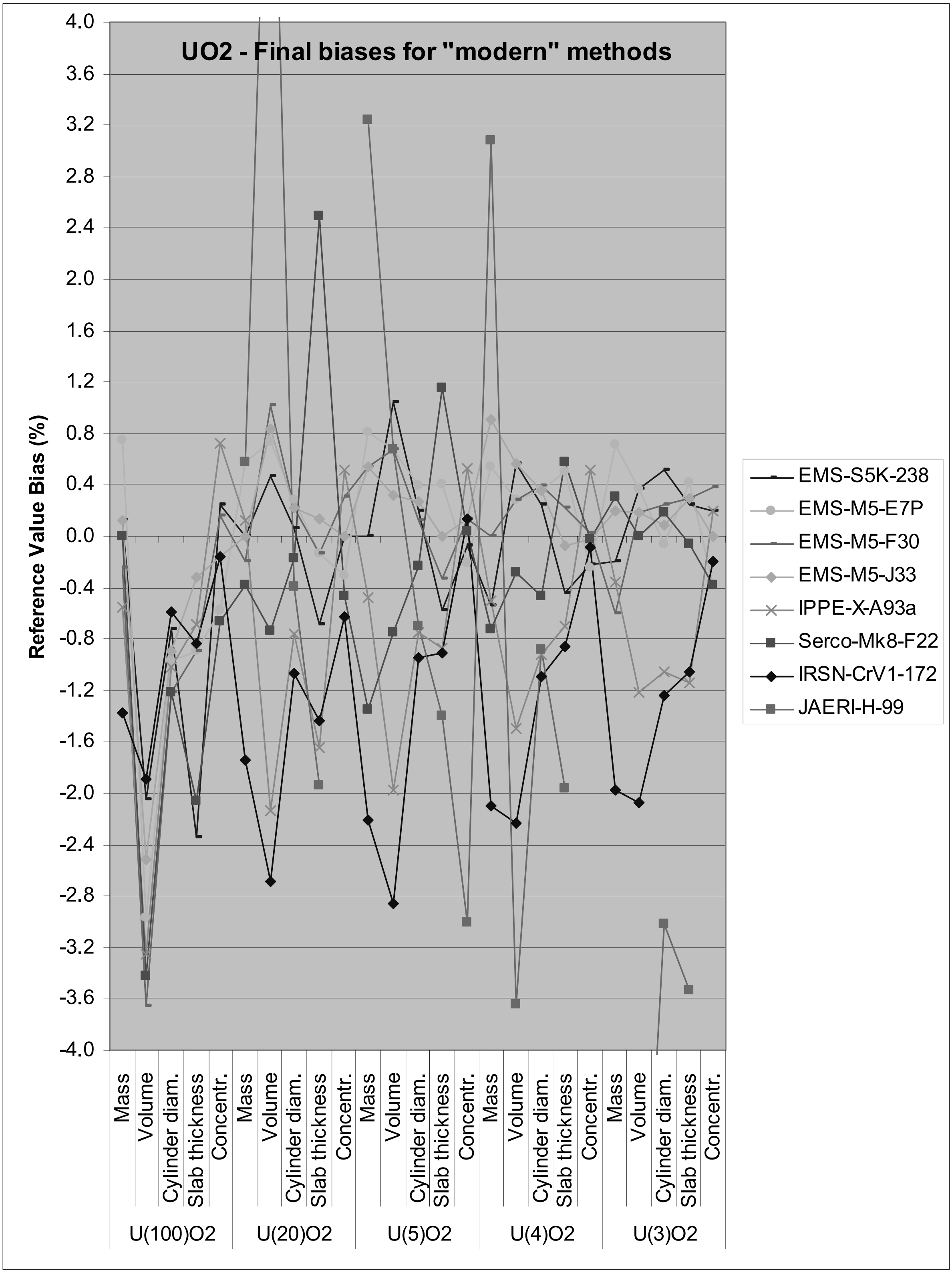


Figure 6. UNH reference values – Estimated total biases for each method

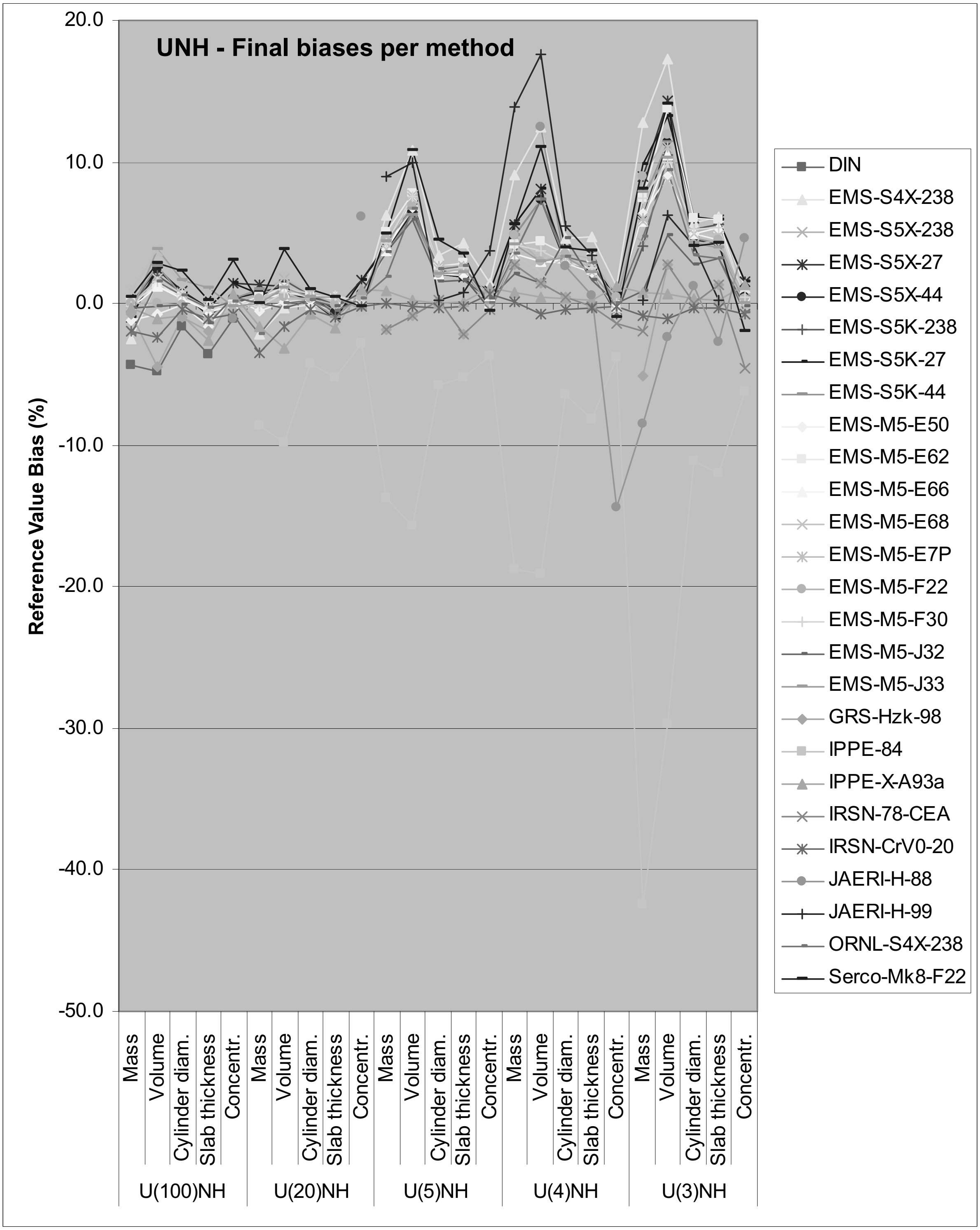


Figure 7. UNH reference values – Estimated total biases for each method (enlarged)

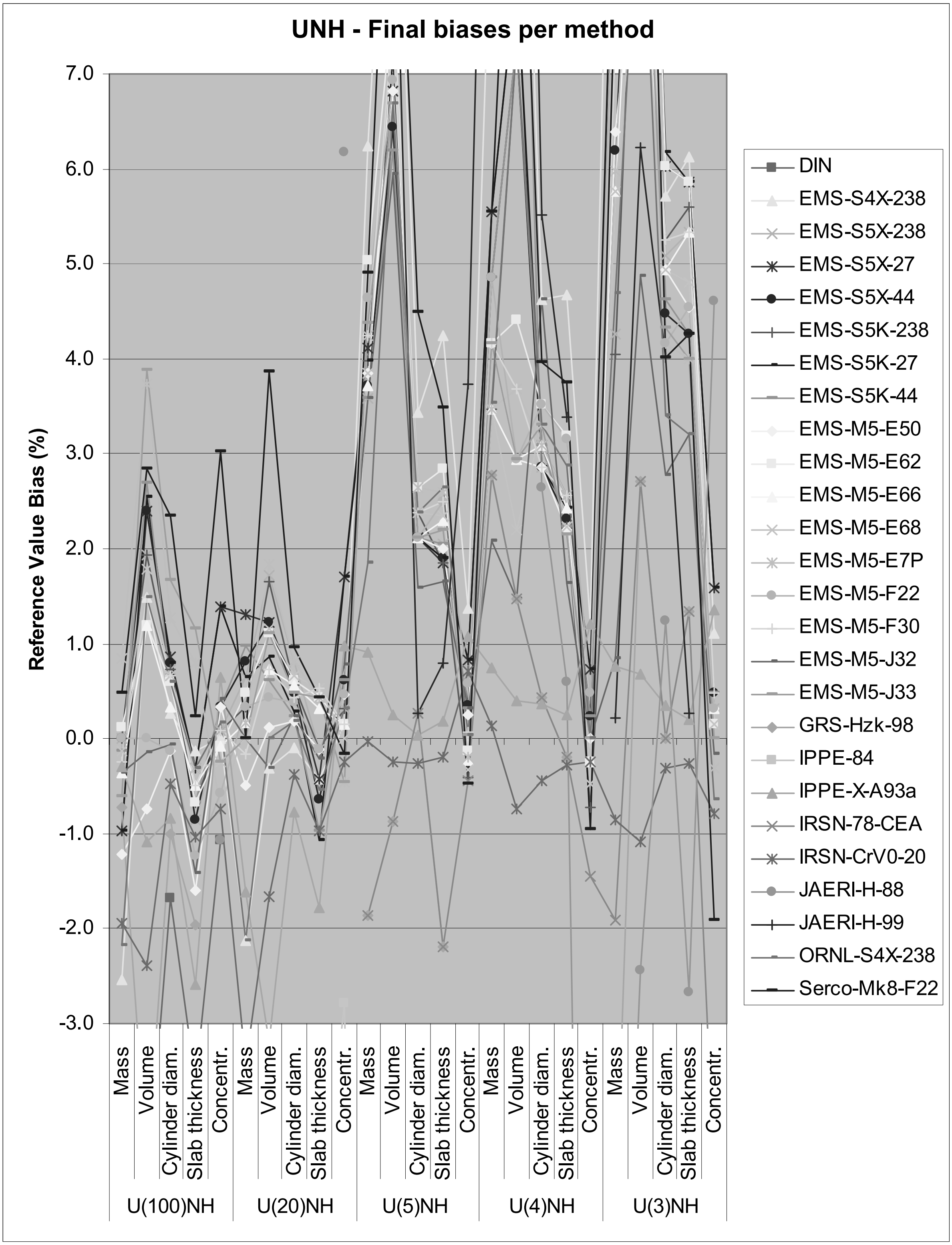


Figure 8. UNH reference values – Estimated total biases for “modern” method (enlarged)

