Appendix L

BEST-ESTIMATE REFERENCE VALUES AND COMMENTS

A minor effort is made here to demonstrate the determination of a best-estimate reference value for each of the 132 systems and parameters selected by the expert group. The evaluation is subjective and there is no time and no formal expert group left for discussion. This should not be a problem since the study is only at an intermediate state. The evaluated best-estimate reference values are for demonstration only and should not even be considered as preliminary.

A calculated result should be considered as having errors, even if the validation shows a zero bias. There is always some remaining uncertainty in every value. The uncertainty allowance could be smaller than the least significant digit in the reference value but the real error will occasionally be larger than the uncertainty allowance.

The bias corrected results from the following "major 6" methods were used in Appendix I to "automatically" calculate the first level of best-estimate reference values: EMS-M5-E7P or -68, EMS-M5-F30, EMS-M5-J33, EMSS5K-238, IPPE-ABBN93 and Serco-Mk8-F22. IPPE's results using the ABBN93 cross-section library were added late and the validation is not independent but based on the same selection of benchmarks as for the validation of EMS methods. IPPE results are not available for all plutonium isotope distributions, reducing the selection to the "major 5" methods. The bias-corrected MONK results are based on a quite general validation and thus quite "crude". However, efforts were made to find significant bias trends and to correct for them when found. For this reason the MONK bias-corrected results are included in the automatic best-estimate calculation.

CRISTAL is validated and normally gives high-quality results. However, there are known (to IRSN and to the Expert Group) biases in the reference values. Since no attempt was made to correct for them, they are not included in the automatic calculation of best-estimate values. However, CRISTAL results normally have low biases and require special consideration when nuclide density effects are evaluated.

JAERI Handbook results are bias-corrected but there is some question about the validity of the biases for best-estimate determination rather than for safe values determination. The same is true for the EMS-S4X-238 results. Those evaluations are of particular value since they include results of explicit calculations of positive and negative levels of confidence due to uncertainties. The levels are not symmetric since the relationships between k_{eff} and the reference parameter are not linear.

Other EMS results (older cross-section releases with SCALE 5 and MCNP5) are of value for many purposes but would not improve the quality of the best-estimates resulting from the current selection. ORNL results are not bias-corrected even though a reference to a general safety verification (same as used for EMS-S4X-238) is made. Values from other handbooks and standards were perhaps intended as best-estimate values at the time given but are not considered so now.

Additional biases are obtained from nuclide density evaluations. Lack of appropriate validation should lead to larger 95% level of confidence uncertainties for some best-estimate reference values.

To determine when uncertainties and discrepancies should be considered large, typical safety factors used in real applications may be considered (but not in this study). The safety factors are usually not the only control. Sometimes there is also a parallel limit on k_{eff}. This seems wise, in particular for large systems. The probability for double-batching (and more!), geometry changes, speed of change (probability of timely discovery), etc. are important.

For mass control where double-batching (and not more) is unlikely but credible, a factor of 0.9 has been used in Germany and other countries. In France, the safety factor is 0.86. The volume safety factor applied in Germany and many other countries is 0.8, while the geometry dimension factor is 0.9.

The reference values will be discussed one by one, but many will have common issues. IPPE-84 values are often very different and the reasons are given in the handbook (often compensating errors, sometimes not). IRSN-96 results are given as a range of values, indicating the uncertainty. The source [99] is not a published document; it is used primarily for internal use. Some values are included to demonstrate typical calculation methods of the past.

Various mean (average) values were calculated during the evaluation and some of them are shown in the charts in Appendix J. The index "c", e.g. in $\bar{m}_c$ stands for calculation-only while the index "bc" in $\bar{m}_{bc}$ stands for bias-corrected. Comparisons are made for methods that are used to obtain both calculated-only and bias-corrected values. The purpose is to observe the influences of validation and bias-correction. The EMS-S4X-238 values are not included, partly because the validation is not suitable for best-estimate determination and since the method is essentially duplicated (except for nuclide densities), using SCALE 5 instead of SCALE 4.4. CRISTAL and Japanese handbook values are not included in the means either, for reasons given earlier.

The automatic calculation of best-averages lead to the mean values $\bar{m}_{c6}$ and $\bar{m}_{bc6}$. Using other information, including results from methods that are not automatically included, number density considerations and "reasoned argument", there will often be additional bias-corrections.

The uncertainties based on statistics on the results are not sufficient. The automatic generation of a total 95% level of confidence is increased from normally two to three standard deviations to cover additional uncertainties. In reality, these statistics are not necessarily related to the real additional uncertainties. Using "argued reasoning", modifications should be considered to obtain a 95% level of confidence (increase or decrease).

The study is only at a demonstration level. It is better to overestimate the uncertainties than to underestimate them. Contributors and other reviewers should express wishes of changing the proposed biases and uncertainties, preferably but not necessarily by some justification.

The calculation of nuclide densities for the 132 reference systems is essential for determination of biases. Since the bias corrections change the densities related to the best-estimate reference values, the following densities are approximations. In particular for hydrated uranyl nitrate with low-enriched uranium, the densities (determined with SCALE 5) are not reliable.

The final estimations of best-estimate reference values that will be used in the main report follow after the section on reference system densities. To be really credible, all validated results need to be covered either by direct inclusion in the averaging or by given reasons for exceptions. Other results should be understood well enough to explain any deviations from the common best-estimate values.

Actinide densities and concentrations of the reference systems

The densities are given in Table L1. For these well-defined reference systems, there is no difference between density and concentration. In safety applications it may be very important to make a clear distinction between the two parameters. The density parameter is a mass to volume ratio while the concentration parameter, as used in criticality safety control, is a mass to mass ratio.

The units may be identical, e.g. g/cm^3, but the difference in the physics interpretation is there. Sometimes concentration, as measured in e.g. g/l, sounds like a mass per volume unit but it is really not. The "litre" is a volume unit but here it is used as a short for a "litre of a uniquely defined material". In criticality safety, this material must be defined not only by mass but also by other properties. The density for a nuclide, element or compound only informs about its mass per volume. It does not inform about other constituents in the material.

The distinction between density and concentration is also a reason why the moderation ratio H/X (also a concentration) often is a better specification than the concentration in g/l to determine limiting critical values. It directly gives the other relevant mass component to control.

Table L1. Actinide densities for all applications

Actinide densities for applications (g/cm^3)						
Parameter	Isotopes	Mass	Volume	Cylinder	Slab	Concentration
UO_2 Uranium density	100	0.0560	9.54[1]	9.54*	9.54*	0.0122
	20	0.266	1.063	1.121	1.449	0.0636
	5	0.918	1.884	1.932	2.174	0.286
	4	1.063	2.077	1.884	2.271	0.369
	3	1.449	2.319	2.367	2.512	0.521
UNH Uranium density	100	0.056	0.33	0.38	0.50	0.0123
	20	0.250	0.58	0.62	0.70[2]	0.0648
	5	0.77[2]	1.05[2]	1.06[2]	1.10[2]	0.311
	4	0.90[2]	1.14[2]	1.14[2]	1.18[2]	0.416
	3	1.15[2]	1.33[3]	1.33[3]	1.33[3]	0.629[2]
PuO_2 Plutonium density	100/0/0/0	0.0313	10.107	10.107	10.107	0.00717
	95/5/0/0	0.0323	10.108	10.108	10.108	0.00771
	80/10/10/0	0.0323	10.109	10.109	10.109	0.00800
	90/10/0/0	0.0334	10.108	10.108	10.108	0.00838
	80/15/5/0	0.0344	10.109	10.109	10.109	0.00892
	71/17/11/1	0.0344	10.109	10.109	10.109	0.00908
PuNH Plutonium density	100/0/0/0	0.031	0.28	0.33	0.55	0.00733
	95/5/0/0	0.032	0.14	0.155	0.212	0.00793
	80/10/10/0	0.032	0.13	0.145	0.22	0.00819
	90/10/0/0	0.033	0.125	0.135	0.175	0.00859
	80/15/5/0	0.034	0.12	0.13	0.18	0.00915
	71/17/11/1	0.034	0.12	0.13	0.16	0.00931

[1] Corrected for UO_2 density 10.84 g/cm^3 for 100% ^{235}U (10.96g/cm^3 for natural U)

[2] Above the solubility limit, below the crystal density. A mixture of saturated solution and crystals assumed.

[3] Crystal density.

Figure L1. Uranium densities for UO_2 reference systems

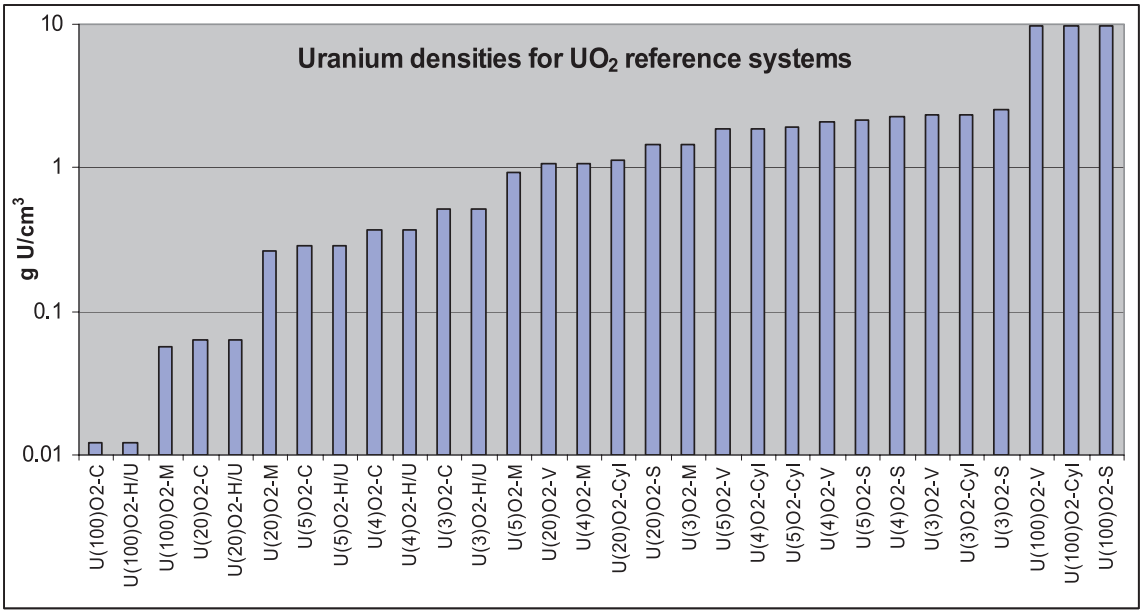


Figure L2. Uranium concentrations for UNH reference systems

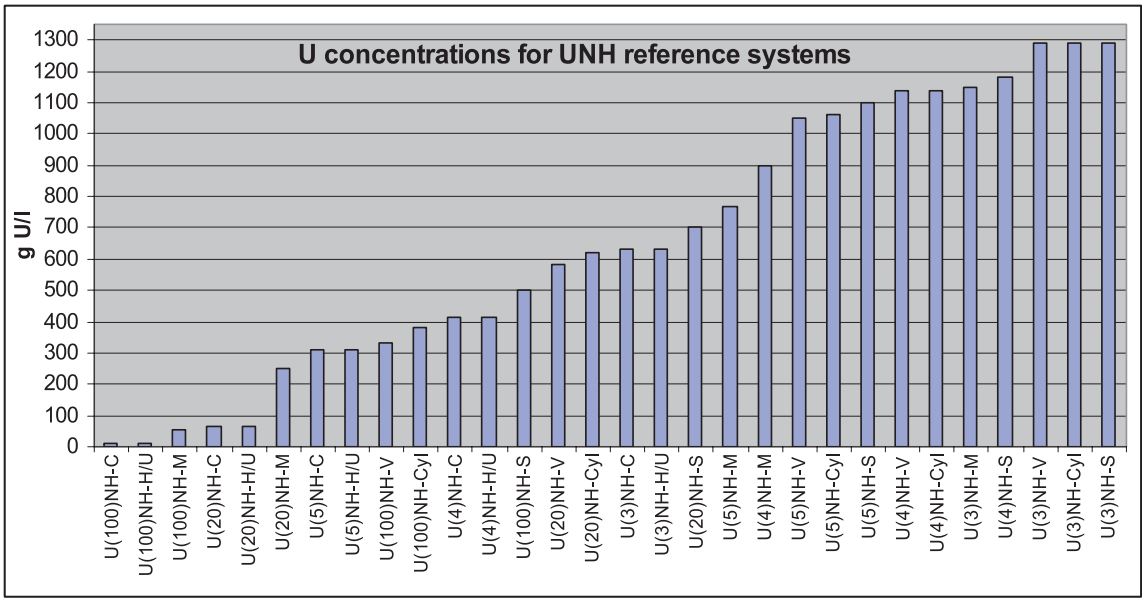


Figure L3. Plutonium densities for PuO_2 reference systems

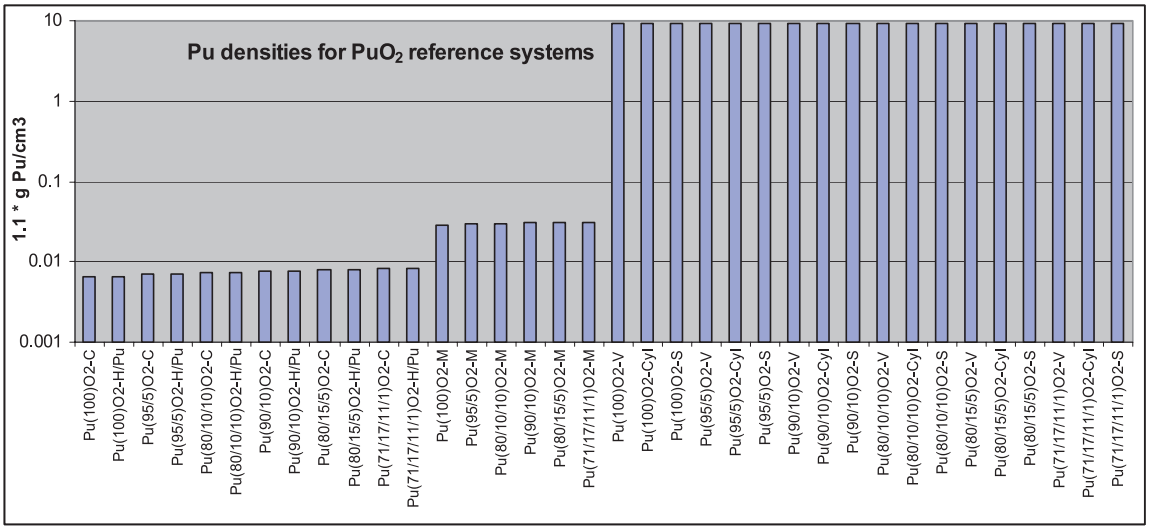
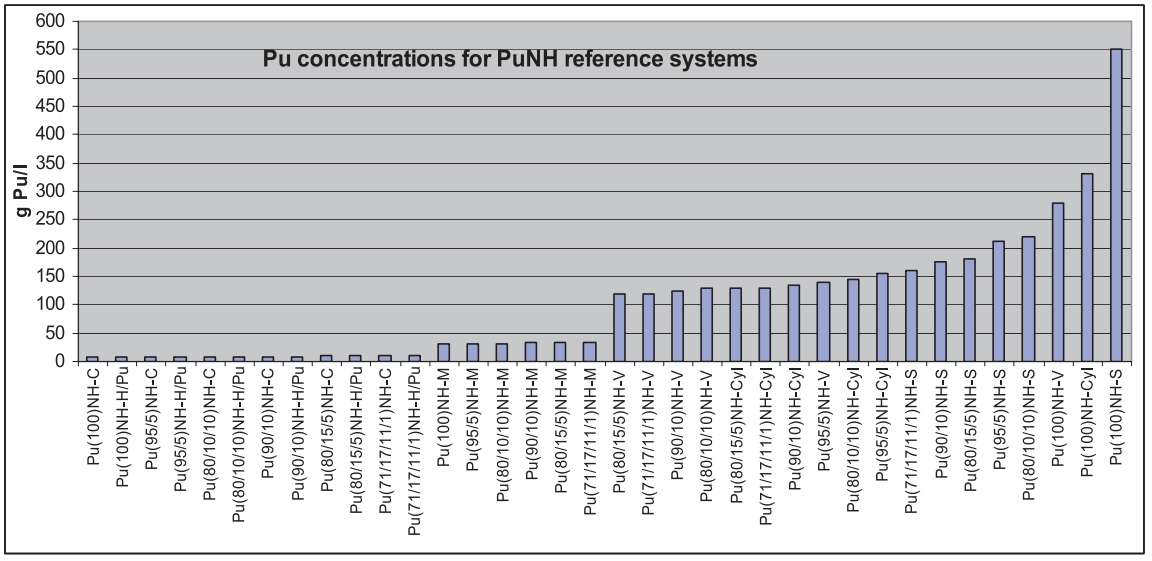


Figure L4. Plutonium concentrations for PuNH reference systems



Uranium dioxide – UO_2

$U(100)O_2$ – Mass

This system does not seem to be sensitive to the nuclide density issue. The material is well moderated. The geometry is not so sensitive to quadrature and mesh. The mean values $\bar{m}_c$ and $\bar{m}_{bc}$ are not so different, but their standard deviations are. The verification reduces the standard deviation by a factor of three, indicating that it really works.

The CRISTAL value is slightly lower, which is not unexpected (should be slightly conservative). The verified IPPE and Serco results agree well with the EMS results. There are no really large discrepancies. The IRSN-96 results were removed since they appear to concern 93.5% and not 100% by mass of ^{235}U and also since they cover a range of values.

The "major 6" average $\bar{m}_{bc6}$ with one standard deviation, is 798 ± 3 g ^{235}U. Considering that other uncertainties are expected to be small, the total 95% level of confidence uncertainty is estimated as 10 g ^{235}U.

$U(20)O_2$ – Mass

This system does not seem to be covered as well by benchmarks as that for 100% ^{235}U. However, the results indicate that the verification works well.

The Japanese Handbook release 2 ([23-24]) result has now been corrected here but the error needs to be pointed out. Even with a safety factor of 0.70, a system based on the handbook value of 7.43 kg could lead to criticality.

There are no additional biases related to nuclide density determination. There are no large discrepancies besides the already corrected value in the Japanese Handbook release 2.

The "major 6" average $\bar{m}_{bc6}$, with one standard deviation, is 5.22 ± 0.02 kg of uranium. Considering that other uncertainties are expected to be small, the total 95% level of confidence uncertainty is estimated as 0.10 kg of uranium.

$U(5)O_2$ – Mass

The standard deviation of $\bar{m}_{bc}$ is not reduced as much related to that for $\bar{m}_c$ as for the higher enrichments of ^{235}U. This may indicate that the verification is not quite as good and that the system may be more complicated (^{238}U and resonances). However, the verification still seems to work reasonably well. It is also reasonable to expect larger standard deviations for larger systems since the relative sensitivity to k_{eff} changes is smaller.

The Serco MONK value is lower and increases the standard deviation. The deviation is much lower than the uncertainty quoted by Serco.

There are no additional biases related to nuclide density determination. There are no large discrepancies besides the low (conservative for safety application) value in the IPPE-84 handbook, which is already known to have large uncertainties.

The mean $\bar{m}_{bc6}$ with one standard deviation is 37.0 ± 0.3 kg of uranium. The CRISTAL value is lower than the mean. This is important when considering the U(5)NH mass. Considering that other

uncertainties are expected to be small, the total 95% level of confidence uncertainty is estimated as 1.0 kg of uranium.

$U(4)O_2$ – Mass

The standard deviation of $\overline{m}_{bc}$ is almost reduced by a factor two by verification and this is not bad. The Serco and IPPE verified results are low while the EMS MCNP results with JENDL3.3 and the preliminary ENDF/B-VII library are high. The CRISTAL result is again low, giving a slightly conservative value, as expected.

There are no additional biases related to nuclide density determination. There are no large discrepancies.

The mean $\overline{m}_{bc6}$ with one standard deviation is 55.4 ± 0.5 kg of uranium. Considering that other uncertainties are expected to be small, the total 95% level of confidence uncertainty is estimated as 1.5 kg of uranium.

$U(3)O_2$ – Mass

The standard deviation of $\overline{m}_{bc}$ is reduced by a factor two by verification and, again, this is quite good. The EMS MCNP result with JEFF-3.0 is low and the preliminary ENDF/B-VII library is high. The CRISTAL result is again low, as expected.

There are no additional biases related to nuclide density determination. There are no large discrepancies. The EMS SCALE result based on ORNL verification is high, indicating that the verification is not focused on this application (this is normal and will not be repeated every time).

The mean $\overline{m}_{bc6}$ with one standard deviation is 99.6 ± 0.6 kg of uranium. Considering that other uncertainties are expected to be small, the total 95% level of confidence uncertainty is estimated as 1.8 kg of uranium.

$U(100)O_2$ – Volume

This system is sensitive to the nuclide density as well as to quadrature and mesh issues for deterministic codes. The nuclide density issue related to the isotopic distribution leads to a reduced theoretical density of UO_2 from 10.96 to 10.84 g/cm^3. If the 10.96 density is used, a bias needs to be determined. Using SCALE 5 (XSDRNPM) and the 238 group library, the bias was determined to be 0.13 litres. Only IRSN in their CRISTAL contribution takes the density issue into account. The Japanese Handbooks deal with the issue but don't contain values for this type of material.

This bias correction is significant when comparing calculation results but is probably not so important for safety or economy. Single lumps of such sizes should not be expected in any environment where handbook values or quick calculations are used as a safety evaluation basis. In a distributed system, the problem with lack of moderation may be more complicated to handle.

The mean values $\overline{v}_c$ and $\overline{v}_{bc}$ are not so different, but their standard deviations are. The verification reduces the standard deviation by more than a factor of two, indicating that it works quite well.

There first appeared to be some really large discrepancies. However, the German Handbook [19] gives the critical volume as 5.6 litres and the safe volume as 4.6 litres, **provided that the uranium density is less than 1 g U/cm^3**. The curve indicates a critical value around 4 kg for higher uranium

densities. This condition was not documented in the tables distributed to the participants (the tables used to collect data on the web site did not allow much explanation).

The ARH-600 handbook value of 6.1 litres is given for uranium, but the reference system is based on UO_2F_2. As can be seen in the German Handbook, the minimum critical volume for UO_2F_2 is close to this value 6.1. The curves stop at a density at 1 g U/cm^3 and do not indicate a potential minimum at the theoretical uranium density.

The IRSN-96 result was removed since it appears to concern 93.5% and not 100% by mass of ^{235}U (later all IRSN-96 results were removed).

The SCALE 27- and 44-group cross-section libraries are not designed to cover this type of application. The verification and associated bias corrections improve their results considerably.

The average verified value with one standard deviation, including the IPPE result, is 4.25 ± 0.03 litres. Adding the density-related bias correction to the best estimate average, the best-estimate value becomes 4.38 ± 0.03 litres.

A final check before completing the final report showed that a sphere is not the optimum shape for this system. Calculations with SCALE 5 and the 238-group library as well as with MCNP5 with the JENDL-3.3 library showed that a cylinder with equal height as diameter and, even clearer, a cube will give smaller critical volumes than a sphere. For both methods, 12 million neutrons were tracked, skipping the first 2 millions. SCALE 5 showed a larger effect, but since the resonance treatment in MCNP5 is more accurate (the EALF values are very different for a cube than for a sphere), MCNP5 results were used. MCNP5 gave a k_{eff} of 1.00965 for the sphere and 1.01108 for a cube with an identical volume. In both cases the standard deviation was 0.00025. The difference, 0.00143 is statistically clear. SCALE 5 increased the difference by a factor two.

Considering the corresponding geometry shape bias 0.03 litres, based on MCNP5 results, the new best-estimate value becomes 4.35 ± 0.03 litres.

The differences are quite small but it was not expected that this situation would occur for any of the specified systems. A few other systems, $U(3)O_2$, $Pu(100)O_2$ and $Pu(80/10/10)O_2$, were also checked for this effect but none was found.

Considering that other uncertainties are expected to be small, the total 95% level of confidence uncertainty is estimated as 0.10 litres. The CRISTAL V1.0 result 4.30 litres include the isotopic density effect, making the value slightly lower than the best-estimate value for this fast system.

$U(20)O_2$ – Volume

This system is not so sensitive to the nuclide density issue.

The mean value standard deviations are not reduced sufficiently by verification. The IPPEABBN93 value is much lower than the other bias-corrected values and this influences the standard deviations. However, the CRISTAL value is even lower. The IPPE value will be kept since there is no direct evidence of error.

The bias-corrected value of 11.5 litres in the Japanese Handbook release 2, as well as the identical value in the IRSN/CEA 1978 handbook appears too high. The IPPE-84 deviation is large as often is the case. The IRSN-96 result was removed since it is not an estimate but a range of values.

The mean $\bar{v}_{bc6}$ with one standard deviation is 10.78 ± 0.13 litres. The total 95% level of confidence uncertainty is estimated as 0.40 litres, including effects of other uncertainties.

$U(5)O_2$ – Volume

This system is not sensitive to the nuclide density issue.

The mean value standard deviations are reduced significantly by verification. The IPPE-ABBN93 value is much lower than the other bias-corrected values and this influences the standard deviations. However, the CRISTAL value is as low. The IPPE value will be kept since there is no direct evidence of error. However, the bias-correction for IPPE-ABBN93 is large and not very accurate.

The IPPE-84 deviation is large as often is the case. The IRSN-96 result was removed since it is not an estimate but a range of values.

The average verified value with one standard deviation, including the IPPE result, is 27.78 ± 0.22 litres. The total 95% level of confidence uncertainty is estimated as 0.7 litre, including effects of other uncertainties.

$U(4)O_2$ - Volume

This system is not sensitive to the nuclide density issue.

The mean value standard deviations are reduced by a factor larger than two by verification. This is better than for the 5% enrichment ^{235}U. The IPPE-ABBN93 value is much lower than the other bias-corrected values and this influences the standard deviations. However, the CRISTAL value is as low. The IPPE value will be kept since there is no direct evidence of error. However, the bias-correction for IPPE-ABBN93 is large and not very accurate.

The IPPE-84 deviation is large as often is the case. The bias-corrected values from the Japanese handbooks are low, in particular the 1988 release.

The best-estimate average verified value with one standard deviation, including the IPPE result, is 35.69 ± 0.28 litres. The total 95% level of confidence uncertainty is estimated as 0.90 litres, including effects of other uncertainties.

$U(3)O_2$ – Volume

This system is not sensitive to the nuclide density issue.

The mean value standard deviations are reduced by a factor larger than two by bias correction from verification. The IPPE-ABBN93 value is much lower than the other bias-corrected values and this influences the standard deviations. The CRISTAL value is low but not as low as the IPPE-ABBN93 value. The IPPE value will be kept since there is no direct evidence of error. However, the bias-correction for IPPE-ABBN93 is large and not very accurate.

The IPPE-84 deviation is large as often is the case. The bias-corrected values from the Japanese handbooks are also very low, in particular the 1988 release.

The best-estimate average verified value with one standard deviation, including the IPPE result, is 53.49 ± 0.32 litres. The total 95% level of confidence uncertainty is estimated as 1.00 litres, including effects of other uncertainties.

$U(100)O_2$ – Cylinder

This system is sensitive to the nuclide density as well as to quadrature and mesh issues for deterministic codes. The nuclide density issue related to the isotopic distribution leads to a reduced theoretical density of UO_2 from 10.96 to 10.84 g/cm^3. If the 10.96 density is used, a bias needs to be determined. Using SCALE 5 (XSDRNPM) and the 238 group library, the bias was determined to be 0.12 cm. Only IRSN in their CRISTAL contribution takes the density issue into account. The Japanese Handbooks deal with the issue but don't contain values for this type of material.

The mean values $\bar{\Phi}_c$ and $\bar{\Phi}_{bc}$ are not so different, but their standard deviations are. The bias correction based on the verification reduces the standard deviation by more than a factor of two, indicating that it works acceptably.

The German Handbook [19] and the ARH-600 Handbook [14] values were removed for the same reason as described under $U(100)O_2$ volume.

The IRSN-96 result was removed since it appears to concern 93.5% and not 100% by mass of ^{235}U.

The SCALE 27- and 44-group cross-section libraries are not designed to cover this type of application. The verification and associated bias corrections improve their results considerably.