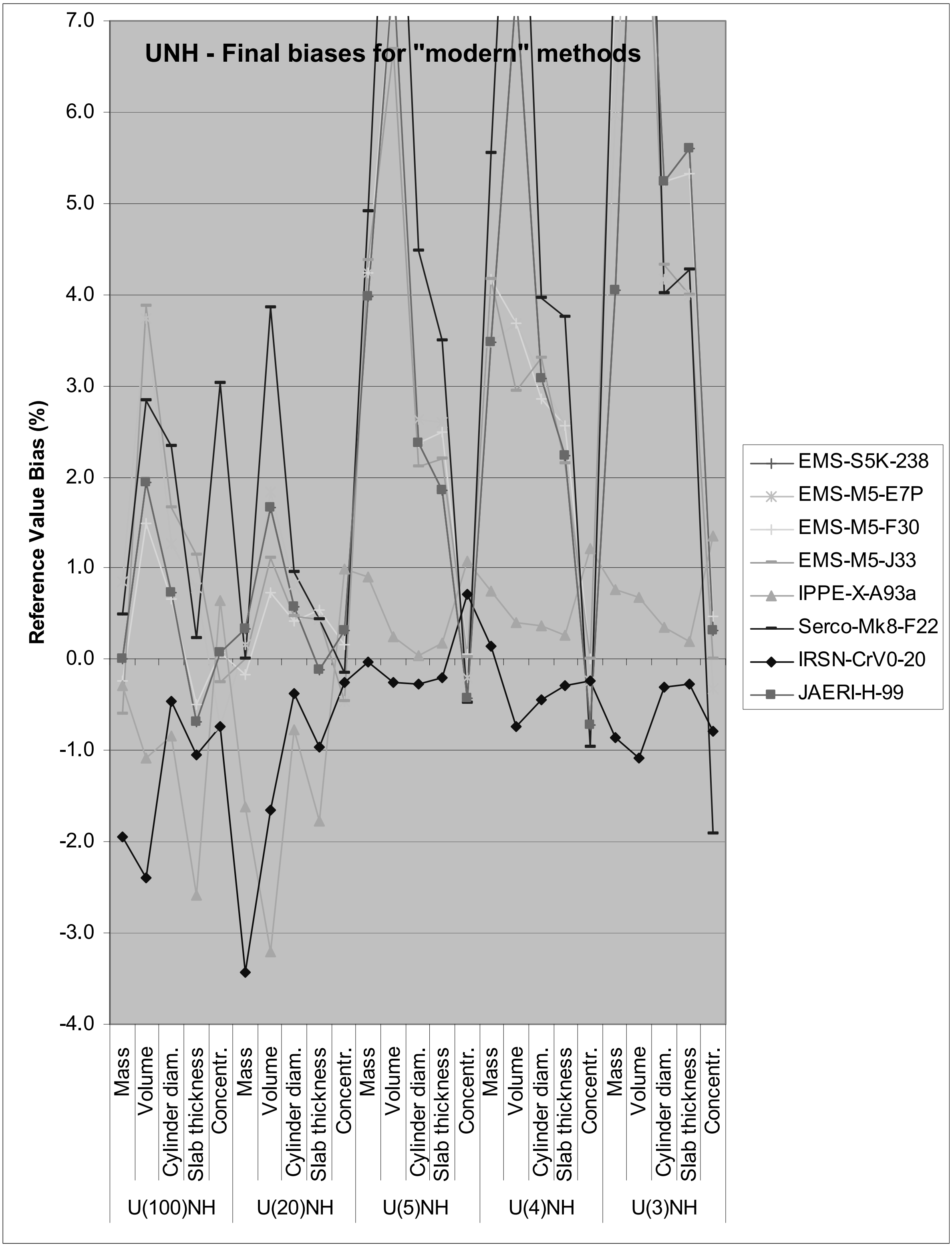


Figure 9. PuO_2 reference values – Estimated total biases for each method

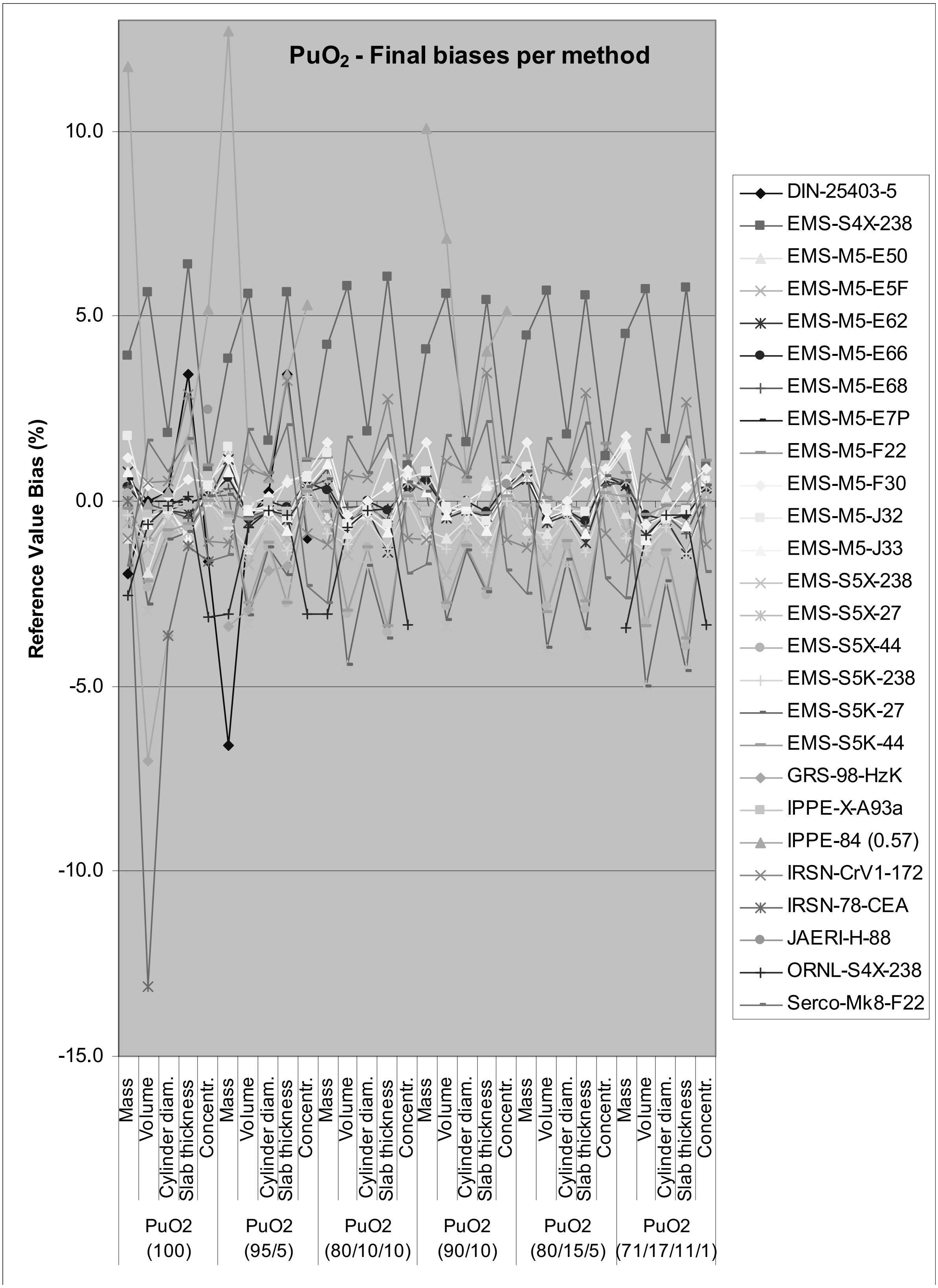


Figure 10. PuO$_2$ reference values – Estimated total biases for each method (enlarged)

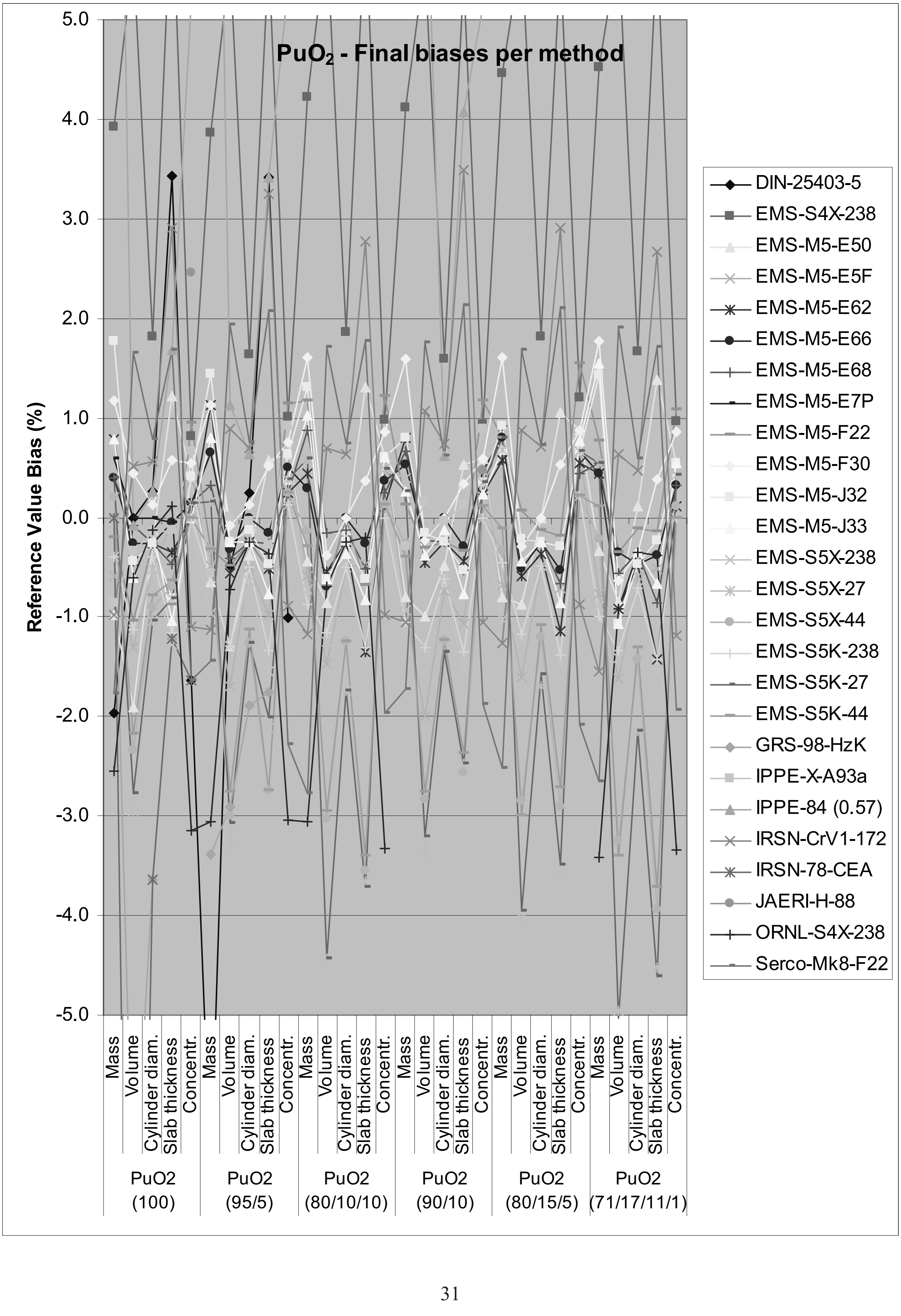


Figure 11. PuO_2 reference values – Estimated total biases for “modern” method (enlarged)

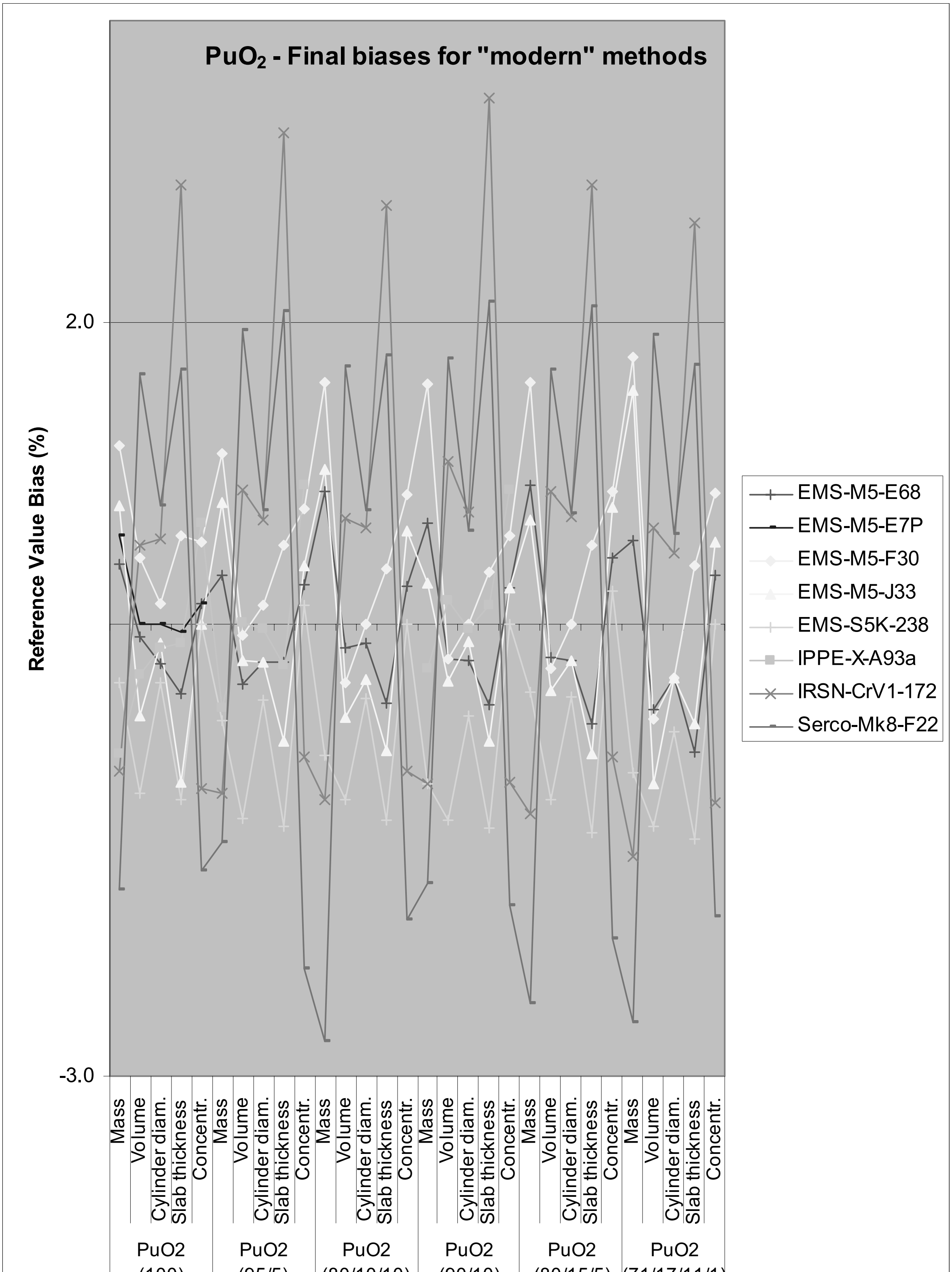


Figure 12. PuNH reference values – Estimated total biases for each method

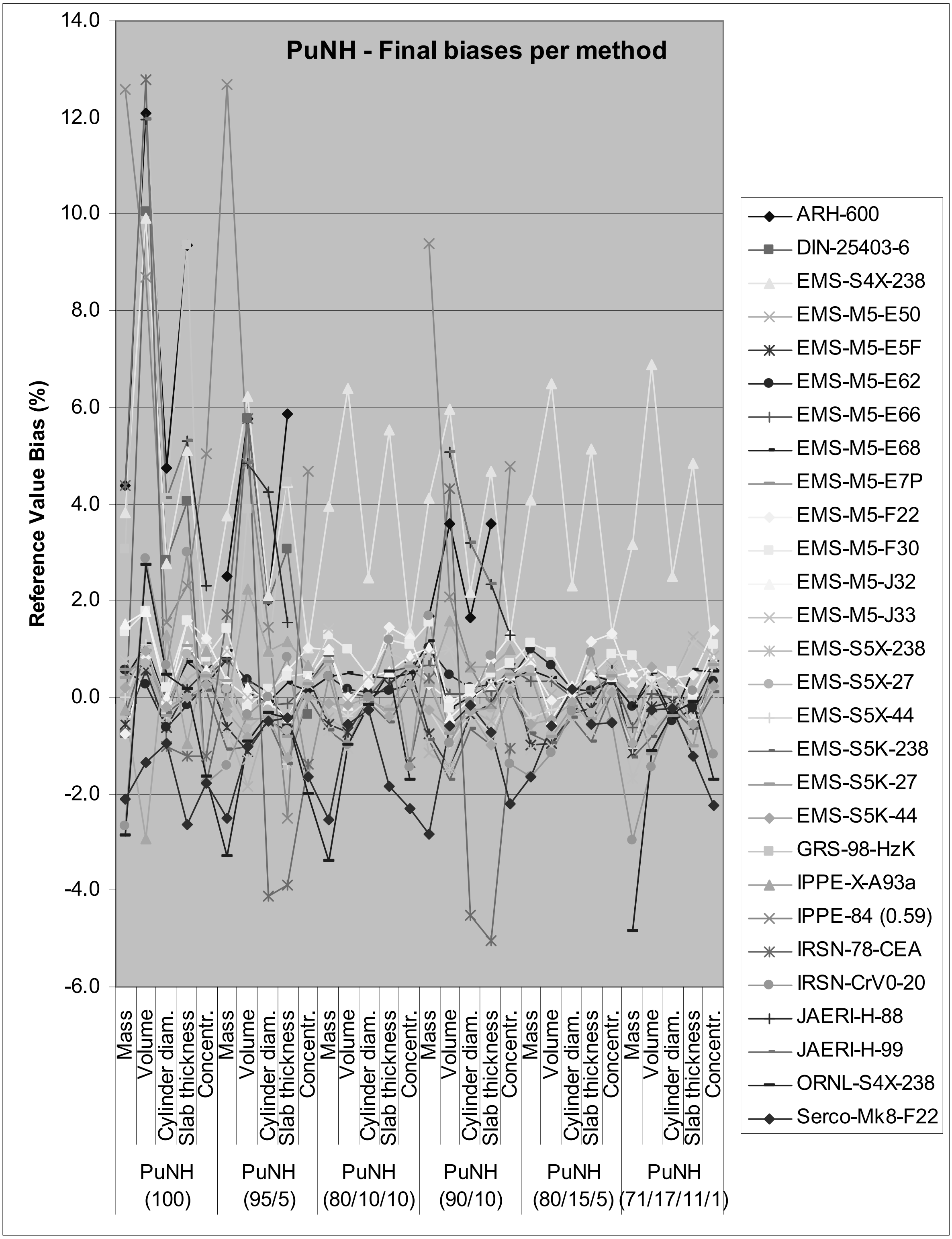


Figure 13. PuNH reference values – Estimated total biases for each method (enlarged)