The average verified value with one standard deviation, including the IPPE result, is 12.35 ± 0.02 cm. The CRISTAL result, without consideration of density effects, is a little higher than other values. This situation changes after such consideration. Adding the density-related bias correction to the best-average, the best-estimate value becomes 12.47 ± 0.02 cm. Considering that other uncertainties are expected to be small, the total 95% level of confidence uncertainty is estimated as 0.06 cm.

$U(20)O_2$ – Cylinder

This system is not so sensitive to the nuclide density issue.

The mean value standard deviations are not reduced so much by bias corrections from verification. The IPPE-ABBN93 value is much lower than the other bias-corrected values and this influences the standard deviations. The IPPE value will be kept since there is no direct evidence of error. Without the IPPE results, the verification seems to work well with EMS methods.

There are no large discrepancies. The IRSN-96 result was removed since it is not an estimate but a range of values.

The average verified value with one standard deviation, including the IPPE result, is 17.97 ± 0.07 cm. The total 95% level of confidence uncertainty is estimated as 0.20 cm, including effects of other uncertainties.

$U(5)O_2$ – Cylinder

This system is not so sensitive to the nuclide density issue.

The mean value standard deviations are reduced by a factor of two by verification. The IPPE-ABBN93 value is much lower than the other bias-corrected values and this influences the standard deviations. However, the CRISTAL value is as low. The IPPE value will be kept since there is no direct evidence of error.

The IRSN-96 result was removed since it is not an estimate but a range of values.

The average verified value with one standard deviation, including the IPPE result, is 25.65 ± 0.09 cm. The total 95% level of confidence uncertainty is estimated as 0.30 cm, including effects of other uncertainties.

$U(4)O_2$ – Cylinder

This system is not sensitive to the nuclide density issue.

The mean value standard deviations are reduced by a factor less than two by bias correction from verification. The IPPE-ABBN93 value is much lower than the other bias-corrected values and this influences the standard deviations. However, the CRISTAL value is as low. The IPPE value will be kept since there is no direct evidence of error.

There are no large discrepancies for this reference value.

The best-estimate average verified value with one standard deviation, including the IPPE result, is 28.25 ± 0.16 cm. The total 95% level of confidence uncertainty is estimated as 0.50 cm, including effects of other uncertainties.

$U(3)O_2$ – Cylinder

This system is not sensitive to the nuclide density issue.

The mean value standard deviations are reduced by a factor two by verification. The IPPE-ABBN93 value is much lower than the other bias-corrected values and this influences the standard deviations. The CRISTAL value is low but not as low as the IPPE-ABBN93 value. The IPPE value will be kept since there is no direct evidence of error.

The IPPE-84 deviation is quite large as often is the case. The bias-corrected value from the Japanese handbook release 2 is also a little low.

The best-estimate average verified value with one standard deviation, including the IPPE result, is 32.66 ± 0.13 cm. The total 95% level of confidence uncertainty is estimated as 0.40 cm, including effects of other uncertainties.

U(100)O_2 – Slab

This system is sensitive to the nuclide density as well as to quadrature and mesh issues for deterministic codes. The nuclide density issue related to the isotopic distribution leads to a reduced theoretical density of UO_2 from 10.96 to 10.84 g/cm^3. If the 10.96 density is used, a bias needs to be determined. Using SCALE 5 (XSDRNPM) and the 238 group library, the bias was determined to be 0.04 cm. Only IRSN in their CRISTAL contribution takes the density issue into account. The Japanese Handbooks deal with the issue but don't contain values for this type of material.

The mean values $\bar{t}_c$ and $\bar{t}_c$ are not so different, neither are the standard deviations. The bias correction based on the verification reduces the standard deviation by less than a factor of two but, since it is quite small, the verification still works acceptably.

The CRISTAL V1.0 result, with proper consideration of density effects, is a little lower than the best-estimate value when the bias for density effects has been considered.

The German Handbook [19] and the ARH-600 Handbook [14] values were removed for the same reason as described under U(100)O_2 volume.

The IRSN-96 results were removed since they appear to concern 93.5% and not 100% by mass of ^{235}U.

The SCALE 27- and 44-group cross-section libraries are not designed to cover this type of application. The verification and associated bias corrections improve their results considerably.

The average verified value with one standard deviation, including the IPPE result, is 3.41 ± 0.03 cm. Adding the density-related bias to the best average, the best-estimate value becomes 3.45 ± 0.03 cm. Considering that other uncertainties are expected to be small, the total 95% level of confidence uncertainty is estimated as 0.10 cm.

U(20)O_2 – Slab

This system is not so sensitive to the nuclide density issue.

The mean value standard deviations are not reduced so much by bias corrections from verification. This time, the Serco MONK value is much higher than the other bias-corrected values and this influences the standard deviations. The Serco value will be kept since there is no direct evidence of error. The verification seems to work well with EMS methods.

There are no large discrepancies. The IRSN-96 result was removed since it is not an estimate but a range of values.

The average verified value with one standard deviation, including the IPPE result, is 7.24 ± 0.10 cm. The total 95% level of confidence uncertainty is estimated as 0.30 cm, including effects of other uncertainties.

$U(5)O_2$ – Slab

This system is not so sensitive to the nuclide density issue.

The mean value standard deviations are not reduced much by bias corrections from verification. The Serco MONK value is much higher than the other bias-corrected values and this influences the standard deviations. The Serco value will be kept since there is no direct evidence of error.

The IRSN-96 result was removed since it is not an estimate but a range of values.

The average verified value with one standard deviation, including the IPPE result, is 12.17 ± 0.09 cm. The total 95% level of confidence uncertainty is estimated as 0.30 cm, including effects of other uncertainties.

$U(4)O_2$ – Slab

This system is not sensitive to the nuclide density issue.

The mean value standard deviations are reduced by a factor less than two by bias correction from verification. The standard deviation is quite low and there are no large deviations from the average of the six major bias corrected values.

There are no other large discrepancies for this reference value.

The best-estimate average verified value with one standard deviation, including the IPPE result, is 13.77 ± 0.07 cm. The total 95% level of confidence uncertainty is estimated as 0.20 cm, including effects of other uncertainties.

$U(3)O_2$ – Slab

This system is not sensitive to the nuclide density issue.

The mean value standard deviations are reduced by a factor two by verification. The IPPE-ABBN93 value is much lower than the other bias-corrected values and this influences the standard deviations. The CRISTAL value is low but not as low as the IPPE-ABBN93 value. The IPPE value will be kept since there is no direct evidence of error.

The IPPE-84 deviation is quite large and conservative for safety use as often is the case. The bias-corrected value from the Japanese handbook release 2 is also low.

The best-estimate average verified value with one standard deviation, including the IPPE result, is 16.61 ± 0.07 cm. The total 95% level of confidence uncertainty is estimated as 0.21 cm, including effects of other uncertainties.

$U(100)O_2$ – Concentration

This system is not sensitive to the nuclide density.

The mean values $\overline{c}_c$ and $\overline{c}_{bc}$ are not so different, but the standard deviation increases almost by a factor two due to bias corrections. That means that the verification certainly has not worked at all even though the standard deviation is quite low.

The IRSN-96 result was removed since it appears to concern 93.5% and not 100% by mass of ^{235}U.

The average verified value with one standard deviation, including the IPPE result, is 12.18 ± 0.06 g/l. Considering that other uncertainties are expected to be small, the total 95% level of confidence uncertainty is estimated as 0.20 g/l.

$U(20)O_2$ – Concentration

This system is not sensitive to the nuclide density issue.

The mean values $\overline{c}_c$ and $\overline{c}_{bc}$ are not so different, but the standard deviation increases due to bias corrections. That means that the verification has not worked, even though the standard deviation is quite low.

The average verified value with one standard deviation, including the IPPE result, is 64.0 ± 0.2 g/l. The total 95% level of confidence uncertainty is estimated as 0.7 g/l, including effects of other uncertainties.

$U(5)O_2$ – Concentration

This system is not sensitive to the nuclide density issue.

The mean value standard deviations are not reduced much by bias corrections from verification. However, the standard deviation is small.

The average verified value with one standard deviation, including the IPPE result, is 286.7 ± 0.8 g/l. The total 95% level of confidence uncertainty is estimated as 2.5 g/l, including effects of other uncertainties.

$U(4)O_2$ – Concentration

This system is not sensitive to the nuclide density issue.

The mean value standard deviation is almost not reduced at all by bias correction from verification. The standard deviation is low and there are no large deviations from the average of the six major bias corrected values.

There are no large discrepancies for this reference value.

The best-estimate average verified value with one standard deviation, including the IPPE result, is 370.6 ± 1.0 g/l. The total 95% level of confidence uncertainty is estimated as 3.0 g/l, including effects of other uncertainties.

$U(3)O_2$ – Concentration

This system is not sensitive to the nuclide density issue.

The mean value standard deviation is slightly increased by bias correction from verification. Since the standard deviation is low, the verification is still considered as successful.

The best-estimate average verified value with one standard deviation, including the IPPE result, is 522.0 ± 1.7 g/l. The total 95% level of confidence uncertainty is estimated as 5.0 g/l, including effects of other uncertainties.

$U(100)O_2$ – Moderation

This system is essentially the same as the concentration system. However, it is not sensitive to the nuclide density laws as the critical concentration is. The moderation parameter for an infinite system is not density dependent. If the different parameter values cover the whole range of moderations, from very dilute to crystal, then a check of corresponding densities obtained by different density laws would be revealing. Thus, since it is less complicated, it makes more sense to start with comparing critical moderations before starting comparing critical concentrations.

At this time, the best-estimate of the critical concentration will be used to find the best-estimate of the critical moderation. SCALE 5 is used for that. Using that moderation, different density laws can be compared.

The critical moderation corresponding to the best-estimate critical concentration (12.18 g/l) is an H/U value of 2 137. The total 95% level of confidence uncertainty is estimated as 34 (corresponds to a density change of 0.20 g/l).

$U(20)O_2$ – Moderation

Determined in the same way as for $U(100)O_2$.

The critical moderation corresponding to the best-estimate critical concentration (64.0 g/l) is an H/U value of 409. The total 95% level of confidence uncertainty is estimated as 5 (corresponds to a density change of 0.7 g/l).

$U(5)O_2$ – Moderation

Determined in the same way as for $U(100)O_2$.

The critical moderation corresponding to the best-estimate critical concentration (285.6 g/l) is an H/U value of 89.63. The total 95% level of confidence uncertainty is estimated as 0.67 (corresponds to a density change of 2.0 g/l).

$U(4)O_2$ – Moderation

Determined in the same way as for $U(100)O_2$.

The critical moderation corresponding to the best-estimate critical concentration (369.3 g/l) is an H/U value of 68.68. The total 95% level of confidence uncertainty is estimated as 0.58 (corresponds to a density change of 3.0 g/l).

$U(3)O_2$ – Moderation

Determined in the same way as for $U(100)O_2$.

The critical moderation corresponding to the best-estimate critical concentration (522.0 g/l) is an H/U value of 47.80. The total 95% level of confidence uncertainty is estimated as 0.48 (corresponds to a density change of 5.0 g/l).

Uranyl nitrate hexahydrate – UNH or $UO_2(NO_3)_2 + 6H_2O$

U(100)NH – Mass

This system does not seem to be sensitive to the nuclide density issue. The material is well moderated. The geometry is not so sensitive to quadrature and mesh. The mean values $\overline{m}_c$ and $\overline{m}_{bc}$ are not so different, but their standard deviations are. The bias correction based on the verification reduces the standard deviation by a factor of more than two, indicating that it really works.

The CRISTAL value is slightly lower, which is not unexpected (should be slightly conservative). The verified IPPE and Serco results agree well with the EMS results. There are no really large discrepancies. The IRSN-96 result was removed since it concerns 93.5% and not 100% by mass of ^{235}U.

The average verified value with one standard deviation, including the IPPE result, is 826 ± 4 g ^{235}U. Considering that other uncertainties are expected to be small, the total 95% level of confidence uncertainty is estimated as 12 g ^{235}U.

U(20)NH – Mass

This system does not seem to be sensitive to the nuclide density issue. The uranium concentration is below the solubility limit. The material is well moderated. The geometry is not so sensitive to quadrature and mesh. The mean values $\overline{m}_c$ and $\overline{m}_{bc}$ are not so different, but their standard deviations are. The bias correction based on the verification reduces the standard deviation by a factor of almost two, indicating that the verification works. The only deviating value is that from IPPE-ABBN93 and that deviation is not so worrying.

The CRISTAL value is slightly lower, which is not unexpected (should be slightly conservative). This was also the case for $U(20)O_2$ so there is no reason to suspect that the nuclide density laws are causing the differences. The verified IPPE and Serco results agree well with the EMS results.

The average verified value with one standard deviation, including the IPPE result, is 6.13 ± 0.04 kg U. Considering that other uncertainties are expected to be small, the total 95% level of confidence uncertainty is estimated as 0.12 kg U.

U(5)NH – Mass

This system is sensitive to the nuclide density issue. The density is above the solubility limit. The mean values $\overline{m}_c$ and $\overline{m}_{bc}$ are quite different and so are their standard deviations. The bias correction based on the verification reduces the standard deviation by a factor of more than two, indicating that the verification works well.

The only deviating value in the group of "major six" is that from IPPE-ABBN93 and that deviation is now large. It completely dominates the uncertainty of the best-estimate value. This method leads to low values for many other systems involving low-enriched uranium but this is not revealed properly by the verification. It is tempting to remove it from the best-estimate evaluation but a justification is required. Later evaluation including the nuclide density effects shows that the IPPEABBN93 is the only credible result of the "major six".

That the verification works really well with all (except for the IPPE method and that is not due to codes or cross-sections) methods is apparent from the very large and successful bias correction for EMS-M5-J32. It goes from a calculated value of 73.8 to a bias corrected value of 78.1 kg uranium.

The CRISTAL value is significantly lower, not expected (until consideration of density effects) since it was identical to the "major 6" mean for $U(5)O_2$ mass. The verified Serco result agrees quite well with the EMS results but is high before bias correction. It was relatively lower for $U(5)O_2$ mass. From the comparison of nuclide density methods, it appears that IPPE overestimates the density (smaller critical mass) while it is underestimated by Serco (larger critical mass). How much the critical mass would be influenced by these deviations has not been determined, but the deviating results could be explained by this.

The average verified value with one standard deviation, including the IPPE result, is 78.68 ± 1.09 kg U. However, all the major 6 values are rejected because the density methods are not appropriate. The IRSN CRISTAL value of 75.4 kg uranium is used as a best-estimate, based on indirect verification for the $U(5)O_2$ mass system. The total 95% level of confidence uncertainty is estimated as 3.00 kg U.

U(4)NH – Mass

This system is sensitive to the nuclide density issue. The reference system density is now 900 g/l. The mean values $\overline{m}_c$ and $\overline{m}_{bc}$ are not so different but their standard deviations are. The bias correction based on the verification reduces the standard deviation by a factor of more than two, indicating that the verification works well.

There are two deviating values in the group of "major six". The value from IPPE-ABBN93 is low and the Serco value is a little high. The IRSN CRISTAL value is close to that from IPPE. These deviations may be explained in a similar way as for the U(5)NH mass system. The IPPE method for density calculations is better for higher uranium densities, the only reasonable method in addition to the new CRISTAL extended isopiestic law.

The cross-section verification works really well with most methods. This is again apparent from the large and successful bias correction for EMS-M5-J32.

The average verified value with one standard deviation, including the IPPE result, is 150.68 ± 2.78 kg U. However, all the major 6 values are rejected because the density methods are not appropriate. The IRSN CRISTAL value of 144.2 kg uranium is used as a best-estimate, based on

indirect verification for UO_2 mass systems. It is also well supported by the IPPE value which is credible in this density range. The total 95% level of confidence uncertainty is estimated as 7.00 kg U.

U(3)NH – Mass

This system is sensitive to the nuclide density issue. The density is 1150 g/l, quite close to the crystal density. The mean values $\overline{m}_c$ and $\overline{m}_{bc}$ are not very different but their standard deviations are. The bias correction based on the verification reduces the standard deviation by a factor two, indicating that the verification works well.

There is one deviating value in the group of "major six". The value from IPPE-ABBN93 is low by 5%. The IRSN CRISTAL value is close to that from IPPE. As is now clear from the evaluation of U(5)NH and U(4)NH mass systems, these are the only credible results.

The cross-section verification works quite well with most methods. See the large but not sufficient bias correction for EMS-M5-J32.

The average verified value with one standard deviation, including the IPPE result, is 499.98 ± 14.50 kg U. All the major 6 values are rejected because the density methods are not appropriate. The average of IRSN CRISTAL and IPPE-ABBN93 values of 469 kg uranium is used as a best-estimate. The total 95% level of confidence uncertainty is estimated as 40.0 kg U.

U(100)NH – Volume

This system is sensitive to the nuclide density issue. The density is well below the solubility limit. The mean values $\overline{v}_c$ and $\overline{v}_{bc}$ are not very different, nor are their standard deviations. This indicates that the verification has not worked well.

There is one deviating value in the group of "major six". The value from IPPE-ABBN93 is low by 3%. The IRSN CRISTAL value is even lower than that from IPPE. The CRISTAL value was lower also for $U(100)O_2$ and some of the difference could be because of cross-sections. However, the isopiestic law seems well verified and agrees with the IPPE density method.

The average verified value with one standard deviation, including the IPPE result, is 6.858 ± 0.116 litres. Due to lower values from CRISTAL and from IPPE, a bias-correction of -0.15 litres for the density methods is introduced. The best-estimate value becomes 6.708 litres. The total 95% level of confidence uncertainty is estimated as 0.400 litres.

U(20)NH – Volume

This system is sensitive to the nuclide density (580 g/l) issue. This is close to the solubility limit. The mean values $\overline{v}_c$ and $\overline{v}_{bc}$ are not very different, nor are their standard deviations. This indicates that the verification has not worked well.

There are two deviating values in the group of "major six". The value from IPPE-ABBN93 is low by 4% and the Serco MONK value is high by 3%. This appears to be consistent with the comparison of density methods.

The IRSN CRISTAL value is closer to that from IPPE but not as low. It is not unusual for CRISTAL to give slightly conservative results for this type of system.

The average verified value with one standard deviation, including the IPPE result, is 16.46 ± 0.38 litres. Both the Serco MONK and the IPPE results are excluded due to density methods. The CRISTAL result is used to introduce a negative bias correction to a best-estimate of 16.3 litres. The total 95% level of confidence uncertainty is estimated as 1.20 litres.

U(5)NH – Volume

This system is sensitive to the nuclide density (1050 g/l) issue. The mean values $\overline{v}_c$ and $\overline{v}_{bc}$ are not very different, but their standard deviations are, even though they differ by a factor less than two. This indicates that the verification may have worked for some methods.

As in the previous system, there are two deviating values in the group of "major six". The value from IPPE-ABBN93 is low by 6% and the Serco MONK value is high by 3%. The IRSN CRISTAL value is close to that from IPPE. This is consistent with previous results.

The average verified value with one standard deviation, including the IPPE result, is 85.87 ± 2.75 litres. Only the IPPE result of the major 6 is credible. The others are rejected because of the density methods. The IRSN and IPPE values are averaged to get a best-estimate of 80.7 litres. The total 95% level of confidence uncertainty is estimated as 8.00 litres.

U(4)NH – Volume

This system is sensitive to the nuclide density (1140 g/l) issue. The mean values $\overline{v}_c$ and $\overline{v}_{bc}$ are not very different, neither are their standard deviations. This indicates that the verification is not so successful.

As in the previous system, there are two deviating values in the group of "major six". The value from IPPE-ABBN93 is low by 3.5% and the Serco MONK value is high by 6%. The IRSN CRISTAL value is again close to that from IPPE. This is consistent with previous results.

The average verified value with one standard deviation, including the IPPE result, is 142.59 ± 5.11 litres. Only the IPPE-ABBN93 and the IRSN CRISTAL results are credible. Other uncertainties are significant but this is probably covered by the large extra standard deviation. The IRSN and IPPE values are averaged to get a best-estimate of 136 litres. The total 95% level of confidence uncertainty is estimated as 15 litres.

U(3)NH – Volume

This system is very sensitive to the nuclide density issue (crystal density, 1 330 g/l). The mean values $\overline{v}_c$ and $\overline{v}_{bc}$ are not very different, but the standard deviation is reduced almost by a factor two by bias corrections. This indicates that the verification is quite successful for some systems.

There is one strongly deviating value in the group of "major six". The value from IPPE-ABBN93 is low by 10%. The IRSN CRISTAL value is very close to that from IPPE. This is consistent with previous results and with the comparison of density methods. These two are the only credible values.

The average "major 6" verified value with one standard deviation, including the IPPE result, is 414.0 ± 17.4 litres. All values, except the IPPE value, are rejected. The IRSN and IPPE values are averaged to get a best-estimate of 370 litres. The total 95% level of confidence uncertainty is estimated as 50.0 litres.

U(100)NH – Cylinder diameter

This system is sensitive to the nuclide density (380 g/l) issue. The mean values $\bar{\Phi}_c$ and $\bar{\Phi}_{bc}$ and their standard deviations are not very different. Considering the large standard deviations, this indicates that the verification is not very successful.

There are two deviating values in the group of "major six". The value from IPPE-ABBN93 is low by 2% and the Serco value is 1.3% high. The IRSN CRISTAL value is very close to that from IPPE. Looking at the comparison of densities, these values are consistent with those results.

The average "major 6" verified value with one standard deviation, including the IPPE result, is 15.09 ± 0.16 cm. The MONK result is rejected due to density biases. The IPPE result is likely to slightly underestimate the diameter due to density biases. A best-estimate value of 14.95 cm, taking the CRISTAL result into account, appears reasonable. The total 95% level of confidence uncertainty is estimated as 0.5 cm.

U(20)NH – Cylinder diameter

This system is sensitive to the nuclide density (620 g/l) issue. The mean values $\bar{\Phi}_c$ and $\bar{\Phi}_{bc}$ and their standard deviations are not very different. Considering the large standard deviations, this indicates that the verification is not very successful.

There are two deviating values in the group of "major six". The value from IPPE-ABBN93 is low by 2% and the Serco value is 0.6% high. The IRSN CRISTAL value is close to that from IPPE. According to the density comparisons, the Serco value should be high and the IPPE value low.

The average "major 6" verified value with one standard deviation, including the IPPE result, is 21.09 ± 0.13 cm. The MONK result is rejected. A best-estimate value of 21.0 cm, taking the CRISTAL result into account, appears reasonable. The total 95% level of confidence uncertainty is estimated as 0.4 cm.

U(5)NH – Cylinder diameter

This system is sensitive to the nuclide density issue (1 060 g/l). The mean values $\bar{\Phi}_c$ and $\bar{\Phi}_{bc}$ and their standard deviations are not very different. Considering the large standard deviations, this indicates that the verification is not very successful.

There are two deviating values in the group of "major six". The value from IPPE-ABBN93 is low by 3% and the Serco value is 1.5% high. The IRSN CRISTAL value is close to that from IPPE. This is the same experience as before.

The average "major 6" verified value with one standard deviation, including the IPPE result, is 38.96 ± 0.54 cm. All values, except that from IPPE, are rejected. Together with the CRISTAL value a best-estimate value of 37.85 cm based on the average appears reasonable. The total 95% level of confidence uncertainty is estimated as 1.6 cm.

U(4)NH – Cylinder diameter

This system is sensitive to the nuclide density (1 140 g/l) issue. The mean values $\bar{\Phi}_c$ and $\bar{\Phi}_{bc}$ and their standard deviations are not very different. Considering the large standard deviations, this indicates that the verification is not very successful.

There are two deviating values in the group of "major six". The value from IPPE-ABBN93 is low by 2% and the Serco value is 1.2% high. The IRSN CRISTAL value is close to that from IPPE. This is consistent with results for other UNH systems.

The average "major 6" verified value with one standard deviation, including the IPPE result, is 46.66 ± 0.56 cm. All values, except that from IPPE, are rejected. Together with the CRISTAL value a best-estimate value of 45.4 cm based on the average appears reasonable. The total 95% level of confidence uncertainty is estimated as 1.7 cm.

U(3)NH – Cylinder diameter

This system is very sensitive to the nuclide density (1 330 g/l; crystal density) issue. The mean values $\bar{\Phi}_c$ and $\bar{\Phi}_{bc}$ and their standard deviations are not very different. Considering the large standard deviations, this indicates that the verification is not very successful for some systems. However, sometimes it works quite well. The EMS-M5-J32 value deviation is almost 5% before bias correction and only 1% after.

There is one deviating value in the group of "major six". The value from IPPE-ABBN93 is low by almost 4%. The IRSN CRISTAL value is close to that from IPPE. The last two values are the only credible.

The average "major 6" verified value with one standard deviation, including the IPPE result, is 66.96 ± 0.96 cm. All "major" values, except that from IPPE, are rejected. Together with the CRISTAL value a best-estimate value of 64.8 cm based on the average appears reasonable. The total 95% level of confidence uncertainty is estimated as 3.5 cm.

U(100)NH – Slab thickness

This system is sensitive to the nuclide density (500 g/l) issue. The mean values $\bar{t}_c$ and $\bar{t}_{bc}$ are not very different. The standard deviation is not reduced significantly (about 30%) after the bias corrections. This indicates that the verification is not too successful.

There is one deviating group of values within the group of "major six". The IRSN CRISTAL value is now very close to the best-estimate values. The IPPE-ABBN93 value is significantly lower than the best-estimate value as well as the CRISTAL value. The IPPE values should be lower due to a bias caused by the density method.

Initially there was a significant difference between SCALE and MCNP results. There was a correlated error in all MCNP results for this slab system; the thermal scattering data (MT card in MCNP) were commented out for the fast UO_2 systems and were not removed for the thermal U(100)NH slabs. This is a typical error when many calculations are carried out in a short time.

The German Handbook value 4.4 cm contributed to the study is low. However, a look at the Handbook figure shows that the proper value should be about 5.35 cm.

The average "major 6" verified value with one standard deviation, including the IPPE result, is 5.453 ± 0.069 cm. To consider density biases, the IPPE result is rejected and the IRSN CRISTAL value is considered instead. The best-estimate value then becomes 5.480 cm. With such a change the standard deviation due to verification would also be significantly reduced. The total 95% level of confidence uncertainty is still estimated as 0.35 cm.

U(20)NH – Slab thickness

This system is sensitive to the nuclide density (700 g/l) issue. The mean values $\overline{t}_c$ and $\overline{t}_{bc}$ are not very different. The standard deviation is dominated by the IPPE-ABBN93 value. The verification appears to be successful for the EMS methods.

There is one deviating value within the group of "major six". The IPPE-ABBN93 value is lower by about 1.7%. The density method used by IPPE seems to be conservative in this middle density region, the water presence is overestimated.

The average "major 6" verified value with one standard deviation, including the IPPE result, is 9.289 ± 0.083 cm. The solubility limit is exceeded, but the error due to this is not expected to change the conclusions significantly. Other uncertainties are significant but this is probably covered by the large extra standard deviation. The total 95% level of confidence uncertainty is estimated as 0.25 cm.

U(5)NH – Slab thickness

This system is sensitive to the nuclide density (1100 g/l) issue. The mean values $\overline{t}_c$ and $\overline{t}_{bc}$ are not very different. The standard deviation is dominated by the IPPE-ABBN93 value. The cross-section verification appears to be successful for the EMS methods.

There are two deviating values within the group of "major six". The IPPE-ABBN93 value is lower by about 1.9% and the Serco MONK value is higher by about 1.3%. The CRISTAL value is close to the IPPE-ABBN93 value. This is similar as for other low-enriched UNH systems.

The average "major 6" verified value with one standard deviation, including the IPPE result, is 20.486 ± 0.222 cm. All "major" values, except that from IPPE, are rejected. Together with the CRISTAL value a best-estimate value of 20.04 cm based on the average appears reasonable. The total 95% level of confidence uncertainty is estimated as 0.70 cm.

U(4)NH – Slab thickness

This system is sensitive to the nuclide density (1 180 g/l) issue. The mean values $\overline{t}_c$ and $\overline{t}_{bc}$ are not very different. The standard deviation is dominated by the IPPE-ABBN93 value. The verification appears to be successful for the EMS methods.

There are two deviating values within the group of "major six". The IPPE-ABBN93 value is lower by about 2.0% and the Serco MONK value is higher by about 1.6%. The CRISTAL value is close to the IPPE-ABBN93 value. This is similar as for other low-enriched UNH systems.