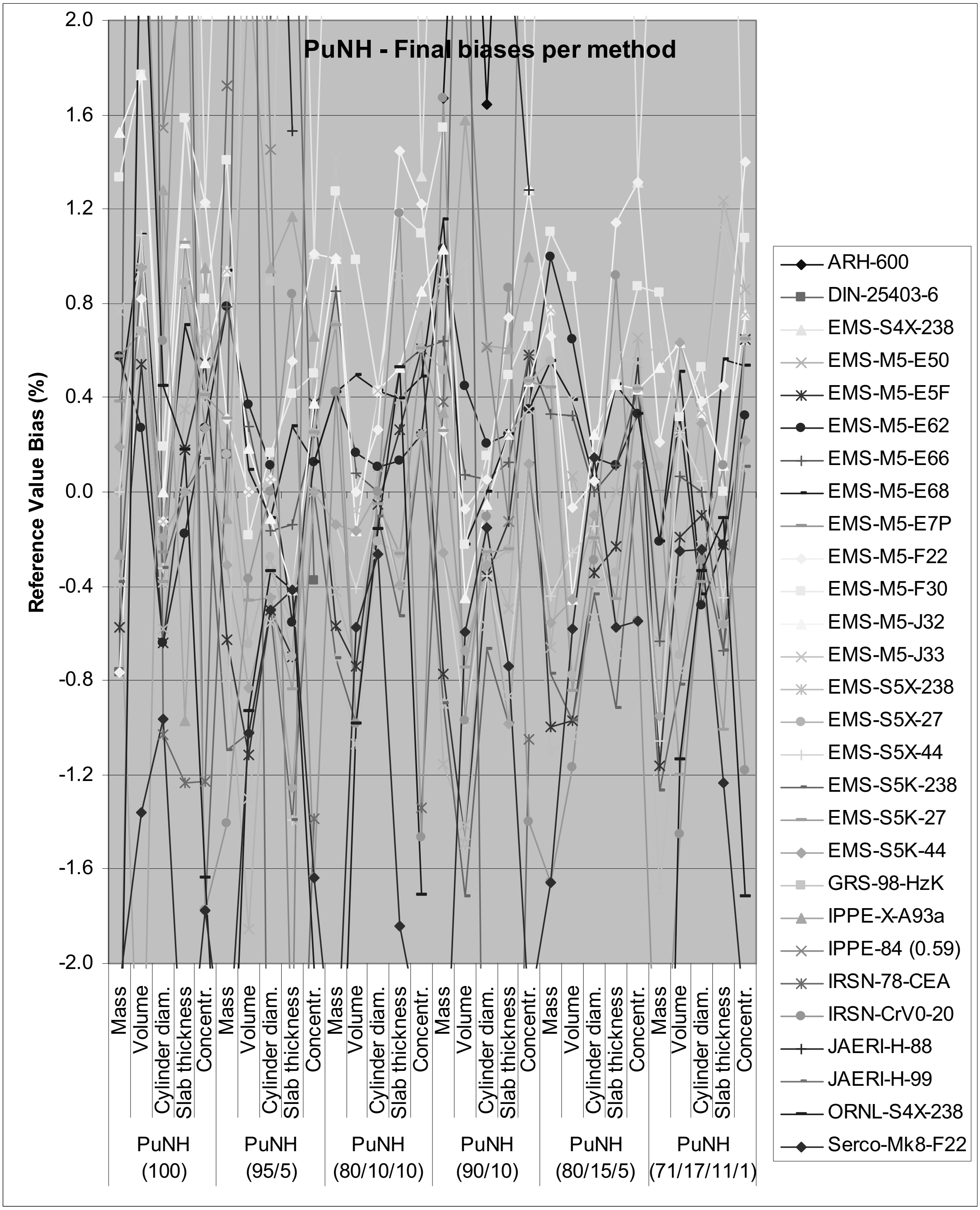
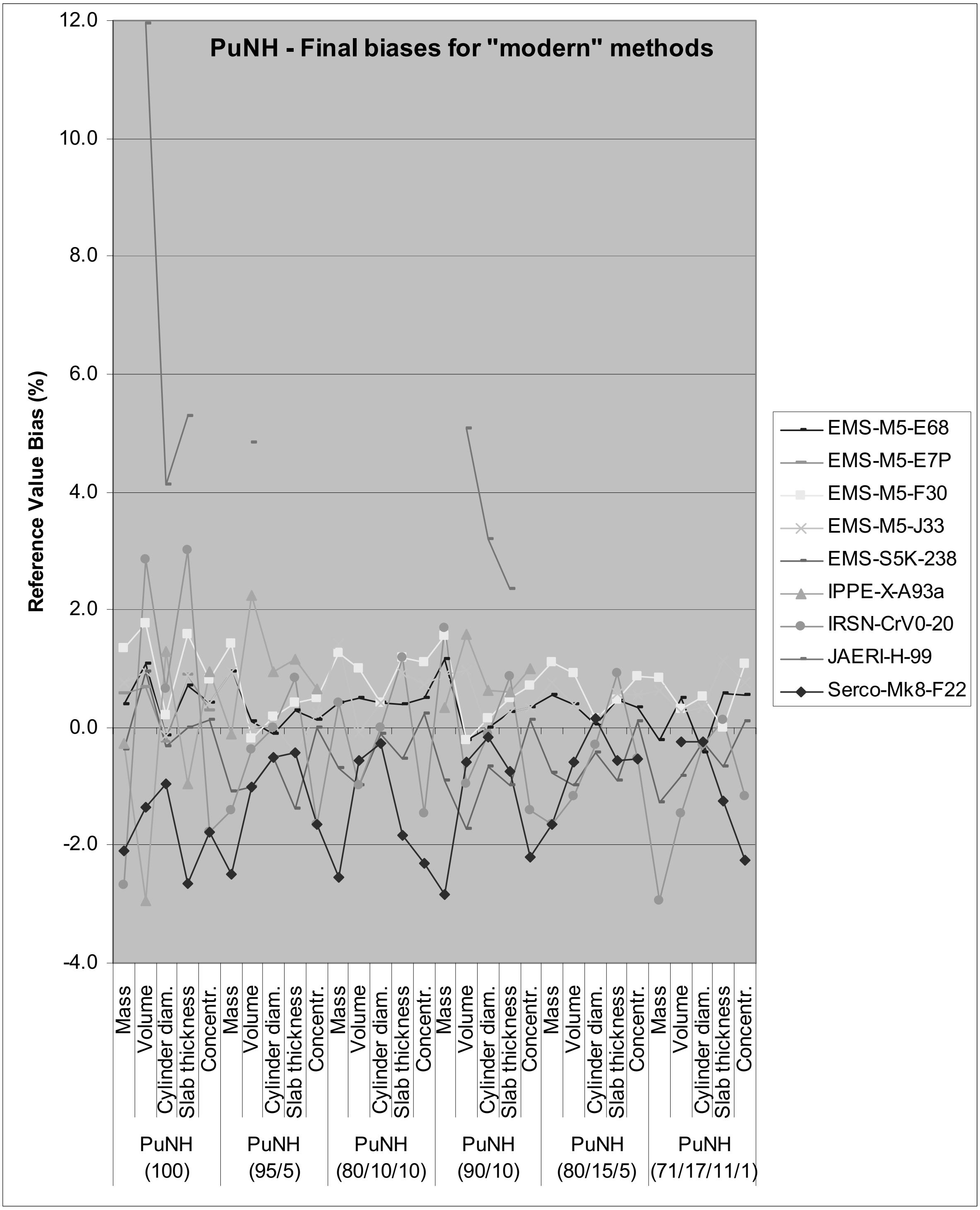


Figure 14. PuNH reference values – Estimated total biases for "modern" methods (enlarged)



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 $U(100)O_2$, 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 $U(20)O_2$ 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 $Pu(80/10/10)O_2$ critical slab is thinner than a water-reflected $Pu(95/5)O_2$ 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 (XSDRNPM/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 $U(20)O_2$ 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)O_2 critical slab is thinner than a solid Pu(95/5)O_2 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 ^{235}U, ^{239}Pu and ^{233}U, 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), U^{235}, Pu^{239}, U^{233} 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 UO_2F_2-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 Isopiestiques – 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 2024, 1999.

[65] T. Ivanova et. al., "Validation of the KENOV/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 2024, 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 2024, 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 2024, 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 h (eta) 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 OBJECTIVES[2]

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}U/^{238}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.

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[2] The formal "Scope and objectives" as published on the OECD/NEA/NSC www 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)O_2F_2 were reported as U(100)O_2 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, MCPNP5 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, KENOVa and XSDRNPM/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 KENOVa 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 KENOVa 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 ^{239}Pu. 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)O_2 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 $H/^{235}U<20$ and $H/^{235}U>800$, 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_l-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/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_l-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/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:

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

where x_5 – uranium enrichment, $C_U = 0.8814 g_{UO2}$ – uranium concentration, g_{UO2} – density of uranium dioxide assumed to be 10.96 g/cm^3.

Concentrations for the homogeneous mixture of crystalohexohydrate of uranyl nitrate $[UO_2(NO_3)_2 \cdot 6H_2O]$ with water were calculated using the equation:

$$\mathrm{H/U} = 26.14/C_\mathrm{U} - 19.65 \quad \left(C_\mathrm{U} \le 1.33\ \mathrm{g/cm^3}\right)$$

Density of $UO_2(NO_3)_2 \cdot 6H_2O$ was assumed to be 2.807 g/cm^3.

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

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

where $C_{Pu} = 0.8819 g_{PuO_2}$ – 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 [$Pu(NO_3)_4$?$6H_2O$] with water were calculated using the equation:

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

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 g/cm^3
- $UO_2(NO_3)_2 \cdot 6H_2O$ – 2.807 g/cm^3
- PuO_2 – 11.44 g/cm^3 (this value has been confirmed – 11.46 is the established value)
- $Pu(NO_3)_4 \cdot 5H_2O$ – 2.9 g/cm^3
- H_2O – 1 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 ststems 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 release 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 $UO_2(NO3)_2$ 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, g/l/mk and H/X/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 wit 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 KENOVa 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	Detail
		1	Simple
HEU-MF-020	Polyethylene-reflected U(90) metal sphere, VNIIEF 1962	1	Detail
		1	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

ICSBEP 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 $U(93)O_2F_2$ solutions. ORNL 1954 and 1958. Large uncertainties.	1
		2
		3
		4
HEU-ST-010	Water-reflected 9.7 litre spheres of $U(93)O_2F_2$ solutions. ORNL 1950.	1
		2
		3
		4
HEU-ST-011	Water-reflected 17 litre spheres of $U(93)O_2F_2$ solutions. ORNL 1954 and 1957.	1
		2
HEU-ST-012	Water-reflected 91 litre sphere of $U(93)O_2F_2$ 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 $U(93)O_2F_2$ solutions. ORNL 1957.	1
		2
		3

Table E4. Thermal LEU compound and solution systems

ICSBEP 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 $U(5)O_2F_2+H_2O$ 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
		39
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.	1
		4
		9
		15
		17