The average "major 6" verified value with one standard deviation, including the IPPE result, is 25.656 ± 0.291 cm. All "major" values, except that from IPPE, are rejected. Together with the CRISTAL value a best-estimate value of 25.05 cm based on the average appears reasonable. The total 95% level of confidence uncertainty is estimated as 0.85 cm.

U(3)NH – Slab thickness

This system is sensitive to the nuclide density (1 330 g/l; crystal density) issue. The mean values $\overline{t}_c$ and $\overline{t}_{bc}$ are quite different and the standard deviation is large. The standard deviation is dominated by the IPPE-ABBN93 value. The verification appears to be successful for the EMS methods.

The IPPE-ABBN93 value is lower by about 3.6%. The CRISTAL and the Japanese handbook version 2 values are close to the IPPE-ABBN93 value. These values are credible.

The average "major 6" verified value with one standard deviation, including the IPPE result, is 38.698 ± 0.579 cm. All "major" values, except that from IPPE, are rejected. Together with the CRISTAL value a best-estimate value of 37.5 cm based on the average appears reasonable. The total 95% level of confidence uncertainty is estimated as 2.2 cm.

U(100)NH – Concentration

This system is sensitive to the nuclide density (12.3 g/l) issue. The mean values $\overline{c}_c$ and $\overline{c}_{bc}$ are not so different but the bias corrected standard deviation is reduced to half. This indicates that the verification is successful.

There is one deviating value within the group of "major six". The Serco value before bias correction is 5.8% high. After the correction it is only 2.5% high.

The average "major 6" verified value with one standard deviation, including the IPPE result, is 12.288 ± 0.163 g/l. The MONK result is rejected without any other cause than that it is not consistent with other results, including MONK results for UO_2. The best-estimate value is then reduced to 12.226 g/l. Other uncertainties are significant but this is probably covered by the large extra standard deviation. The total 95% level of confidence uncertainty is estimated as 0.5 g/l.

U(20)NH – Concentration

This system is sensitive to the nuclide density (64.8 g/l) issue. The mean values $\overline{c}_c$ and $\overline{c}_{bc}$ are not so different but the bias corrected standard deviation is larger than the uncorrected standard deviation. This indicates that the verification is not adequate.

The average "major 6" verified value with one standard deviation, including the IPPE result, is 64.840 ± 0.357 g/l. Other uncertainties are significant but this is probably covered by the large extra standard deviation. The total 95% level of confidence uncertainty is estimated as 1.0 g/l.

U(5)NH – Concentration

This system is sensitive to the nuclide density (311 g/l) issue. The mean values $\overline{c}_c$ and $\overline{c}_{bc}$ are not so different and this is true for their standard deviations as well. This could indicate that the verification is not adequate but in this case it is also due to small variations.

The average "major 6" verified value with one standard deviation, including the IPPE result, is 312.5 ± 1.6 g/l. Other uncertainties are significant but this is probably covered by the large extra standard deviation. The total 95% level of confidence uncertainty is estimated as 5.3 g/l.

U(4)NH – Concentration

This system is sensitive to the nuclide density (416 g/l) issue. The mean values $\overline{c}_c$ and $\overline{c}_{bc}$ are not so different and this true for their standard deviations as well. This could indicate that the verification is not adequate but in this case it is also due to small variations.

The average "major 6" verified value with one standard deviation, including the IPPE result, is 417.0 ± 3.0 g/l. Other uncertainties are significant but this is probably covered by the large extra standard deviation. The total 95% level of confidence uncertainty is estimated as 10.0 g/l.

U(3)NH – Concentration

This system is sensitive to the nuclide density (629 g/l) issue. The mean values $\overline{c}_c$ and $\overline{c}_{bc}$ are not so different and this is true for their standard deviations as well. This could indicate that the verification is not adequate but in this case it is also due to small variations.

The IPPE-ABBN93 value seems high and the Serco value low. This is opposite to the situation for geometry-limited systems. However, this is consistent from a physics point of view. For those systems additional water should reduce the critical value (smaller system). For concentration, more water at a fixed density increases absorption in an over-moderated system. The density trends are thus confirmed.

The average "major 6" verified value with one standard deviation, including the IPPE result, is 628.9 ± 6.8 g/l. Other uncertainties are significant but this is probably covered by the large extra standard deviation. The total 95% level of confidence uncertainty is estimated as 20.0 g/l.

U(100)NH – Moderation

This parameter is essentially the same as the concentration parameter. However, it is not sensitive to the nuclide density laws as the critical concentration is. The moderation parameter for an infinite system is not density dependent. If the different parameter values cover the whole range of moderations, from very dilute to crystal, then a check of corresponding densities obtained by different density laws would be revealing. Thus, since it is less complicated, it makes more sense to start with comparing critical moderations before starting comparing critical concentrations.

Even if the density method is very wrong, the computer code systems should find the correct moderation ratio. This assumes that the H/U ratio is based on what is the actual input to the code and can be verified by the output. An equation or another, separate conversion of concentration to H/U ratio introduces error sources.

At this time, the best-estimate of the critical concentration will be used to find the best-estimate of the critical moderation. SCALE 5 is used for that. Using that moderation, different density laws can be compared.

The critical moderation corresponding to the best-estimate critical concentration (12.288 g/l) is an H/U value of 2 109. The total 95% level of confidence uncertainty is estimated as 83 (corresponds to a density change of 0.50 g/l).

U(20)NH – Moderation

The average "major 6" verified value with one standard deviation, including the IPPE result, is an H/U value of 397.1. The total 95% level of confidence uncertainty is estimated as 6.2.

U(5)NH – Moderation

The average "major 6" verified value with one standard deviation, including the IPPE result, is an H/U value of 76.22. The total 95% level of confidence uncertainty is estimated as 1.41.

U(4)NH – Moderation

The average "major 6" verified value with one standard deviation, including the IPPE result, is an H/U value of 55.07. The total 95% level of confidence uncertainty is estimated as 1.49.

U(3)NH – Moderation

The average "major 6" verified value with one standard deviation, including the IPPE result, is an H/U value of 33.64. The total 95% level of confidence uncertainty is estimated as 1.28.

Plutonium dioxide – PuO_2

$Pu(100)O_2$ – Mass

This system does not seem to be sensitive to the nuclide density issue. The material is well moderated. The mean values $\overline{m}_c$ and $\overline{m}_{bc}$ are quite different due to large bias corrections. The standard deviation is reduced by a factor of two due to the bias corrections.

The IPPE-84 value which is almost always very low (conservative) for uranium systems is now very high (non-conservative); about 12%. The bias correction for the old EMS SCALE 4 value (based on ORNL verification) is too high, overestimating the critical mass by 4%.

The average verified value with one standard deviation, including the IPPE result, is 510 ± 6 g ^{239}Pu. The total 95% level of confidence uncertainty is estimated as 18 g ^{239}Pu.

$Pu(95/5)O_2$ – Mass

This system does not seem to be sensitive to the nuclide density issue. The isotopic distribution influence is very small. The material is well moderated. The mean values $\overline{m}_c$ and $\overline{m}_{bc}$ are quite different due to large bias corrections. The standard deviation is reduced significantly, by a factor almost three, by the corrections.

The average verified value with one standard deviation, including the IPPE result, is 621 ± 6 g of Pu. The total 95% level of confidence uncertainty is estimated as 18 g of Pu.

$Pu(80/10/10)O_2$ – Mass

This system does not seem to be sensitive to the nuclide density issue. The isotopic distribution influence is small. The material is well moderated. The mean values $\overline{m}_c$ and $\overline{m}_{bc}$ are quite different due to large bias corrections. The standard deviation is reduced by a factor less than two by the corrections. This is less than what was seen for $Pu(100)O_2$ where the initial spread was larger, and the standard deviation is not as small.

A difference from the uranium evaluations is that the influence of the actinide isotopic distribution was not included in the verification. Another difference is that no IPPE-ABBN93 value was obtained for this system.

The Serco bias correction moves the value from average to about 3% low.

The average verified value with one standard deviation is 686 ± 12 g of Pu. The total 95% level of confidence uncertainty is estimated as 36 g of Pu.

$Pu(90/10)O_2$ – Mass

This system does not seem to be sensitive to the nuclide density issue. The isotopic distribution influence is small. The material is well moderated. The mean values $\overline{m}_c$ and $\overline{m}_{bc}$ are quite different due to large bias corrections. The standard deviation is reduced by a factor more than two by the corrections.

The Serco bias correction moves the value from average to about 2% low. The CRISTAL value is a bit lower than the bias corrected average. This appears to be the case for many plutonium systems.

The average verified value with one standard deviation, including the IPPE result, is 754 ± 9 g of Pu. The total 95% level of confidence uncertainty is estimated as 27 g of Pu.

$Pu(80/15/5)O_2$ – Mass

This system does not seem to be sensitive to the nuclide density issue. The isotopic distribution influence is small. The material is well moderated. The mean values $\overline{m}_c$ and $\overline{m}_{bc}$ are quite different due to large bias corrections. The standard deviation is reduced by a factor two by the corrections.

There is no IPPE-ABBN93 value for this system. The Serco bias correction moves the value from average to about 2% low. The CRISTAL value is a bit lower than the corrected average.

The average verified value with one standard deviation is 874 ± 14 g of Pu. The total 95% level of confidence uncertainty is estimated as 42 g of Pu.

$Pu(71/17/11/1)O_2$ – Mass

This system does not seem to be sensitive to the nuclide density issue. The isotopic distribution influence is small. The material is well moderated. The mean values $\overline{m}_c$ and $\overline{m}_{bc}$ are quite different due to large bias corrections. The standard deviation is reduced by a factor less than two by the corrections.

There is no IPPE-ABBN93value for this system. The Serco bias correction moves the value from average to about 2.5% low.

The average verified value with one standard deviation is 907 ± 17 g of Pu. The total 95% level of confidence uncertainty is estimated as 50 g of Pu.

$Pu(100)O_2$ – Volume

This system does not seem to be sensitive to the nuclide density issue. The material is not moderated. The mean values $\overline{v}_c$ and $\overline{v}_{bc}$ are quite similar. The standard deviation is reduced by a factor slightly less than two by the corrections.

The SCALE 27- and 44-group libraries were not developed or intended for this type of fast system. This is probably why the bias corrections are not sufficient.

The average verified value for the “major 6” with one standard deviation is 1.151 ± 0.011 litres. The total 95% level of confidence uncertainty is estimated as 0.033 litres.

$Pu(95/5)O_2$ – Volume

This system does not seem to be sensitive to the nuclide density issue. The material is not moderated. The mean values $\overline{\nu}_c$ and $\overline{\nu}_{bc}$ are similar. The standard deviation is reduced by a factor less than two by the corrections.

The average verified value with one standard deviation is 1.236 ± 0.013 litres. The total 95% level of confidence uncertainty is estimated as 0.040 litres.

$Pu(80/10/10)O_2$ – Volume

This system is somewhat sensitive to the nuclide density issue. Consideration of the plutonium isotopic distribution reduces the theoretical density very slightly, influencing the leakage. The material is not moderated. The mean values $\overline{\nu}_c$ and $\overline{\nu}_{bc}$ are similar. The standard deviation is reduced by a factor less than two by the corrections.

The bias for the plutonium distribution 71/17/11/1 is -0.005. It was not determined for the current distribution but is set to -0.002.

There is no IPPE-ABBN93 value for this system.

The average "major 5" verified value with one standard deviation is 1.286 ± 0.014 litres. This is bias corrected to 1.288 litres, due to the reduced density. The total 95% level of confidence uncertainty is estimated as 0.042 litres.

$Pu(90/10)O_2$ – Volume

This system does not seem to be sensitive to the nuclide density issue. The material is not moderated. The mean values $\overline{\nu}_c$ and $\overline{\nu}_{bc}$ are similar. The standard deviation is reduced by a factor less than two by the corrections.

The average "major 6" verified value with one standard deviation is 1.307 ± 0.013 litres. The total 95% level of confidence uncertainty is estimated as 0.040 litres.

$Pu(80/15/5)O_2$ – Volume

This system is somewhat sensitive to the nuclide density issue. Consideration of the plutonium isotopic distribution reduces the theoretical density; increasing the leakage. The material is not moderated. The mean values $\overline{\nu}_c$ and $\overline{\nu}_{bc}$ are similar. The standard deviation is reduced by a factor less than two by the corrections.

The bias caused by the reduced theoretical density was determined for the distribution 71/17/11/1 using SCALE 5, XSDRNPM and the 238-group library. The result is -0.005 litres. For the current distribution, the bias is smaller. It is set to -0.001 litres.

Similar observations as for the previous system are made. There is no IPPE-ABBN93 value.

The average "major 5" verified value with one standard deviation is 1.366 ± 0.014 litres. The additional bias correction due to the reduced density is 0.001 litres, making the best-estimate value 1.367. The total 95% level of confidence uncertainty is estimated as 0.042 litres.

$Pu(71/17/11/1)O_2$ – Volume

This system is somewhat sensitive to the nuclide density issue. Consideration of the plutonium isotopic distribution reduces the theoretical density; increasing the leakage. The material is not moderated. The mean values $\overline{v}_c$ and $\overline{v}_{bc}$ are similar. The standard deviation is reduced by a factor less than two by the corrections.

The bias caused by the reduced theoretical density was determined using SCALE 5, XSDRNPM and the 238-group library. The result is -0.005 litres.

The same observations as for the previous system are made. There is no IPPE-ABBN93 value.

The average "major 5" verified value with one standard deviation is 1.408 ± 0.018 litres. The additional bias correction due to the reduced density is 0.005, making the best-estimate value 1.413. The total 95% level of confidence uncertainty is estimated as 0.054 litres.

$Pu(100)O_2$ – Cylinder diameter

This system does not seem to be sensitive to the nuclide density issue. The material is not moderated. The mean values $\overline{\Phi}_c$ and $\overline{\Phi}_{bc}$ are quite similar. The standard deviation is reduced by a factor slightly less than two by the corrections.

Similar conclusions as for the volume can be drawn. The CRISTAL value is slightly higher than the "major 6" average.

The average verified value for the "major 6" with one standard deviation is 7.683 ± 0.031 cm. The total 95% level of confidence uncertainty is estimated as 0.10 cm.

$Pu(95/5)O_2$ – Cylinder diameter

This system does not seem to be sensitive to the nuclide density issue. The material is not moderated. The mean values $\overline{\Phi}_c$ and $\overline{\Phi}_{bc}$ are quite similar. The standard deviation is reduced by a factor slightly less than two by the corrections.

Similar conclusions as for the volume can be drawn. The CRISTAL value is again slightly higher than the "major 6" average.

The average verified value for the "major 6" with one standard deviation is 7.948 ± 0.035 cm. The total 95% level of confidence uncertainty is estimated as 0.11 cm.

$Pu(80/10/10)O_2$ – Cylinder diameter

This system is somewhat sensitive to the nuclide density issue. Consideration of the plutonium isotopic distribution reduces the theoretical density very slightly, influencing the leakage. The material is not moderated. The mean values $\overline{\Phi}_c$ and $\overline{\Phi}_{bc}$ are similar. The standard deviation is reduced by a factor less than two by the corrections.

The bias for the plutonium distribution 71/17/11/1 was estimated as -0.016 cm. It will be smaller for the current distribution. It is set to -0.006 cm.

There is no IPPE-ABBN93 value for this system. Similar conclusions as for the volume can be drawn. The CRISTAL value is consistently slightly higher than the "major 5" average.

The average "major 5" verified value with one standard deviation is 8.036 ± 0.039 cm. This is bias corrected to 8.042 cm, due to the reduced density. The total 95% level of confidence uncertainty is estimated as 0.12 cm.

$Pu(90/10)O_2$ – Cylinder diameter

This system does not seem to be sensitive to the nuclide density issue. The material is not moderated. The mean values $\bar{\Phi}_c$ and $\bar{\Phi}_{bc}$ are similar. The standard deviation is reduced by a factor less than two by the corrections.

Similar conclusions as for the volume can be drawn. The CRISTAL value is slightly (about 1%) higher than the "major 6" average.

The average "major 6" verified value with one standard deviation is 8.145 ± 0.033 cm. The total 95% level of confidence uncertainty is estimated as 0.10 cm.

$Pu(80/15/5)O_2$ – Cylinder diameter

This system is somewhat sensitive to the nuclide density issue. Consideration of the plutonium isotopic distribution reduces the theoretical density, increasing the leakage. The material is not moderated. The mean values and are similar. The standard deviation is reduced by a factor less than two by the corrections.

The bias for the plutonium distribution 71/17/11/1 was estimated as -0.016 cm. It will be smaller for the current distribution. It is set to -0.004 cm.

There is no IPPE-ABBN93 value for this system. Similar conclusions as for the volume can be drawn. The CRISTAL value is slightly higher than the "major 5" average.

The average "major 5" verified value with one standard deviation is 8.266 ± 0.038 cm. The additional bias correction due to the reduced density is 0.004 cm, making the best-estimate value 8.270 cm. The total 95% level of confidence uncertainty is estimated as 0.120 cm.

$Pu(71/17/11/1)O_2$ – Cylinder diameter

This system is somewhat sensitive to the nuclide density issue. Consideration of the plutonium isotopic distribution reduces the theoretical density, increasing the leakage. The material is not moderated. The mean values $\bar{\Phi}_c$ and $\bar{\Phi}_{bc}$ are similar. The standard deviation is reduced by a factor less than two by the corrections.

The bias for the plutonium distribution 71/17/11/1 and the volume parameter is -0.005 litres (0.5%). It was not determined for the current system but is set to 0.2% (different leakage fractions and different moderation effects in the water reflector for a cylinder compared with a sphere makes this estimate very crude, probably too low) giving -0.016 cm.

The same observations as for the previous system are made. There is no IPPE-ABBN93 value. The CRISTAL value is slightly higher than the "major 5" average. This is very consistent with previous plutonium cylinder values. The consistency in the differences is positive information.

The results for SCALE with the 27- and 44-group libraries may not be easy to correct for biases since the libraries are not designed to give all the information required for good results with fast

systems. The 238-group library seems to be quite good.

The average "major 5" verified value with one standard deviation is 8.350 ± 0.041 cm. The additional bias correction due to the reduced density is 0.016 cm, making the best-estimate value 8.366 cm. The total 95% level of confidence uncertainty is estimated as 0.130 cm.

$Pu(100)O_2$ – Slab thickness

This system does not seem to be sensitive to the nuclide density issue. The material is not moderated. The mean values $\bar{t}_c$ and $\bar{t}_{bc}$ are quite similar. The standard deviation is reduced by a factor slightly less than two by the corrections.

Similar conclusions as for the volume and cylinder diameter can be drawn. The CRISTAL value is higher (about 3%) than the "major 6" average. This is within the 95% level of confidence.

The average verified value for the "major 6" with one standard deviation is 1.721 ± 0.018 cm. The total 95% level of confidence uncertainty is estimated as 0.060 cm.

$Pu(95/5)O_2$ – Slab thickness

This system does not seem to be sensitive to the nuclide density issue. The material is not moderated. The mean values $\bar{t}_c$ and $\bar{t}_{bc}$ are quite similar. The standard deviation is reduced by a factor slightly less than two by the corrections.

Similar conclusions as for the volume can be drawn. The CRISTAL value is again about 3% higher than the "major 6" average.

The average verified value for the "major 6" with one standard deviation is 1.934 ± 0.023 cm. The total 95% level of confidence uncertainty is estimated as 0.070 cm.

$Pu(80/10/10)O_2$ – Slab thickness

This system is somewhat sensitive to the nuclide density issue. Consideration of the plutonium isotopic distribution reduces the theoretical density very slightly, influencing the leakage. The material is not moderated. The mean values $\bar{t}_c$ and $\bar{t}_{bc}$ are similar. The standard deviation is reduced by a factor less than two by the corrections.

The bias for the plutonium distribution 71/17/11/1 was estimated as -0.004 cm. It will be smaller for the current distribution. It is set to -0.002 cm.

There is no IPPE-ABBN93 value for this system. Similar conclusions as for the volume can be drawn. The CRISTAL value is 2.5% higher than the "major 5" average.

The average "major 5" verified value with one standard deviation is 1.910 ± 0.023 cm. This is bias corrected to 1.912 cm, due to the reduced density. The total 95% level of confidence uncertainty is estimated as 0.070 cm.

$Pu(90/10)O_2$ – Slab thickness

This system does not seem to be sensitive to the nuclide density issue. The material is not moderated. The mean values $\bar{t}_c$ and $\bar{t}_{bc}$ are similar. The standard deviation is reduced by a factor less than two by the corrections.

Similar conclusions as for the volume can be drawn. The CRISTAL value is about 3% higher than the "major 6" average.

The average "major 6" verified value with one standard deviation is 2.066 ± 0.025 cm. The total 95% level of confidence uncertainty is estimated as 0.080 cm.

$Pu(80/15/5)O_2$ – Slab thickness

This system is somewhat sensitive to the nuclide density issue. Consideration of the plutonium isotopic distribution reduces the theoretical density, increasing the leakage. The material is not moderated. The mean values and are similar. The standard deviation is reduced by a factor less than two by the corrections.

The bias for the plutonium distribution 71/17/11/1 was estimated as -0.004 cm. It will be smaller for the current distribution. It is set to -0.001 cm.

There is no IPPE-ABBN93 value for this system. Similar conclusions as for the volume can be drawn. The CRISTAL value is consistently 3% higher than the "major 5" average.

The average "major 5" verified value with one standard deviation is 2.095 ± 0.029 cm. The additional bias correction due to the reduced density is 0.001 cm, making the best-estimate value 2.096 cm. The total 95% level of confidence uncertainty is estimated as 0.090 cm.

$Pu(71/17/11/1)O_2$ – Slab thickness

This system is somewhat sensitive to the nuclide density issue. Consideration of the plutonium isotopic distribution reduces the theoretical density, increasing the leakage. The material is not moderated. The mean values and are similar. The standard deviation is reduced by a factor less than two by the corrections.

The bias for the plutonium distribution 71/17/11/1 and the volume parameter is -0.005 litres (0.5%). It was not determined for the current system but is set to 0.2% (different leakage fractions and different moderation effects in the water reflector for a cylinder compared with a sphere makes this estimate very crude, probably too low) giving -0.004 cm.

The same observations as for the previous systems are made. There is no IPPE-ABBN93 value. The CRISTAL value is 3.0% higher than the "major 5" average.

The average "major 5" verified value with one standard deviation is 2.100 ± 0.026 cm. The additional bias correction due to the reduced density is 0.004 cm, making the best-estimate value 2.104 cm. The total 95% level of confidence uncertainty is estimated as 0.080 cm.

$Pu(100)O_2$ – Concentration

This system does not seem to be sensitive to the nuclide density issue. However, the criticality is determined by the moderation ratio H/Pu, not by the concentration in g/l. If the same concentration leads to different H/Pu ratios, there may be some problem with the nuclide density determination. The material is well moderated. The mean values $\overline{c}_c$ and $\overline{c}_{bc}$ are not so similar. The standard deviation is reduced by less than a factor of two by the corrections.

There are quite large differences for this simple system. The EMS methods benefit significantly from the verification procedure. However, the MONK value is 4% high. The IPPE-ABBN93 is very close to the average.

After looking at the next systems, it became clear that the MONK result was not consistent or credible. The value 7.7 g/l in the 2002 report [55] was the same as for the distribution 95/5 but for 90/10 the value increased to 8.4 g/l. The error was confirmed and corrected by Serco in March 2005. Normally this type of editorial mistakes would be corrected during the study and not published.

All contributors to this type of comparison make editorial mistakes occasionally. This report contains so many new values and evaluations that there are bound to be remaining mistakes. The independent review required for safety evaluations is normally not performed by the contributor since a comparison will be made later by the Group. This report will not be as thoroughly checked and this will be indicated in the text (e.g. "for demonstration only"). The experience shows the importance of independent reviews and the value of international comparisons.

The average verified value for the "major 6" (including revised MONK value) with one standard deviation is 7.317 ± 0.061 g/l. The CRISTAL V1.0 value of 7.24 g/l has been considered. The total 95% level of confidence uncertainty is estimated as 0.20 g/l.

$Pu(95/5)O_2$ – Concentration

This system is similar to the previous system. The mean value for calculated only systems $\overline{c}_c$ is significantly lower than the mean value $\overline{c}_{bc}$ for bias corrected results. The standard deviation is not reduced at all by the corrections.

The reason for the lack of success is that the EMS and Serco verifications lead to a larger spread in the results. The EMS bias corrections appear to be consistent with each other and leads to a much smaller spread. However, they are strongly correlated, except for cross-sections.

The average verified value for the "major 6" with one standard deviation is 7.882 ± 0.092 g/l. The total 95% level of confidence uncertainty is estimated as 0.300 g/l.

$Pu(80/10/10)O_2$ – Concentration

This system is similar to the previous system. The mean value for calculated only systems $\overline{c}_c$ is significantly lower than the mean value $\overline{c}_{bc}$ for bias corrected results. The standard deviation is not reduced at all by the corrections. There is no IPPE-ABBN93 value for this system.

The reason for the lack of success is that the EMS and Serco verifications lead to a larger spread in the results. The EMS bias corrections appear to be consistent with each other and leads to a much smaller spread.

The average verified value for the "major 5" with one standard deviation is 8.156 ± 0.091 g/l. The total 95% level of confidence uncertainty is estimated as 0.300 g/l.

$Pu(90/10)O_2$ – Concentration

This system is similar to the previous system. The mean value for calculated results $\overline{c}_c$ is significantly lower than the mean value $\overline{c}_{bc}$ for bias corrected results. The standard deviation is reduced somewhat by the corrections.

Similar observations as for the previous plutonium concentration systems are made.

The average verified value for the "major 6" with one standard deviation is 8.561 ± 0.083 g/l. The total 95% level of confidence uncertainty is estimated as 0.250 g/l.

$Pu(80/15/5)O_2$ – Concentration

This system is similar to the previous system. The mean value for calculated results $\bar{c}_c$ is significantly lower than the mean value $\bar{c}_{bc}$ for bias corrected results. The standard deviation is increased somewhat by the corrections. The EMS verification appears to over-compensate for biases. There is no IPPE-ABBN93 value for this system.

Similar observations as for the previous plutonium concentration systems are made.

The average verified value for the "major 5" with one standard deviation is 9.094 ± 0.111 g/l. The total 95% level of confidence uncertainty is estimated as 0.250 cm.

$Pu(71/17/11/1)O_2$ – Concentration

This system is similar to the previous system. The mean value for calculated results $\bar{c}_c$ is significantly lower than the mean value $\bar{c}_{bc}$ for bias corrected results. The standard deviation is increased somewhat by the corrections. The EMS verification appears to over-compensate for biases. There is no IPPE-ABBN93 value for this system.

Similar observations as for the previous plutonium concentration systems are made.

The average verified value for the "major 5" with one standard deviation is 9.276 ± 0.103 g/l. The total 95% level of confidence uncertainty is estimated as 0.350 g/l.

$Pu(100)O_2$ – Moderation

This system is essentially the same as the concentration system. However, it is not sensitive to the nuclide density laws as the critical concentration is. The moderation parameter for an infinite system is not density dependent. If the different parameter values cover the whole range of moderations, from very dilute to crystal, then a check of corresponding densities obtained by different density laws would be revealing. Thus, since it is less complicated, it makes more sense to start with comparing critical moderations before starting comparing critical concentrations.

At this time, the best-estimate of the critical concentration will be used to find the best-estimate of the critical moderation. SCALE 5 is used for that. Using that moderation, different density laws can be compared.

The critical moderation corresponding to the best-estimate critical concentration (7.283 g/l) is an H/Pu value of 3636. The total 95% level of confidence uncertainty is estimated as 190 (corresponds to a density change of 0.40 g/l).

$Pu(95/5)O_2$ – Moderation

The critical moderation corresponding to the best-estimate critical concentration (7.882 g/l) is an H/Pu value of 3360. The total 95% level of confidence uncertainty is estimated as 123 (corresponds to a density change of 0.300 g/l).

$Pu(80/10/10)O_2$ – Moderation

The critical moderation corresponding to the best-estimate critical concentration (8.156 g/l) is an H/Pu value of 3 250. The total 95% level of confidence uncertainty is estimated as 115 (corresponds to a density change of 0.300 g/l).

$Pu(90/10)O_2$ – Moderation

The critical moderation corresponding to the best-estimate critical concentration (8.561 g/l) is an H/Pu value of 3 094. The total 95% level of confidence uncertainty is estimated as 88 (corresponds to a density change of 0.250 g/l).