Appendix F
BENCHMARK CALCULATION RESULTS

Fast high-enriched uranium system validation results

Figure F1. Fast HEU. S5+ 238

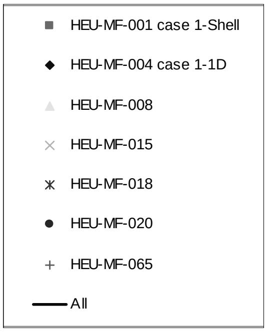


Figure F2. Fast HEU. S5+ 238

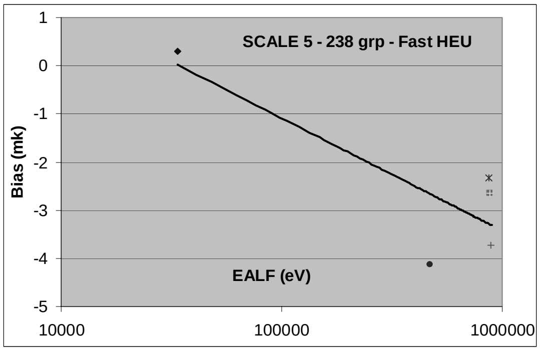


Figure F3. Fast HEU. S5+ 238

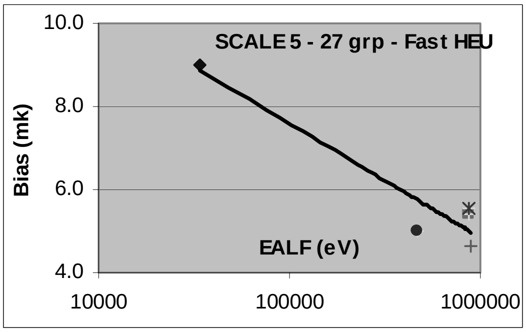


Figure F4. Fast HEU. S5+ 238

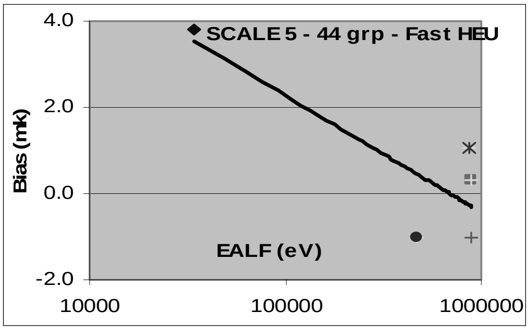


Figure F5. Fast HEU. M5+E50

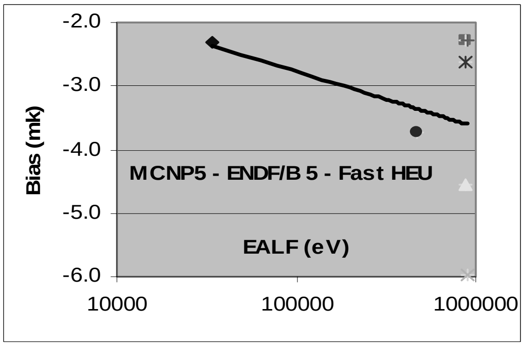


Figure F6. Fast HEU. M5+E62

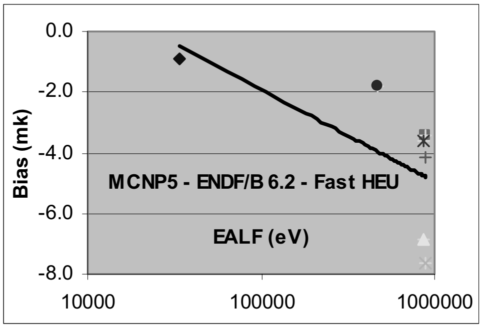


Figure F7. Fast HEU. M5+E66

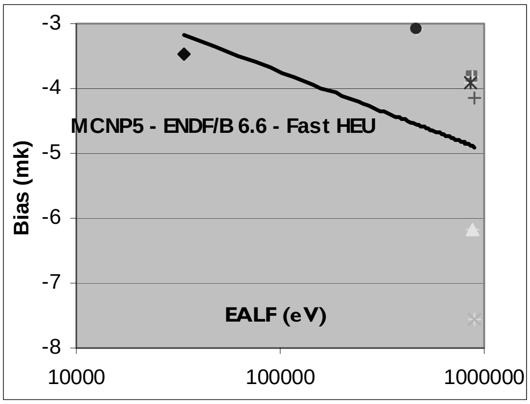


Figure F8. Fast HEU. M5+E68

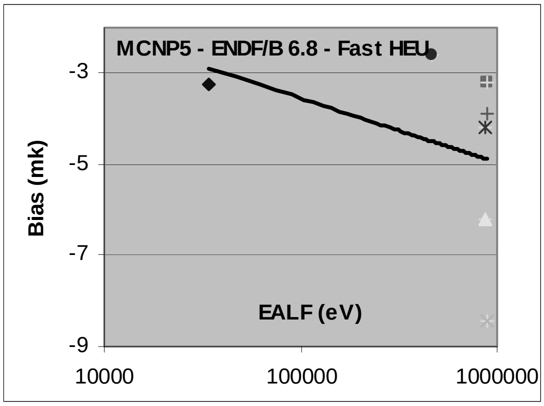


Figure F9. Fast HEU. M5+E7P

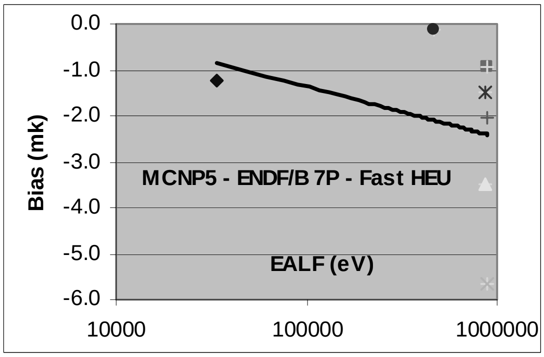


Figure F10. Fast HEU. M5+JF 2.2

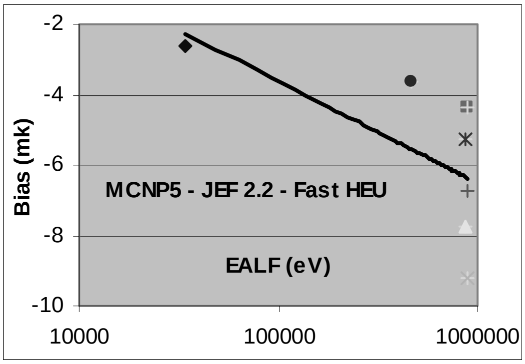


Figure F11. Fast HEU. M5+ JF3.0

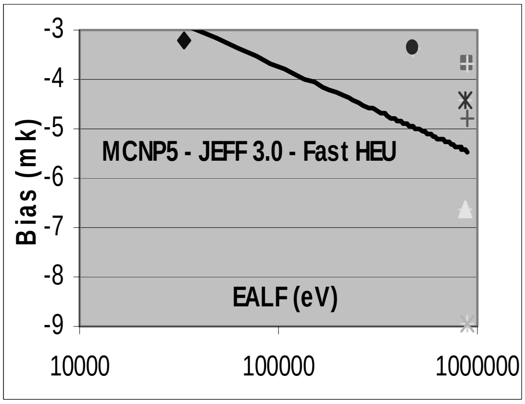


Figure F12. Fast HEU. M5+ JENDL 3.2

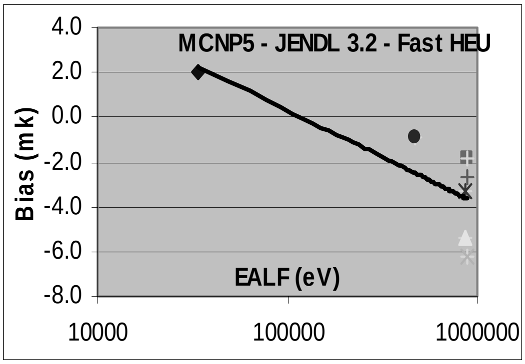


Figure F13. Fast HEU. M5 + JENDL 3.3

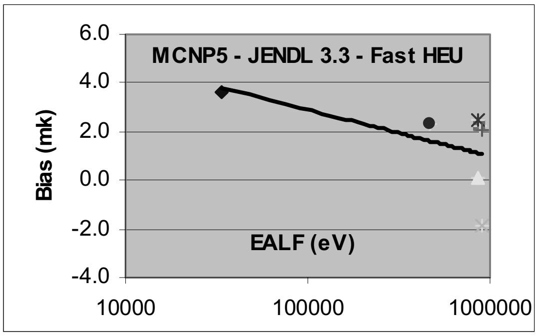


Figure F14. Fast HEU. ABBN-93

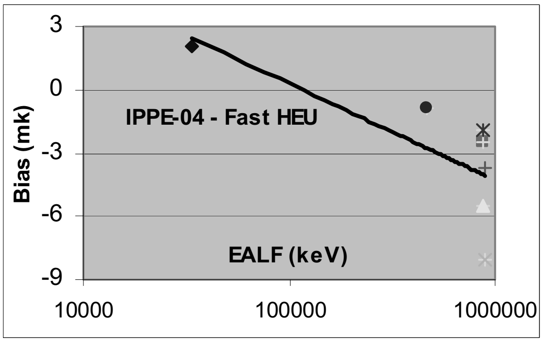


Figure F15. Legend for all HEU results

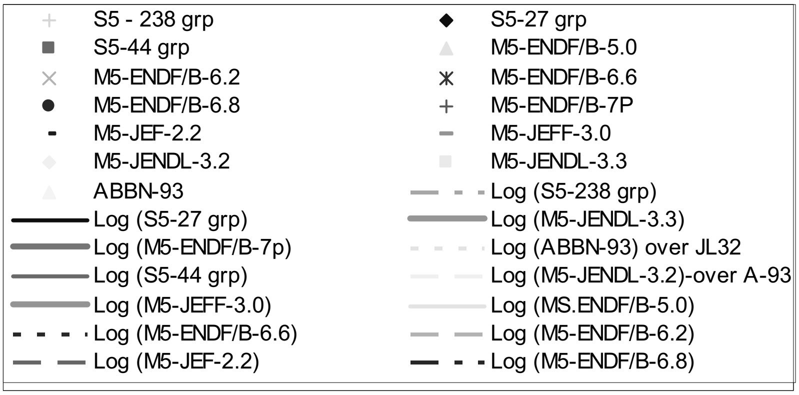


Figure F16. All results for fast HEU benchmark

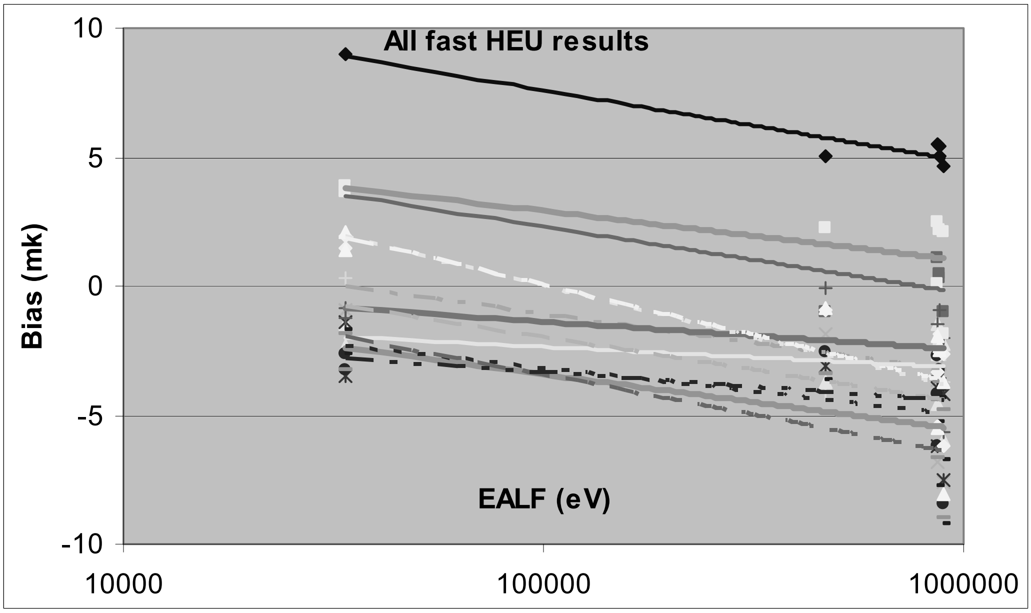


Table F1. HEU-MF-001 Case 1

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

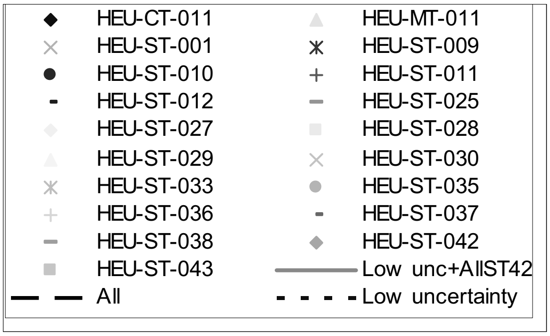


Figure F18. EALF. SCALE 5 + 238-grp

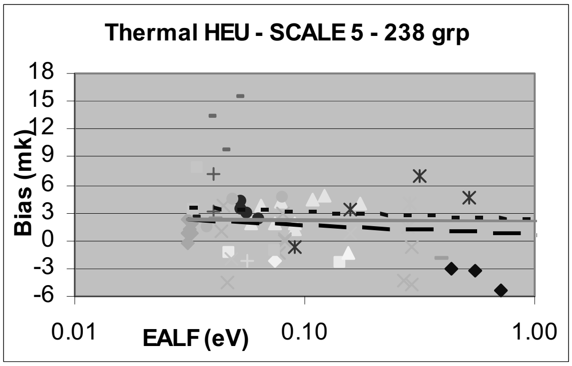


Figure F19. EALF. SCALE 5 + 27-group

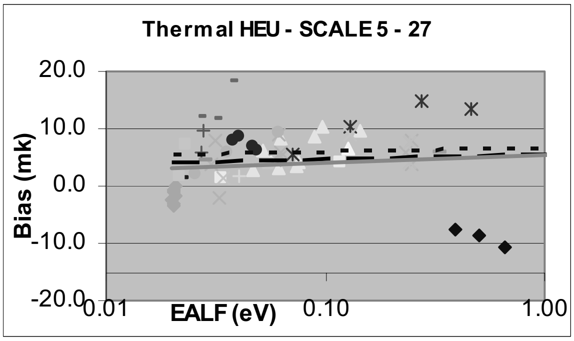


Figure F20. EALF. SCALE 5 + 44-group

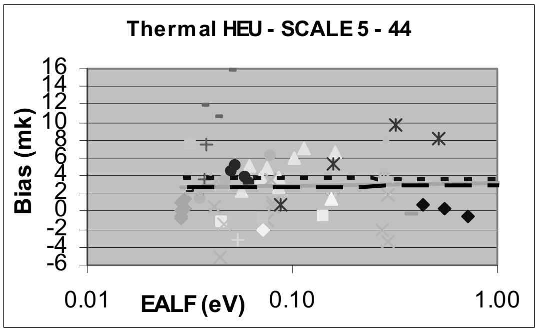


Figure F21. EALF. MCNP5+ENDF/B-5

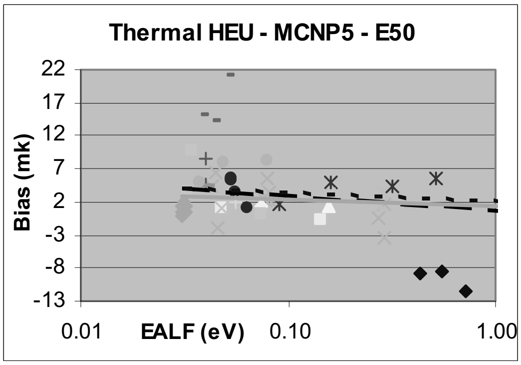


Figure F22. EALF. MCNP5+ENDF/B-6.2

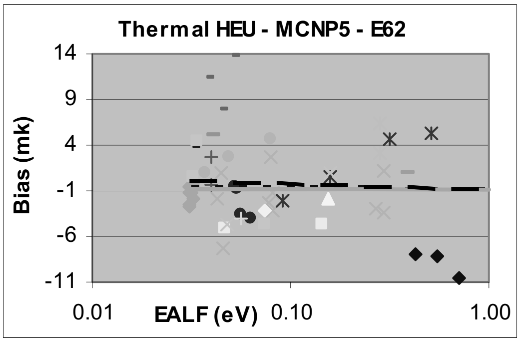


Figure F23. EALF. MCNP5+ENDF/B-6.6

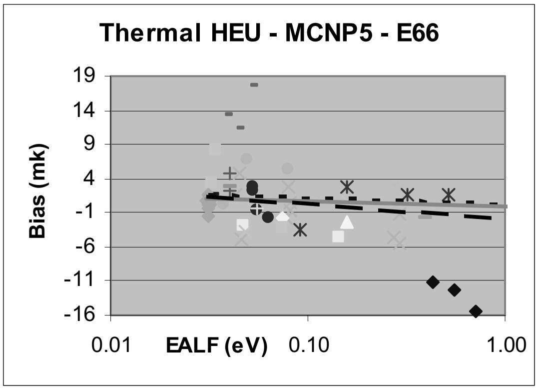


Figure F24. EALF. MCNP5+ENDF/B-6.8

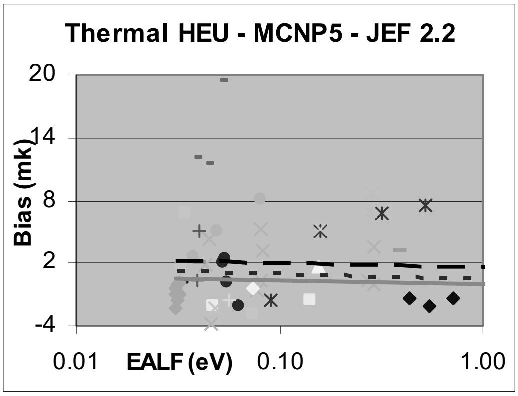


Figure F25. EALF. MCNP5+prel ENDF/B-7

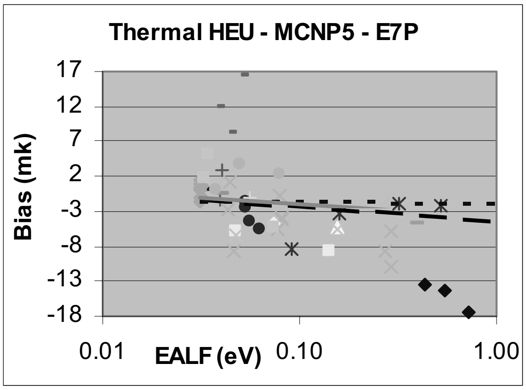


Figure F26. EALF. MCNP5+ JEF 2.2

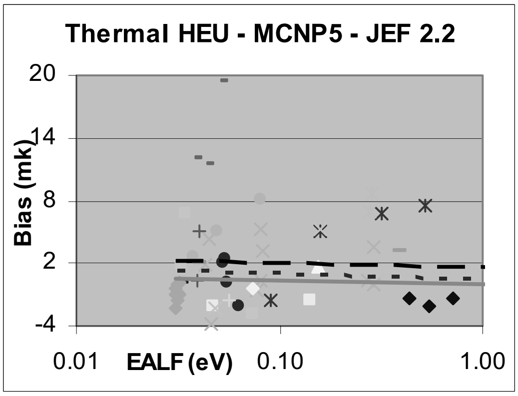


Figure F27. EALF. MCNP5+ JEFF 3.0

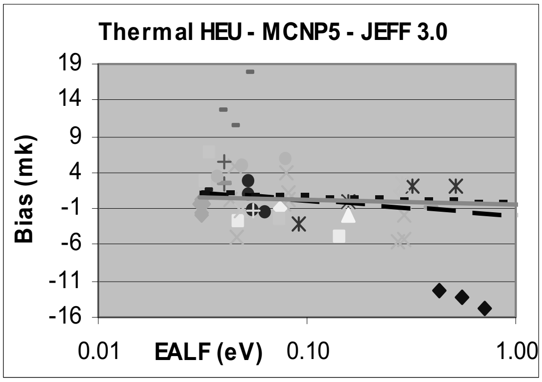


Figure F28. EALF. MCNP5+ JENDL 3.2

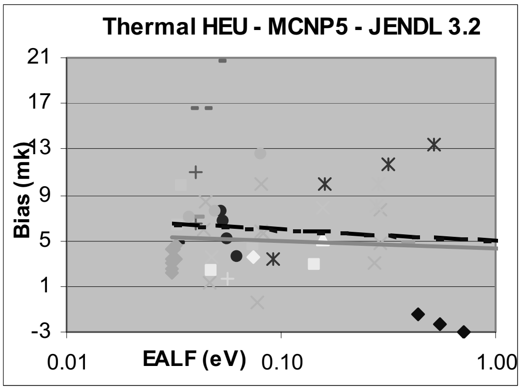


Figure F29. EALF. MCNP5+ JENDL 3.3

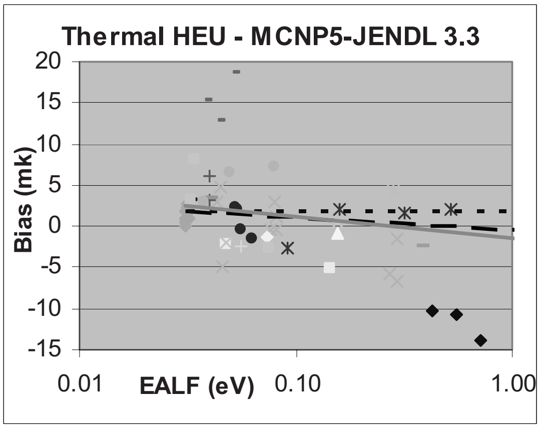


Figure F30. EALF. IPPE-ABBN93

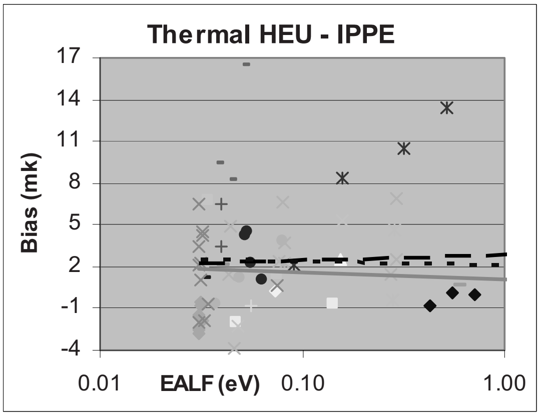


Figure F31. EALF. All MCNP5 results

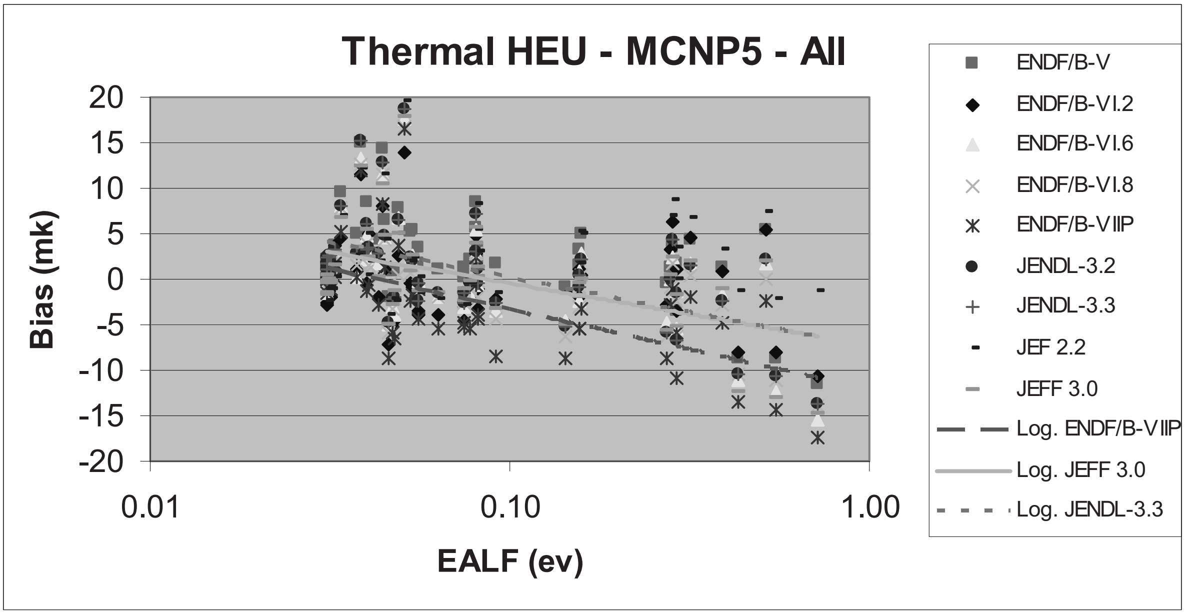


Table F8. HEU-CT-011 Case 1

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

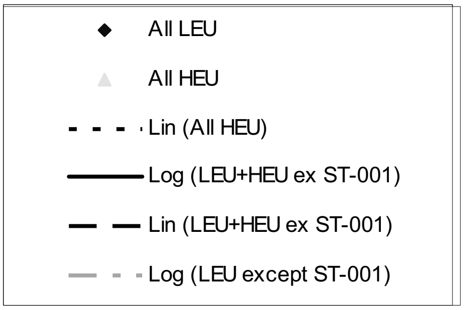


Figure F33. Enr ^{235}U. LEU + HEU, S5-238

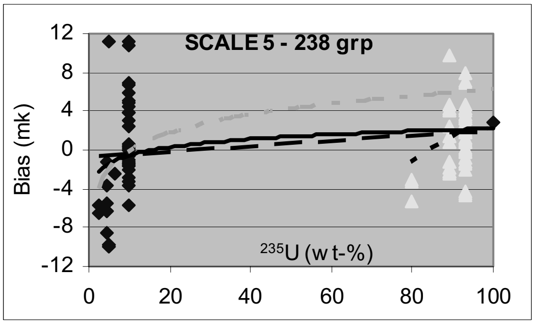


Figure F34. Enr ^{235}U. LEU, S5-238

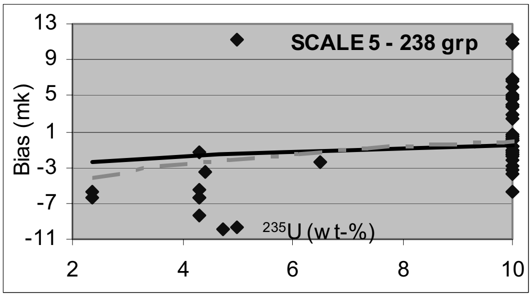


Figure F35. Enr ^{235}U. LEU + HEU, S5-27

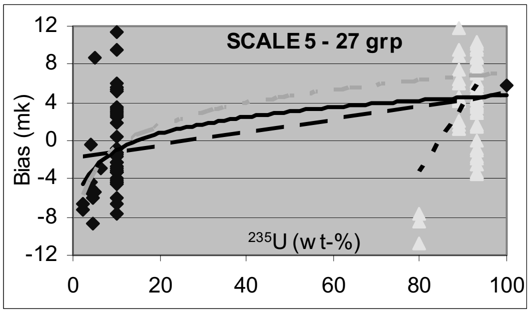


Figure F36. Enr ^{235}U. LEU, S5-27

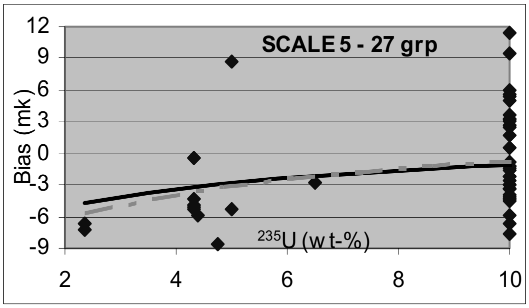


Figure F37. Enr ^{235}U. LEU + HEU, S5-44

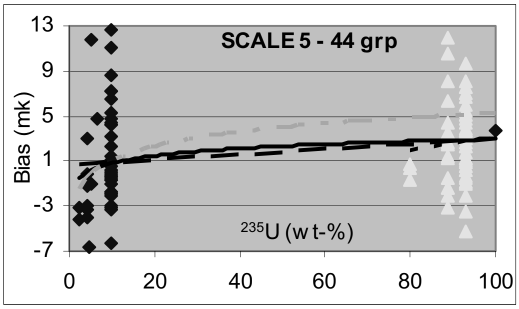


Figure F38. Enr ^{235}U. LEU, S5-44

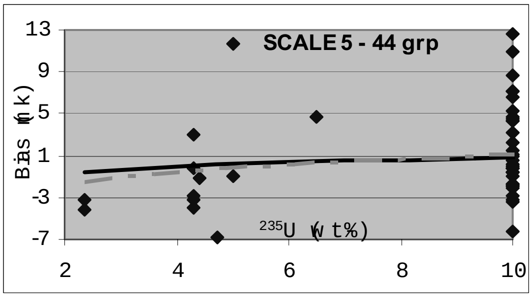
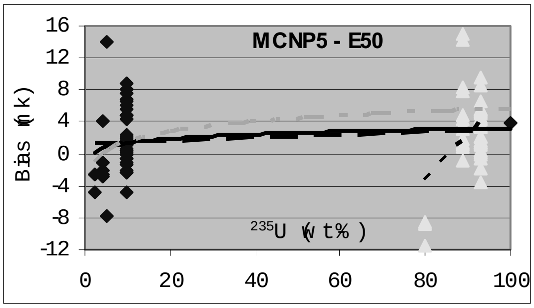