$Pu(80/15/5)O_2$ – Moderation

The critical moderation corresponding to the best-estimate critical concentration (9.094 g/l) is an H/Pu value of 2 914. The total 95% level of confidence uncertainty is estimated as 78 (corresponds to a density change of 0.250 g/l).

$Pu(71/17/11/1)O_2$ – Moderation

The critical moderation corresponding to the best-estimate critical concentration (9.276 g/l) is an H/Pu value of 2 859. The total 95% level of confidence uncertainty is estimated as 104 (corresponds to a density change of 0.350 g/l).

Plutonium nitrate pentahydrate – PuNH or $Pu(NO_3)_4 + 5H_2O$

Pu(100)NH – Mass

This system is sensitive to the nuclide density (31 g/l) issue. The material is well moderated. The geometry is not so sensitive to quadrature and mesh. The mean $\bar{m}_{bc}$ of bias corrected values is higher than the mean $\bar{m}_c$ without corrections. The standard deviation after bias corrections is reduced to half. This indicates that the verification works.

The old EMS SCALE 4 bias corrected value (4% high) using ORNL verification is not used in the evaluation since the verification is not focused on this application. A revised method using SCALE 5 and different verification is included.

The CRISTAL value is slightly lower, which is not unexpected (often slightly conservative). An IRSN evaluation of different density laws for this system is of special interest. IRSN used similar methods, except that the density laws used at IRSN during different periods were different. The older ARH-600 method (1968 version, not 1972 revised version of handbook!), the isopiestic law and the combined isopiestic/volume fraction law were used. For this system, the reference values change very little using the three density methods. That was the conclusion of IRSN and remains so in perspective of other differences between contributed values. For geometry reference parameters, the conclusions are different.

The MONK and CRISTAL values are lower than the average (dominated by correlated EMS methods). The IPPE-ABBN93 value is close to the average.

The "major 6" average verified value with one standard deviation, including the IPPE result, is 524 ± 6 g ^{235}U. Considering additional uncertainties (the density laws appear to have very small

uncertainties for this application), the total 95% level of confidence uncertainty is estimated as 20 g ^{235}U.

Pu(95/5)NH – Mass

This system is sensitive to the nuclide density (32 g/l) issue. The material is well moderated. The geometry is not so sensitive to quadrature and mesh. The mean $\bar{m}_{bc}$ of bias corrected values is higher than the mean $\bar{m}_c$ without corrections. The standard deviation after bias corrections is reduced to half. This indicates that the verification works.

The conclusions for this system are similar to the previous system.

The "major 6" average verified value with one standard deviation, including the IPPE result, is 639 ± 10 g ^{235}U. Considering additional uncertainties (the density laws appear to have very small uncertainties for this application), the total 95% level of confidence uncertainty is estimated as 30 g ^{235}U.

Pu(80/10/10)NH – Mass

This system is sensitive to the nuclide density (32 g/l) issue. The material is well moderated. The geometry is not so sensitive to quadrature and mesh. The mean $\bar{m}_{bc}$ of bias corrected values is higher than the mean $\bar{m}_c$ without corrections. The standard deviation before bias corrections is more than 50% higher. This lower reduction could indicate that the verification works less well than in previous systems but is also the result of the lack of an IPPE-ABBN93 value. The low MONK value increases the uncertainty.

The conclusions for this system are similar to the previous system. However, the IRSN value is close to the average, leaving the low MONK value isolated. On the other hand; the differences are mostly due to different verification and the associated bias corrections. Before the bias corrections, the MONK result is higher than almost all of the EMS values.

The "major 5" (no IPPE value) average verified value with one standard deviation is 707 ± 12 g ^{235}U. Considering additional uncertainties (the density laws appear to have very small uncertainties for this application), the total 95% level of confidence uncertainty is estimated as 40 g ^{235}U.

Pu(90/10)NH – Mass

This system is sensitive to the nuclide density (33 g/l) issue. The material is well moderated. The geometry is not so sensitive to quadrature and mesh. The mean $\bar{m}_{bc}$ of bias corrected values is higher than the mean $\bar{m}_c$ without corrections. The standard deviation before bias corrections is 100% higher. This indicates that the verification works

The conclusions for this system are similar to the previous system. The IRSN value is now higher than the bias corrected average, leaving the low MONK value isolated. On the other hand; the differences are mostly due to different verification and the associated bias corrections. Before the bias corrections, the MONK result is right on the average.

The "major 6" average verified value with one standard deviation is 777 ± 13 g ^{235}U. Considering additional uncertainties (the density laws appear to have very small uncertainties for this application), the total 95% level of confidence uncertainty is estimated as 40 g ^{235}U.

Pu(80/15/5)NH – Mass

This system is sensitive to the nuclide density (34 g/l) issue. The material is well moderated. The geometry is not so sensitive to quadrature and mesh. The mean $\bar{m}_{bc}$ of bias corrected values is much higher than the mean $\bar{m}_c$ without corrections. The standard deviation before bias corrections is more than 100% higher. The significant reduction of the spread in EMS values (excluding the old EMS SCALE 4 bias corrected result) is easy to see. The verification appears reasonable from that point of view. The low MONK value increases the uncertainty.

The conclusions for this system are similar to the previous system. However, the IRSN value is now closer to the low MONK value. Again; the differences are mostly due to different verification and the associated bias corrections. Before the bias corrections, the MONK result is much higher than almost all of the EMS values.

The "major 5" (no IPPE value) average verified value with one standard deviation is 905 ± 11 g ^{235}U. Considering additional uncertainties (the density laws appear to have very small uncertainties for this application), the total 95% level of confidence uncertainty is estimated as 40 g ^{235}U.

Pu(71/17/11/1)NH – Mass

This system is sensitive to the nuclide density (34 g/l) issue. The material is well moderated. The geometry is not so sensitive to quadrature and mesh. The mean $\bar{m}_{bc}$ of bias corrected values is much higher than the mean $\bar{m}_c$ without corrections. The standard deviation before bias corrections is more than 100% higher.

However, the CRISTAL value is much lower than the average, inconsistent with other PuNH mass results. The very high MONK value before bias correction is not consistent with previous results. Removing the bias corrected MONK value will not change the best-estimate. If the MONK value had been consistent with previous results, the average would have been lower. An extra 15 g of uncertainty is added to consider this, the low CRISTAL value and the fact that the IPPE value is missing..

The "major 5" (no IPPE value) average verified value with one standard deviation is 948 ± 8 g ^{235}U. Considering additional uncertainties (the density laws appear to have very small uncertainties for this application), the total 95% level of confidence uncertainty is estimated as 40 g ^{235}U.

Pu(100)NH – Volume

This system is sensitive to the nuclide density (280 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean $\bar{v}_{bc}$ of bias corrected values is lower than the mean $\bar{v}_c$ without corrections. This is a change from the mass system results. The standard deviation after bias corrections is reduced a little. This indicates problems with verification.

The CRISTAL value is about 3% higher than the average for the "major 6" bias corrected value. This is different than for plutonium oxide systems. An IRSN evaluation of different density laws for this system is of special interest. IRSN used similar methods, except that the density laws used at IRSN during different periods were different. The older ARH-600 method (ARH-600 from 1968, not revised from 1972) and the new combined isopiestic/volume fraction law were used. For this system, the reference values change dramatically when using the two density methods. The ARH-600 "law" gives

highly non-conservative values. That was the conclusion of IRSN but has been shown to be valid only for the density equation in the 1968 edition. It does not apply to the 1972 revision and to implementations in SCALE 4.

Results that could be too high due to inappropriate nuclide density methods include the original ARH-600 handbook (8.25 litres), the DIN standard (8.1 litres) and the German Handbook (8.3 litres). The IRSN/CEA 1978 Handbook refers to an H/U equation which gives better results. Both of the Japanese Handbook releases (single evaluation?) give very high values and this appears to be known to JAERI (Moeken equation problem) and will be corrected in a future Data Collection release 2.

SCALE 4 uses the ARH-600 method, but the results appear to be reasonable, often conservative. The reason is that it uses the 1972 revised equations of ARH-600..

The old EMS SCALE 4 bias corrected value (9% high) using ORNL verification is not used in the evaluation since the verification is not focused on this application. A revised method using SCALE 5 and different verification is included. The large bias correction due to the old verification is not related to the density issue. It should also be recognized that the stated uncertainty in the associated verification is large and covers the best-estimate value (a general conclusion of this verification from ORNL).

The MONK and IPPE-ABBN93 bias corrected values are lower than the average (dominated by correlated EMS methods). The density equation for MONK should give conservative deviations from the IRSN CRISTAL densities, see Figure K8. The IPPE method should give opposite trends, an over-estimation of the volume.

The "major 6" average verified value with one standard deviation, including the IPPE result, is 7.361 ± 0.131 litres. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95% level of confidence uncertainty is estimated as 0.5 litres.

Pu(95/5)NH – Volume

This system is sensitive to the nuclide density (140 g/l) issue. The material is well moderated, though not as well as for mass systems and not as well as for the previous system with 100% ^{239}Pu. The geometry is not so sensitive to quadrature and mesh. The mean $\bar{v}_{bc}$ of bias corrected values is lower than the mean $\bar{v}_c$ without corrections. This is a change from the mass system results. The standard deviation after bias corrections is reduced to less than half. This indicates a successful verification.

The conclusions are similar as for the previous system, that for Pu(100)NH. The CRISTAL value is now just slightly lower than the average. The IPPE-ABBN93 values are very high, which is unexpected compared with the previous Pu(100)NH system value, but consistent with the comparison of density methods..

The "major 6" average verified value with one standard deviation, including the IPPE result, is 10.782 ± 0.129 litres. Considering additional uncertainties (the density laws cause large uncertainties for this application), the total 95% level of confidence uncertainty is estimated as 0.5 litres.

Pu(80/10/10)NH – Volume

This system is sensitive to the nuclide density (130 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean $\bar{v}_{bc}$ of bias corrected values is slightly lower than the mean $\bar{v}_c$ without corrections. The standard

deviation after bias corrections is reduced to less than a third. This indicates a very successful verification.

The conclusions are similar as for the previous system. The CRISTAL value is now slightly lower than the average.

The methods that resulted in high values due to the density issue for the previous system are absent for this system. This includes IPPE-ABBN93.

The "major 5" (IPPE missing) average verified value with one standard deviation, including the IPPE result, is 12.176 ± 0.097 litres. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95% level of confidence uncertainty is estimated as 0.5 litres.

Pu(90/10)NH – Volume

This system is sensitive to the nuclide density (125 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean $\bar{v}_{bc}$ of bias corrected values is slightly higher than the mean $\bar{v}_c$ without corrections. The standard deviation after bias corrections is reduced to less than half. This indicates a successful verification.

The conclusions are similar as for a previous system, that for Pu(95/5)NH. The CRISTAL value is lower than the average.

The "major 6" average verified value with one standard deviation, including the IPPE result, is 13.415 ± 0.157 litres. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95% level of confidence uncertainty is estimated as 0.5 litres.

Pu(80/15/5)NH – Volume

This system is sensitive to the nuclide density (120 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean $\bar{v}_{bc}$ of bias corrected values is higher than the mean $\bar{v}_c$ without corrections. The standard deviation after bias corrections is reduced to less than a third. This indicates a successful verification even though the lack of a bias-corrected IPPE value makes the basis weaker.

The conclusions are similar as for the previous systems. The CRISTAL value is lower than the average.

The "major 5" (no IPPE value) average verified value with one standard deviation, including the IPPE result, is 15.424 ± 0.120 litres. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95% level of confidence uncertainty is estimated as 0.5 litres.

Pu(71/17/11/1)NH – Volume

This system is sensitive to the nuclide density (120 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean $\bar{v}_{bc}$ of bias corrected values is higher than the mean $\bar{v}_c$ without corrections. The standard deviation after bias corrections is reduced to a quarter. This indicates a successful verification even though the

lack of a bias corrected IPPE value makes the basis weaker.

The conclusions are similar as for the previous systems. The CRISTAL value is again lower than the average. The MONK bias corrected values have consistently resulted in values close to the best-estimate average for the last systems.

The "major 5" (no IPPE value) average verified value with one standard deviation, including the IPPE result, is 15.830 ± 0.085 litres. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95% level of confidence uncertainty is estimated as 0.5 litres.

Pu(100)NH – Cylinder diameter

This system is sensitive to the nuclide density (330 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean Φ_{bc} of bias corrected values is lower than the mean $\bar{\Phi}_c$ without corrections. This is similar to the volume system results but a change from the mass system results. The standard deviation after bias corrections is reduced to a half. This indicates a successful verification.

The conclusions are similar as for the volume system, see Pu(100)NH. The IRSN demonstrations of influences of density laws apply to the cylinder diameter as well as to the volume parameter. The CRISTAL value is now higher than the average. This is similar as for Pu(100)NH mass. The IPPE-ABBN93 value is high, which is similar to values from volume systems except for Pu(100). The Serco value before bias correction is the same as the bias corrected average but after bias correction the Serco value is lower.

The "major 6" average verified value with one standard deviation, including the IPPE result, is 15.555 ± 0.116 cm. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95% level of confidence uncertainty is estimated as 0.4 cm.

Pu(95/5)NH – Cylinder diameter

This system is sensitive to the nuclide density (155 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean $\bar{\Phi}_{bc}$ of bias corrected values is the same as the mean $\bar{\Phi}_c$ without corrections. The standard deviation after bias corrections is reduced to less than a half. This indicates a successful verification.

The conclusions are similar as for the Pu(100)NH cylinder diameter system. The CRISTAL value is now identical to the bias corrected best-estimate average. The IPPE-ABBN93 value is still high, but the bias correction helps.

The "major 6" average verified value with one standard deviation, including the IPPE result, is 17.942 ± 0.097 cm. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95% level of confidence uncertainty is estimated as 0.4 cm.

Pu(80/10/10)NH – Cylinder diameter

This system is sensitive to the nuclide density (145 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean Φ_{bc} of bias corrected values is about the same as the mean $\bar{\Phi}_c$ without corrections. The standard deviation after bias corrections is reduced to a third. This indicates a successful verification.

The conclusions are similar as for the previous PuNH cylinder diameter system.

The "major 5" average (no IPPE-ABBN93 value) verified value with one standard deviation is 18.774 ± 0064 cm. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95% level of confidence uncertainty is estimated as 0.20 cm.