Figure F39. Enr 2^{35}U. LEU + HEU, M5-E50



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

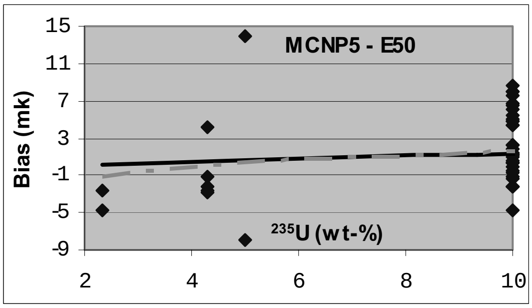


Figure F41. Enr ^{235}U. LEU+HEU, M5-E62

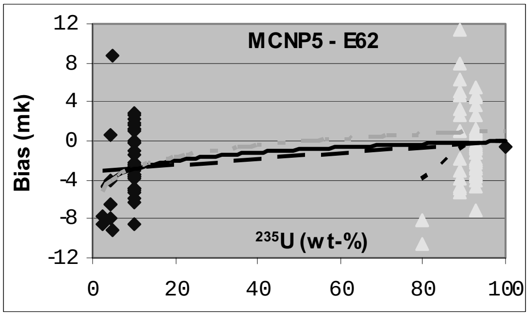


Figure F42. Enr ^{235}U. LEU, M5-E62

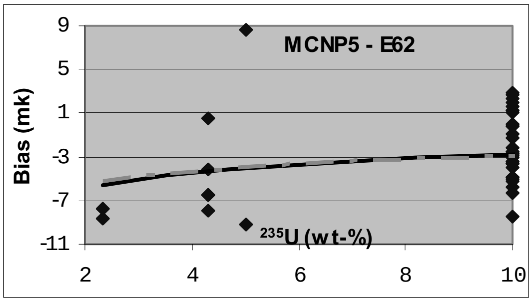


Figure F43. Enr ^{235}U. LEU+HEU, M5-E66

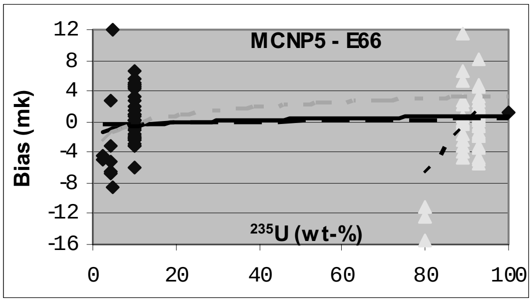


Figure F44. Enr ^{235}U. LEU, M5-E66

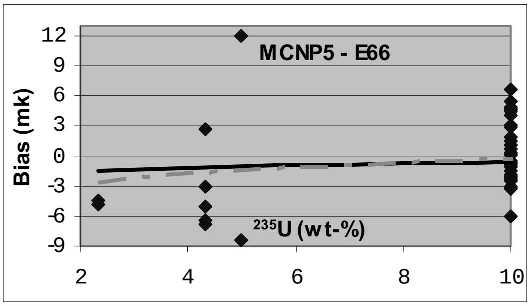


Figure F45. Enr ^{235}U. LEU+HEU, M5-E68

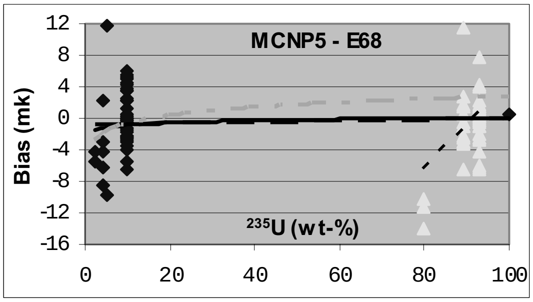


Figure F46. Enr ^{235}U. LEU, M5-E68

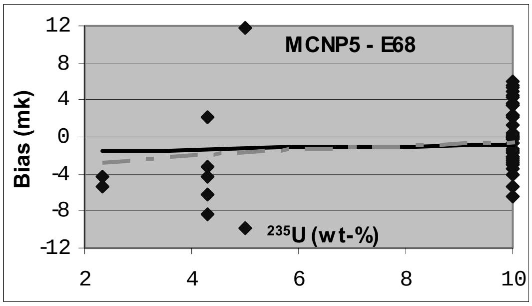


Figure F50. Enr ^{235}U. LEU, M5-F22

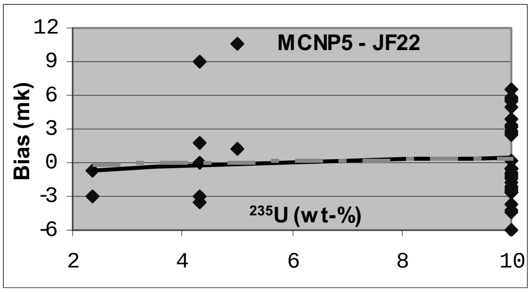


Figure F47. Enr ^{235}U. LEU+HEU, M5-E7P

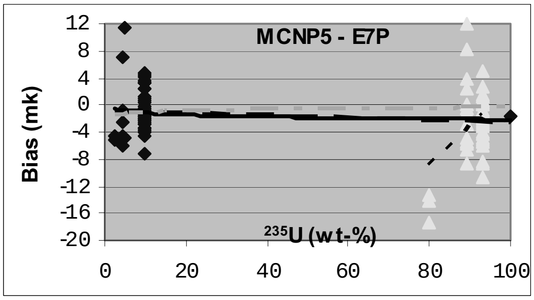


Figure F51. Enr ^{235}U. LEU+HEU, M5-F30

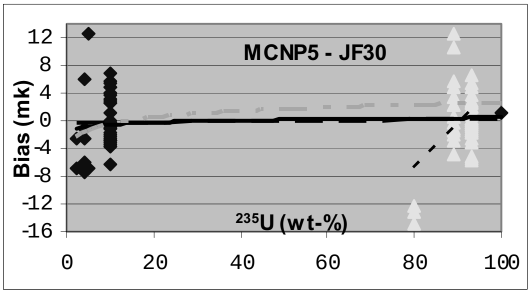


Figure F48. Enr ^{235}U. LEU, M5-E7P

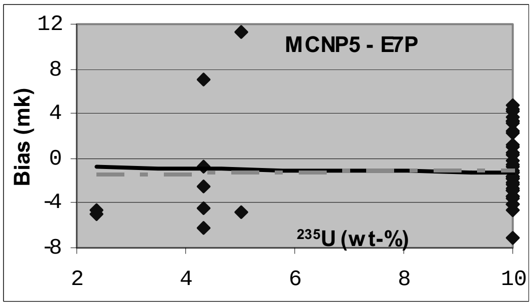


Figure F52. Enr ^{235}U. LEU, M5-F30

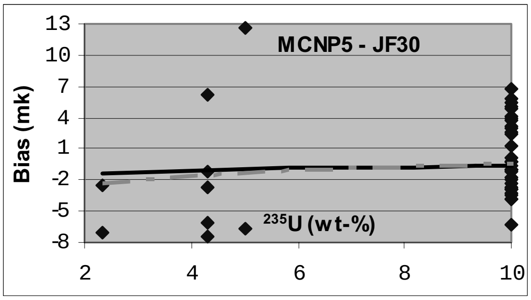


Figure F49. Enr ^{235}U. LEU+HEU, M5-F22

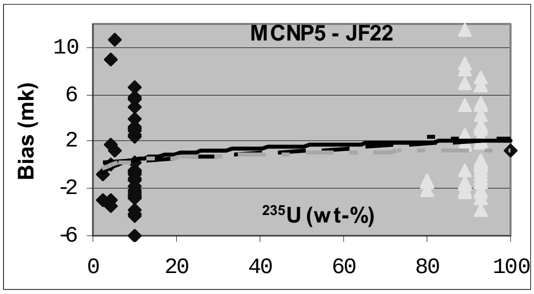


Figure F53. Enr ^{235}U. LEU+HEU, M5-J32

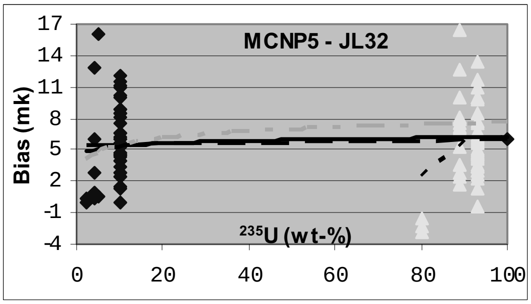


Figure F54. Enr ^{235}U. LEU, M5-J32

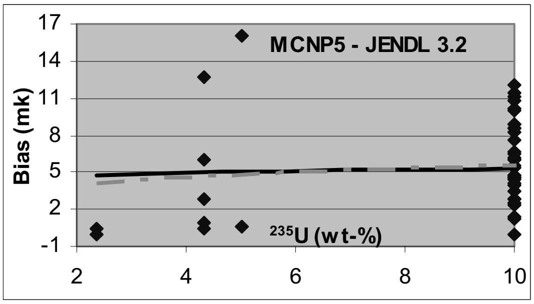


Figure F55. Enr ^{235}U. LEU+HEU, M5-J33

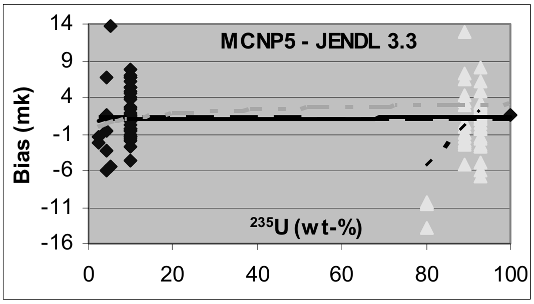


Figure F56. Enr ^{235}U. LEU, M5-J33

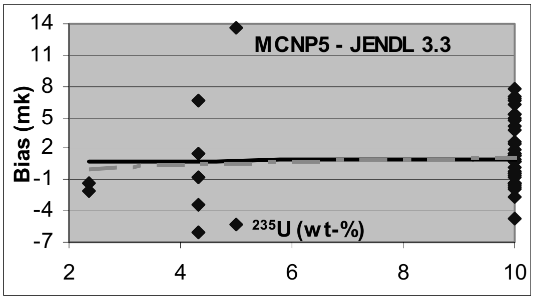


Figure F57. Enr ^{235}U. LEU+HEU, IPPE-04

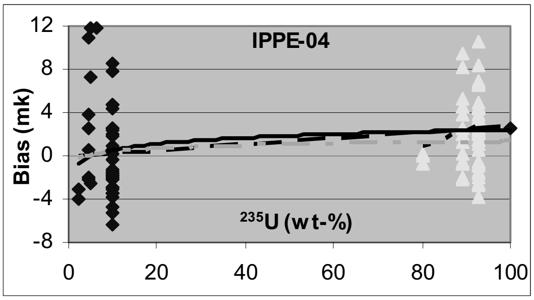


Figure F58. Enr ^{235}U. LEU, IPPE-04

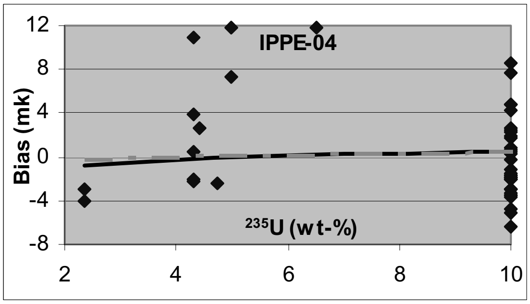


Figure F59. Legend for EALF trends

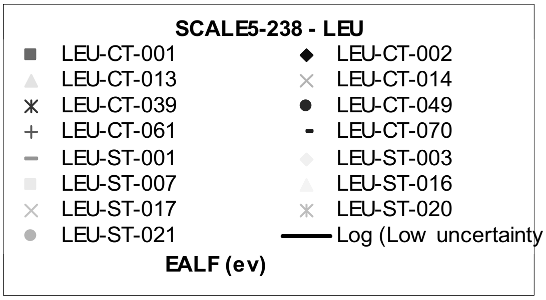


Figure F60. EALF. SCALE5+238 group

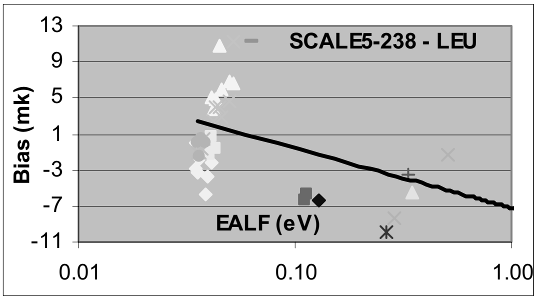


Figure F61. EALF. SCALE5+27 group

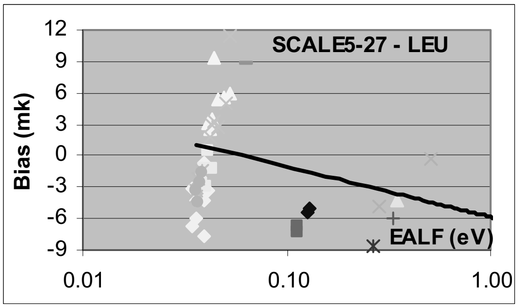


Figure F62. EALF. SCALE5+44 group

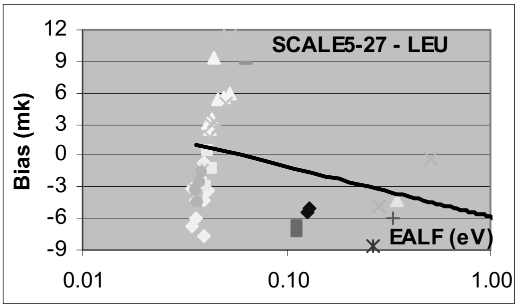


Figure F63. EALF. MCNP5+ENDF/B-50

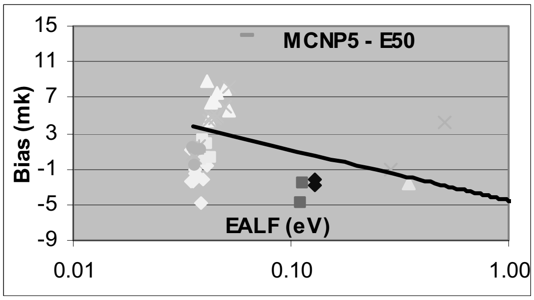


Figure F64. EALF. MCNP5+ENDF/B-62

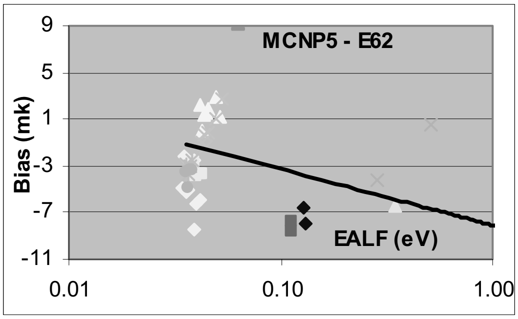


Figure F65. EALF. MCNP5+ENDF/B-66

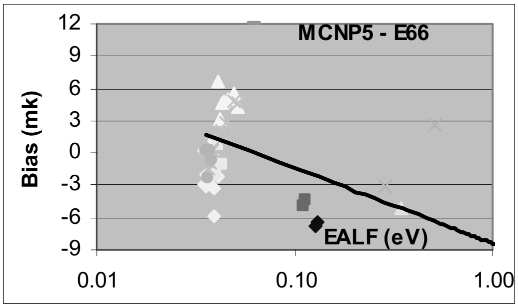


Figure F66. EALF. MCNP5+ENDF/B-68

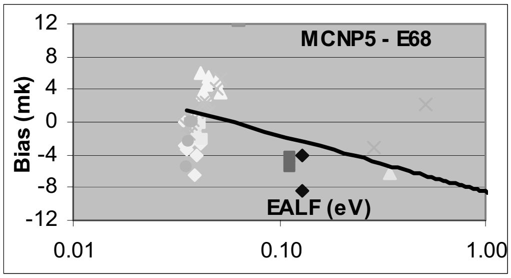


Figure F67. EALF. MCNP5+ENDF/B-7P

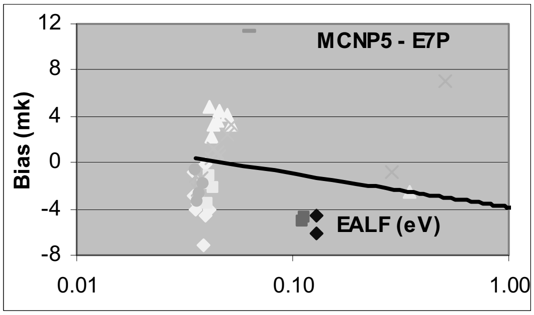


Figure F68. EALF. MCNP5+JEF 2.2

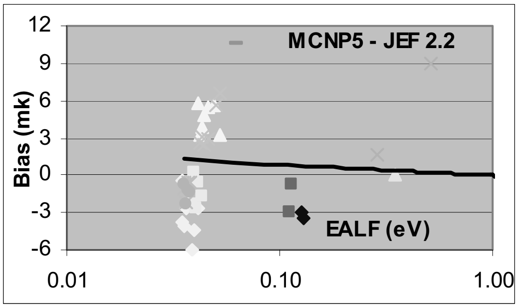


Figure F69. EALF. MCNP5+JEFF 3.0

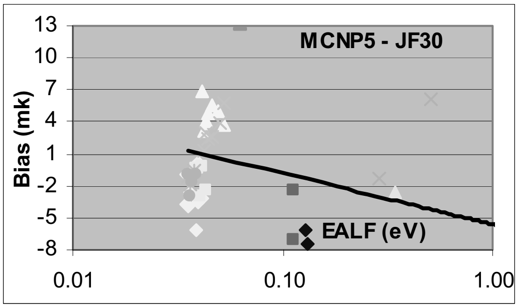


Figure F70. EALF. MCNP5+JENDL-3.2

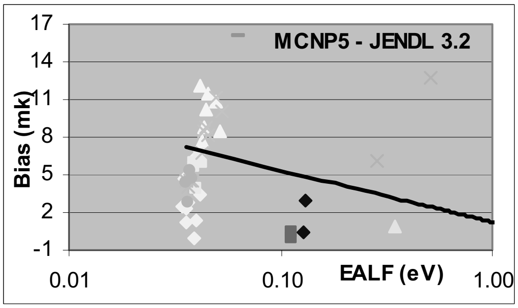


Figure F72. EALF. IPPE-04

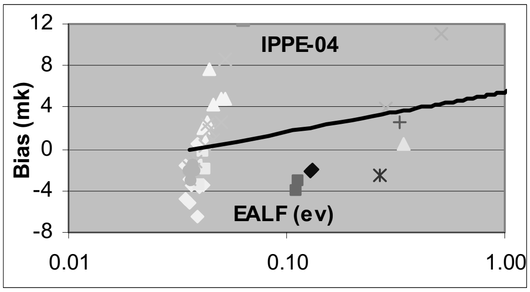


Figure F71. EALF. MCNP5+ JENDL-3.3

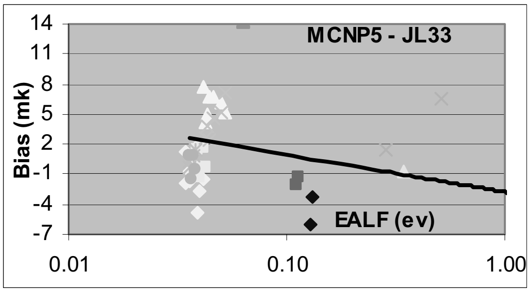


Figure F73. Legend: Chart with all results

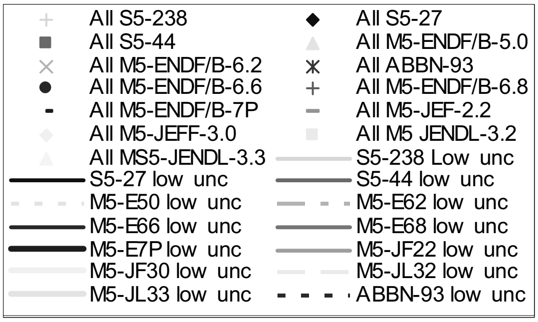


Figure F74. All results for LEU benchmarks (Note: EALF/3)

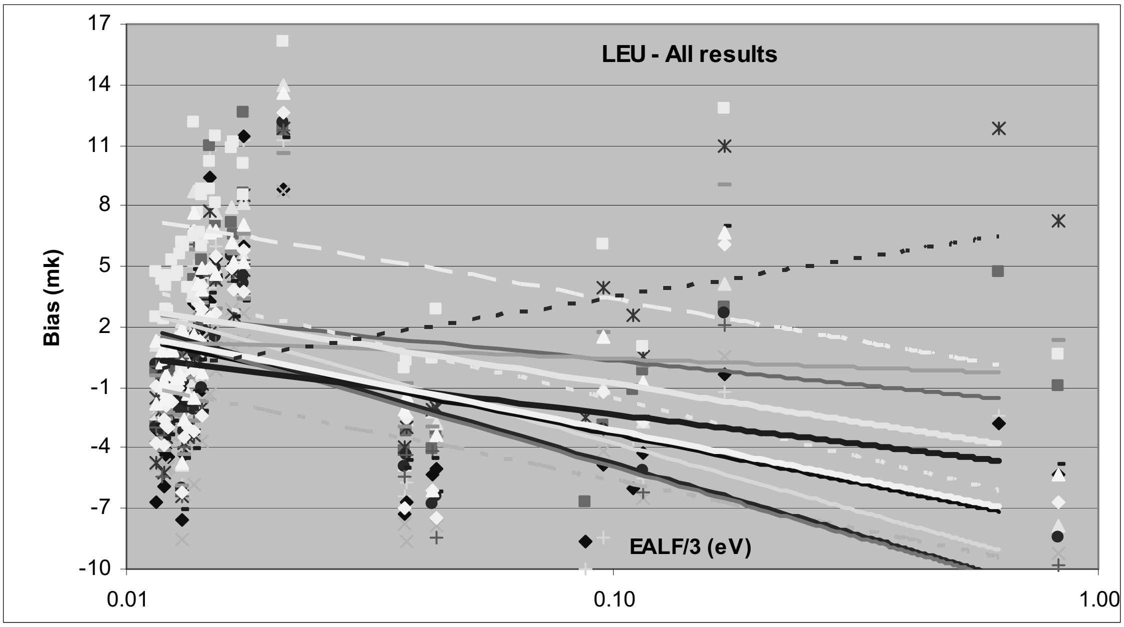


Table F70. LEU-CT-001 Case 01

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

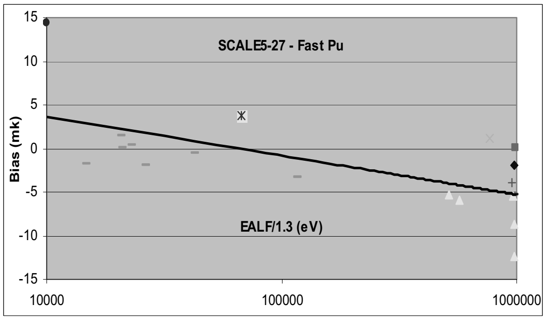


Figure F78. Fast Pu. SCALE5+44 grp

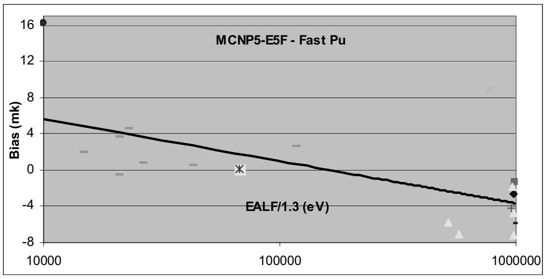


Figure F76. Fast Pu. SCALE5+238 grp

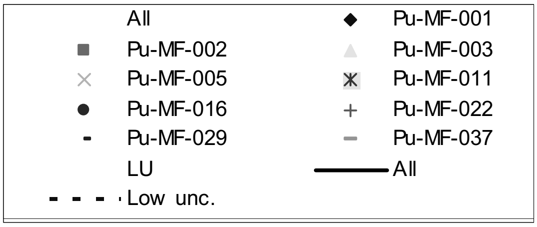


Figure F79. Fast Pu. MCNP5+ENDF/B-5.0

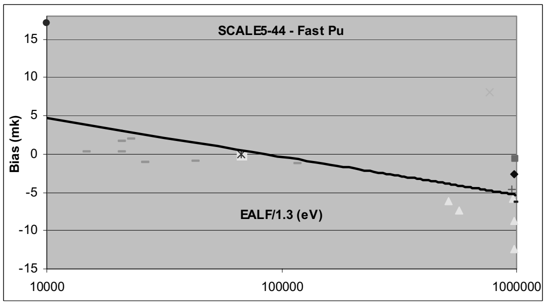


Figure F77. Fast Pu. SCALE5+27 grp

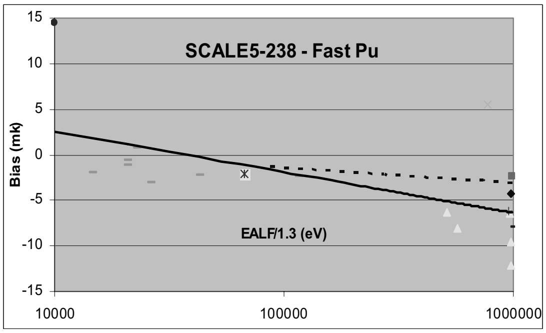


Figure F80. Fast Pu. MCNP5+ENDF/B-5F

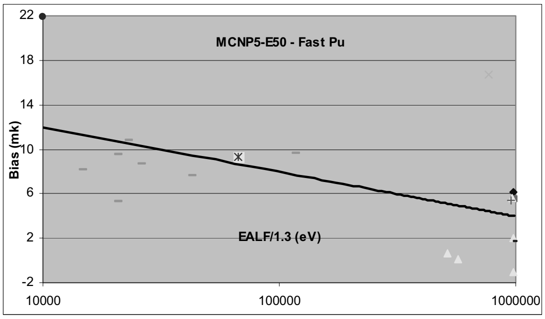


Figure F81. Fast Pu. MCNP5+ENDF/B-6.2

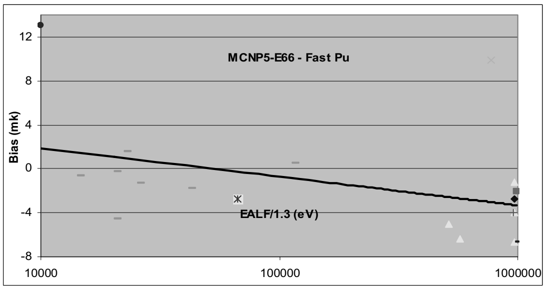


Figure F82. Fast Pu. MCNP5+ENDF/B-6.6

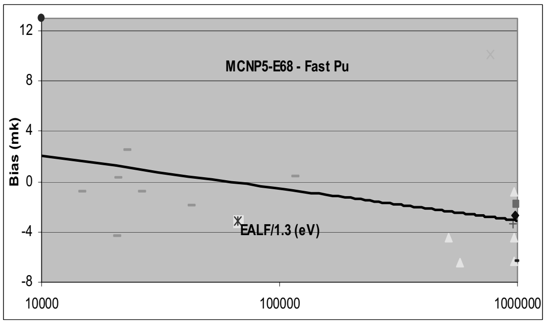


Figure F83. Fast Pu. MCNP5+ENDF/B-6.8

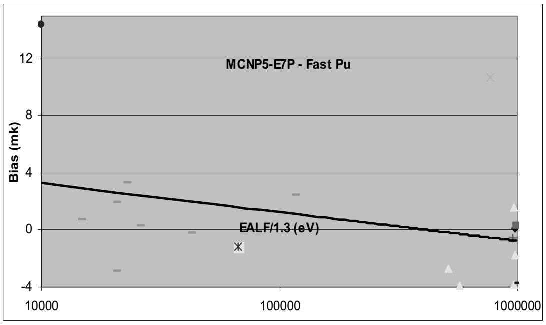


Figure F84. Fast Pu. MCNP5+ENDF/B-7P

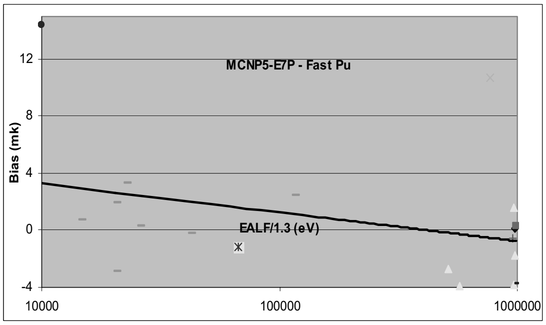


Figure F85. Fast Pu. MCNP5+JEF-2.2

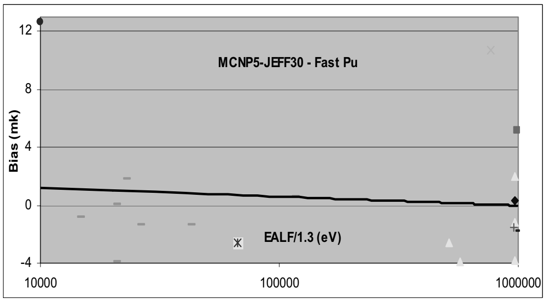


Figure F86. Fast Pu. MCNP5+JEFF-3.0

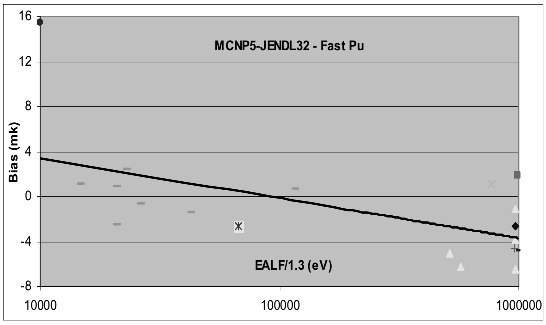


Figure F87. Fast Pu. MCNP5+JENDL-3.2

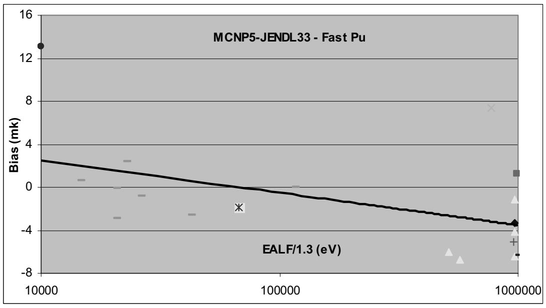


Figure F88. Fast Pu. MCNP5+JENDL-3.3

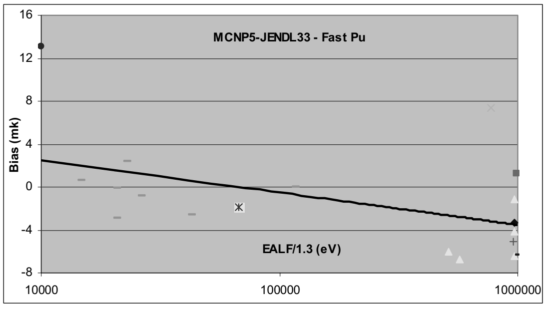


Figure F89. Fast Pu. ABBN-93

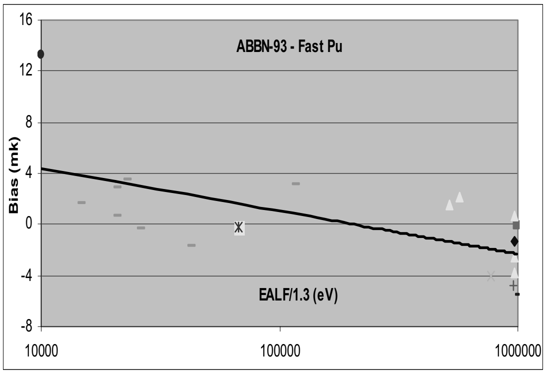


Figure F90. Legend for all methods chart

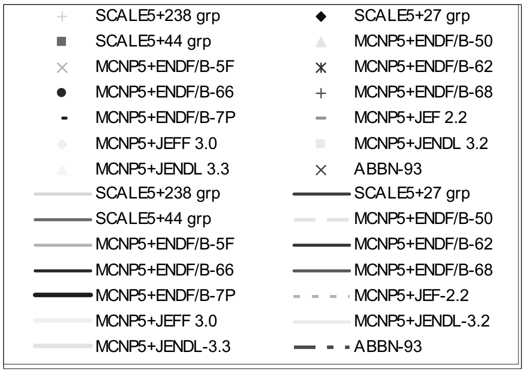


Figure F91. Fast Pu. All methods

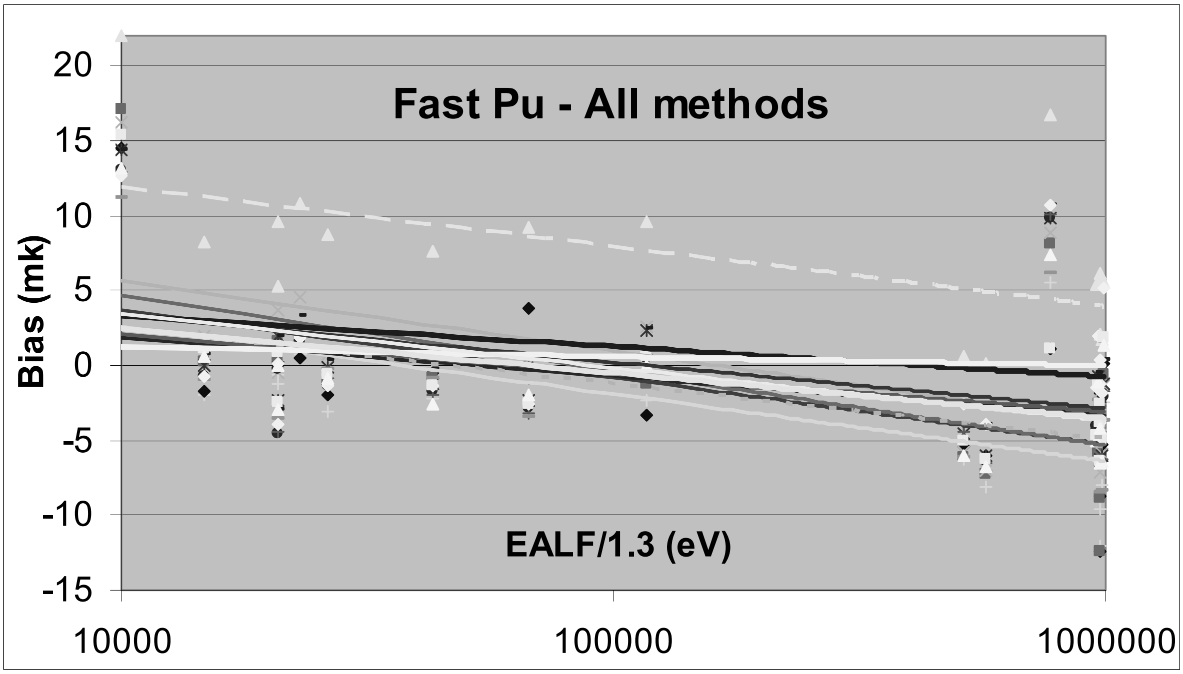


Table F117. Pu-MF-001 Case 01

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

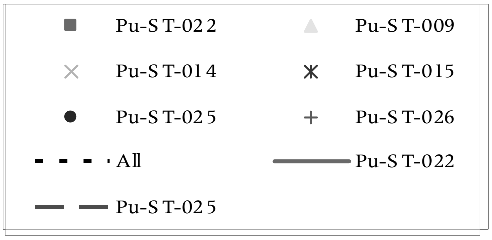


Figure F93. Thermal Pu. S5-238 grp

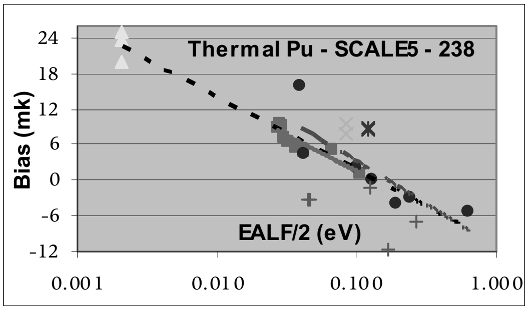


Figure F94. Thermal Pu. S5-27 grp

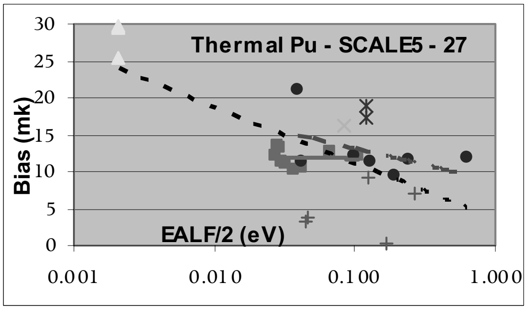


Figure F95. Thermal Pu. S5-44 grp

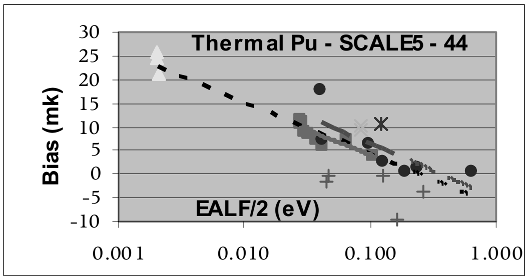


Figure F96. Thermal Pu. M5-E50

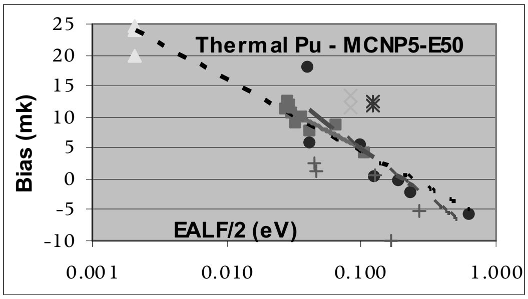


Figure F97. Thermal Pu. M5-E5F

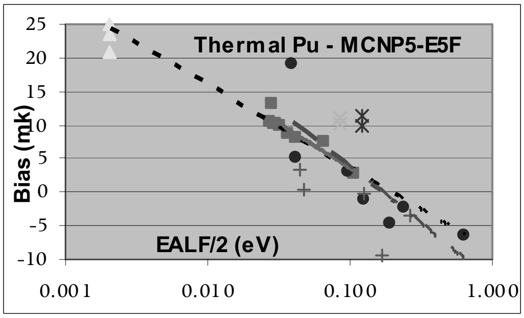


Figure F98. Thermal Pu. M5-E62

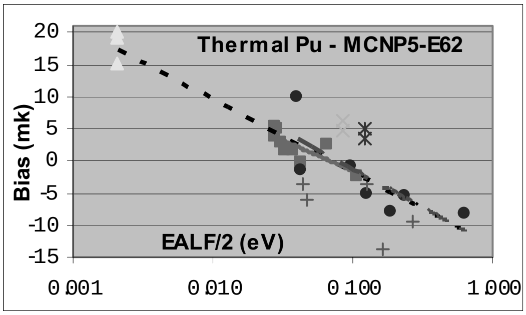


Figure F102. Thermal Pu. M5-JF22

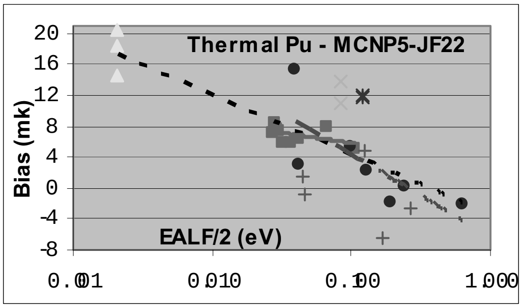


Figure F99. Thermal Pu. M5-E66

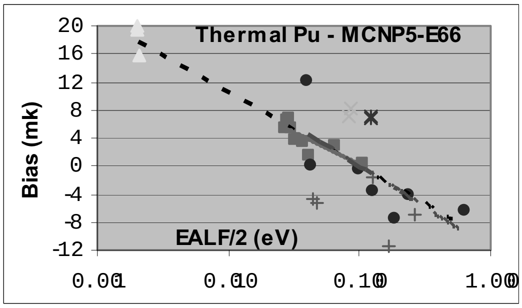


Figure F103. Thermal Pu. M5-JF30

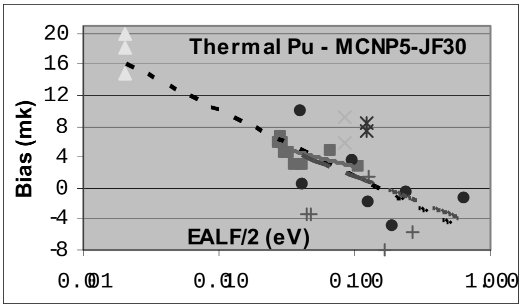


Figure F100. Thermal Pu. M5-E68

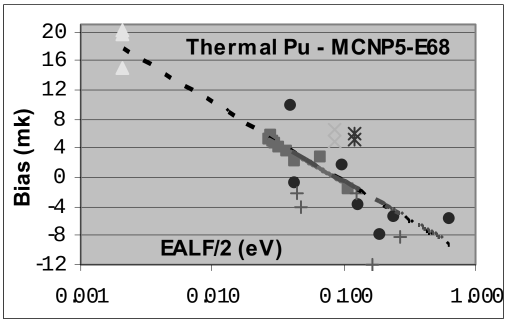


Figure F104. Thermal Pu. M5-JL32

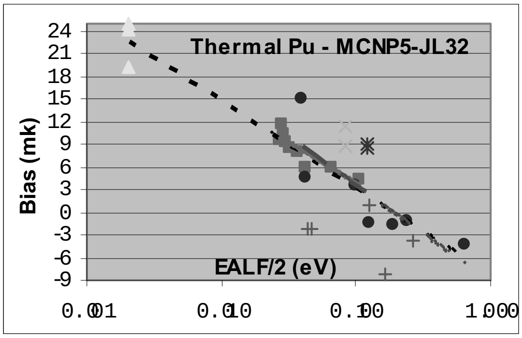


Figure F101. Thermal Pu. M5-E7P

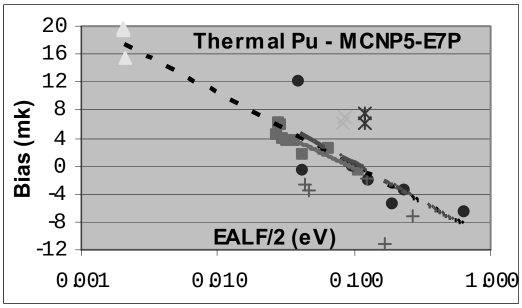


Figure F105. Thermal Pu. M5-JL33

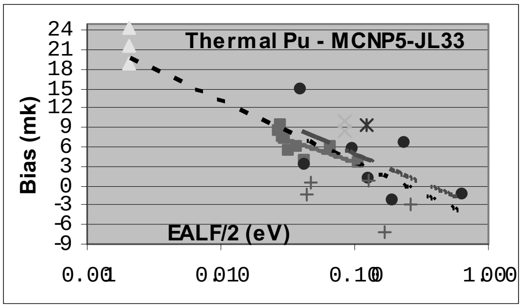


Figure F106. Thermal Pu. ABBN-93

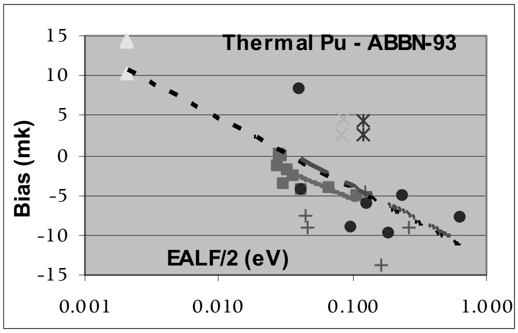


Figure F107. Legend. Thermal Pu. All

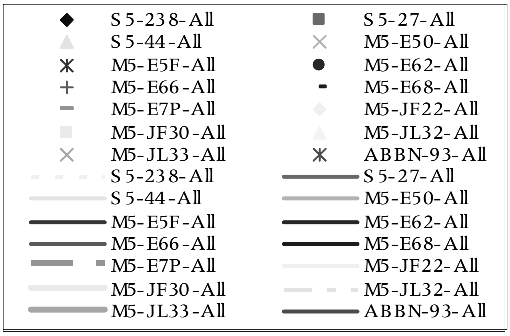


Figure F108. Thermal Pu. All

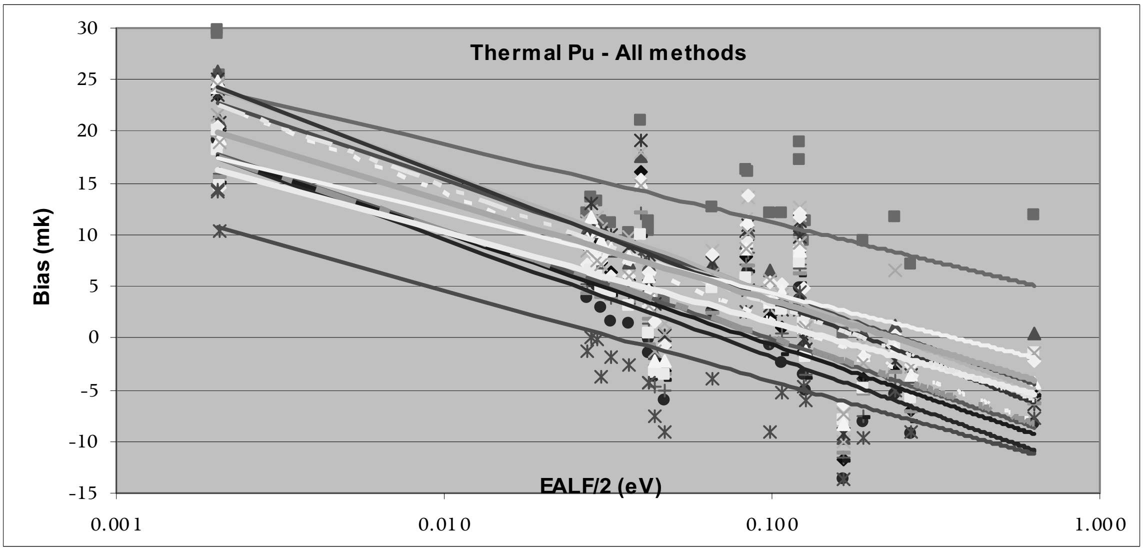


Table F136. Pu-ST-009 Case 1

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	