Pu(90/10)NH – Cylinder diameter

This system is sensitive to the nuclide density (135 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean Φ_{bc} of bias corrected values is the same as the mean $\bar{\Phi}_c$ without corrections. The standard deviation after bias corrections is reduced to a third. This indicates a successful verification.

The conclusions are similar as for the Pu(100)NH cylinder diameter system. The MONK and CRISTAL values are now almost identical to the bias corrected best-estimate average. The IPPE-ABBN93 value is still high, but the bias correction helps.

The "major 6" average verified value with one standard deviation, including the IPPE result, is 19.475 ± 0.082 cm. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95% level of confidence uncertainty is estimated as 0.4 cm.

Pu(80/15/5)NH – Cylinder diameter

This system is sensitive to the nuclide density (130 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean $\bar{\Phi}_{bc}$ of bias corrected values is about the same as the mean $\bar{\Phi}_c$ without corrections. The standard deviation after bias corrections is reduced to a quarter. This indicates a successful verification even though the IPPE-ABBN93 value is missing.

The conclusions are similar as for the previous PuNH cylinder diameter systems. The CRISTAL value is slightly lower than the bias corrected best-estimate average. The bias corrected MONK value is slightly higher.

The "major 5" average (no IPPE-ABBN93 value) verified value with one standard deviation is 20.542 ± 0.052 cm. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95% level of confidence uncertainty is estimated as 0.4 cm.

Pu(71/17/11/1)NH – Cylinder diameter

This system is sensitive to the nuclide density (130 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean $\bar{\Phi}_{bc}$ of bias corrected values is about the same as the mean $\bar{\Phi}_c$ without corrections. The standard deviation after bias corrections is reduced to less than a half. This indicates a successful verification even though the IPPE-ABBN93 value is missing.

The conclusions are similar as for the previous PuNH cylinder diameter systems. The CRISTAL value is slightly lower than the bias corrected best-estimate average. The bias corrected MONK value is close to the CRISTAL value.

The "major 5" average (no IPPE-ABBN93 value) verified value with one standard deviation is 20.718 ± 0.087 cm. Considering additional uncertainties (the density laws appear to cause large

uncertainties for this application), the total 95% level of confidence uncertainty is estimated as 0.4 cm.

Pu(100)NH – Slab thickness

This system is sensitive to the nuclide density (550 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean $\bar{t}_{bc}$ of bias corrected values is lower than the mean $\bar{t}_{c}$ without corrections. The standard deviation after bias corrections is slightly reduced. This indicates a not so successful overall verification. The EMS methods seem to benefit from the bias corrections.

The conclusions are similar as for the Pu(100)NH volume and cylinder systems. The IRSN demonstrations of influences of density laws apply. The CRISTAL value is again, like for the volume and cylinder systems higher than the average (for isotopic distribution 100% ^{239}Pu only). The bias corrected IPPE-ABBN93 value is close the bias corrected average. The MONK value after bias correction is lower.

The "major 6" average verified value with one standard deviation, including the IPPE result, is 5.668 ± 0.088 cm. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95% level of confidence uncertainty is estimated as 0.3 cm.

Pu(95/5)NH – Slab thickness

This system is sensitive to the nuclide density (212 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean $\bar{t}_{bc}$ of bias corrected values is almost the same as the mean $\bar{t}_{c}$ without corrections. The standard deviation after bias corrections is reduced to less than half. This indicates a successful overall verification.

The conclusions are similar as for other PuNH volume and cylinder systems. However, the variations between bias corrected values (excluding as always the EMS SCALE 4 and the JAERI handbook values) all seem to be limited. Also the CRISTAL value is within this limited range of values.

The "major 6" average verified value with one standard deviation, including the IPPE result, is 7.176 ± 0.063 cm. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95% level of confidence uncertainty is estimated as 0.3 cm.

Pu(80/10/10)NH – Slab thickness

This system is sensitive to the nuclide density (220 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean $\bar{t}_{bc}$ of bias corrected values is lower than the mean $\bar{t}_{c}$ without corrections. The standard deviation after bias corrections is reduced to about 65%. This may indicate some problem with the overall verification.

The conclusions are similar as for other PuNH volume and cylinder systems. The CRISTAL value is higher than the best-estimate while the bias corrected MONK value is lower.

The "major 5" average verified value with one standard deviation, including the IPPE result, is 7.612 ± 0.094 cm. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95% level of confidence uncertainty is estimated as 0.3 cm.

Pu(90/10)NH – Slab thickness

This system is sensitive to the nuclide density (175 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean $\bar{t}_{bc}$ of bias corrected values is the same as the mean $\bar{t}_c$ without corrections. The standard deviation after bias corrections is reduced to about 40%. This indicates a successful overall verification.

The conclusions are similar as for other PuNH volume and cylinder systems. The CRISTAL value and the IPPE-ABBN93 bias corrected value are higher than the best-estimate while the bias corrected MONK value is lower.

The "major 6" average verified value with one standard deviation, including the IPPE result, is 8.108 ± 0.054 cm. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95% level of confidence uncertainty is estimated as 0.3 cm.

Pu(80/15/5)NH – Slab thickness

This system is sensitive to the nuclide density (180 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean $\bar{t}_{bc}$ of bias corrected values is the same as the mean $\bar{t}_c$ without corrections. The standard deviation after bias corrections is reduced to less than 50%. This indicates a successful overall verification.

The conclusions are similar as for other PuNH volume and cylinder systems. The CRISTAL value is higher than the best-estimate while the bias corrected MONK value is lower. The EMS SCALE bias corrected values are lower while the EMS MCNP bias corrected values are higher than the best-estimate value. The spread of results is small.

The "major 5" average verified value with one standard deviation, including the IPPE result, is 8.750 ± 0.060 cm. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95% level of confidence uncertainty is estimated as 0.3 cm.

Pu(71/17/17/1)NH – Slab thickness

This system is sensitive to the nuclide density (160 g/l) issue. The material is well moderated, though not as well as for mass systems. The geometry is not so sensitive to quadrature and mesh. The mean $\bar{t}_{bc}$ of bias corrected values is the same as the mean $\bar{t}_c$ without corrections. The standard deviation after bias corrections is reduced less than 50%. This indicates a successful overall verification.

The conclusions are similar as for other PuNH volume and cylinder systems. The CRISTAL value is close to the best-estimate while the bias corrected MONK value is lower. The EMS SCALE bias corrected values are lower than the best-estimate value. The spread of results is small.

It appears so far as if the MONK densities are not as bad as indicated by the comparison in Appendix k.

The "major 5" average verified value with one standard deviation, including the IPPE result, is 8.886 ± 0.084 cm. Considering additional uncertainties (the density laws appear to cause large uncertainties for this application), the total 95% level of confidence uncertainty is estimated as 0.3 cm.

Pu(100)NH – Concentration

This system does not seem to be sensitive to the nuclide density (7.33 g/l) issue. However, the criticality is determined by the moderation ratio H/Pu, not by the concentration in g/l. If the same concentration leads to different H/Pu ratios, there may be some problem with the nuclide density determination. The material is well moderated. The mean value $\overline{c}_c$ is higher than $\overline{c}_{bc}$. The standard deviation is reduced to about 40% by the corrections.

There are quite large differences for this simple system. The EMS methods appear to benefit from the verification procedure. The MONK value reported to the Group [55] was 6% high. It was clearly some editorial mistake and this was confirmed and corrected by Serco in March 2005. The IPPE-ABBN93 value is above the best-estimate, the CRISTAL value is below.

The average verified value for the "major 6" (including revised MONK value) with one standard deviation is 7.328 ± 0.026 g/l. The total 95% level of confidence uncertainty is estimated as 0.20 g/l.

Pu(95/5)NH – Concentration

This system does not seem to be sensitive to the nuclide density (7.93 g/l) issue. The mean value $\overline{c}_c$ is lower than $\overline{c}_{bc}$. The standard deviation is reduced to about a third by the corrections. This indicates that the bias corrections work well.

The spread of the bias corrected values is quite small, except for the MONK value.

The average verified value for the "major 6" with one standard deviation is 7.929 ± 0.066 g/l. The total 95% level of confidence uncertainty is estimated as 0.20 g/l.

Pu(80/10/10)NH – Concentration

This system does not seem to be sensitive to the nuclide density (8.19 g/l) issue. The mean value $\overline{c}_c$ is lower than $\overline{c}_{bc}$. The standard deviation is increased by the corrections. This indicates that there is a problem with the overall verification. The spread of the EMS is reduced significantly. However, the MONK value is bias corrected in the other direction, causing a large difference.

There is no IPPE value. The CRISTAL value is between the MONK bias corrected value and the best-estimate value.

The average verified value for the "major 5" with one standard deviation is 8.194 ± 0.111 g/l. The total 95% level of confidence uncertainty is estimated as 0.20 g/l.

Pu(90/10)NH – Concentration

This system does not seem to be sensitive to the nuclide density (8.59 g/l) issue. The mean value $\overline{c}_c$ is lower than $\overline{c}_{bc}$. The standard deviation is not reduced at all. This indicates a problem with the overall verification.

The spread of the bias corrected values is quite small, except for the MONK value. However, the MONK values are close to the EMS values before bias correction.

The average verified value for the "major 6" with one standard deviation is 8.594 ± 0.099 g/l. The total 95% level of confidence uncertainty is estimated as 0.20 g/l.

Pu(80/15/5)NH – Concentration

This system does not seem to be sensitive to the nuclide density (9.15 g/l) issue. The mean value $\overline{c}_c$ is lower than $\overline{c}_{bc}$. The standard deviation is unchanged by the corrections. This indicates that there is a problem with the overall verification. The spread of the EMS is reduced significantly. However, the MONK value, being higher than any of the EMS values before bias corrections, is reduced by the bias correction while the EMS values are increased.

There is no IPPE value. The CRISTAL value is between the MONK bias corrected value and the best-estimate value.

The average verified value for the "major 5" with one standard deviation is 9.154 ± 0.090 g/l. The total 95% level of confidence uncertainty is estimated as 0.20 g/l.

Pu(71/17/11/1)NH – Concentration

This system does not seem to be sensitive to the nuclide density (9.31 g/l) issue. The mean value $\overline{c}_c$ is lower than $\overline{c}_{bc}$. The standard deviation is increased by the corrections. This indicates that there is a problem with the overall verification. The spread of the EMS is reduced significantly. However, the MONK value, being similar to the EMS values before bias corrections, is reduced by the bias correction while the EMS values are increased.

There is no IPPE value. The CRISTAL value is between the MONK bias corrected value and the best-estimate value.

The average verified value for the "major 5" with one standard deviation is 9.314 ± 0.124 g/l. The total 95% level of confidence uncertainty is estimated as 0.25 g/l.

Pu(100)NH – Moderation

This system is essentially the same as the concentration system. However, it is not sensitive to the nuclide density laws as the critical concentration is. The moderation parameter for an infinite system is not density dependent. If the different parameter values cover the whole range of moderations, from very dilute to crystal, then a check of corresponding densities obtained by different density laws would be revealing. Thus, since it is less complicated, it makes more sense to start with comparing critical moderations before starting comparing critical concentrations.

At this time, the best-estimate of the critical concentration will be used to find the best-estimate of the critical moderation. SCALE 5 is used for that. Using that moderation, different density laws can be compared.

The critical moderation corresponding to the best-estimate critical concentration (7.328 g/l) is an H/Pu value of 3598. The total 95% level of confidence uncertainty is estimated as 96 (corresponds to a density change of 0.20 g/l).

Pu(95/5)NH – Moderation

The critical moderation corresponding to the best-estimate critical concentration (7.929 g/l) is an H/Pu value of 3325. The total 95% level of confidence uncertainty is estimated as 82 (corresponds to a density change of 0.20 g/l).

Pu(80/10/10)NH – Moderation

The critical moderation corresponding to the best-estimate critical concentration (8.194 g/l) is an H/Pu value of 3221. The total 95% level of confidence uncertainty is estimated as 97 (corresponds to a density change of 0.20 g/l).

Pu(90/10)NH – Moderation

The critical moderation corresponding to the best-estimate critical concentration (8.594 g/l) is an H/Pu value of 3068. The total 95% level of confidence uncertainty is estimated as 70 (corresponds to a density change of 0.20 g/l).

Pu(80/15/5)NH – Moderation

The critical moderation corresponding to the best-estimate critical concentration (9.154 g/l) is an H/Pu value of 2881. The total 95% level of confidence uncertainty is estimated as 62 (corresponds to a density change of 0.20 g/l).

Pu(71/17/11/1)NH – Moderation

The critical moderation corresponding to the best-estimate critical concentration (9.314 g/l) is an H/Pu value of 2833. The total 95% level of confidence uncertainty is estimated as 74 (corresponds to a density change of 0.25 g/l).

Preliminary summary of accuracies of different methods

Since the best-estimate reference values are not known very accurately for some systems, it is difficult to correctly express the accuracies of individual methods. The benchmarks only cover cross-sections and codes, not nuclide density determinations. These are important for the hydrated nitrate systems. All the EMS MCNP5 and SCALE 5 methods for each system are based on a single nuclide density determination (CSAS in SCALE 5).

The concept "conservative" is used here to mean an overestimation of k_{eff}. It is normally used as a safety concept, but here it is rather used for simplicity. K_{eff} increases with an increase in most of the reference parameters but for the moderation ratio the relationship is reversed. A conservative method thus means that the critical mass, geometry and concentration values are underestimated and the H/U ratio is overestimated.

ARH-600 handbook

Some of the contributed ARH-600 values were not intended for the associated reference systems. Some were for uranium with 93% by mass of ^{235}U, other were for UO_2F_2 rather than for UO_2. Most of the values are for PuNH and they are usually non-conservative. It seems likely that the inaccurate density equation used by IRSN until recently was also used to derive many of the values and curves in the ARH-600 Handbook. A revised page from October 1968 still contains an inaccurate density equation. In the 1972 revision, a better equation was quoted, but it was probably not used to revise the curves. The equations used in SCALE before version 5 were based on the 1972 revised equations of the ARH-600 Handbook.

DIN standards

For UO_2, all values seem to be slightly conservative or close to the best-estimate values. The similar is true for UNH (only 100% enrichment ^{235}U available). For PuO_2, there could be some non-conservatory values for cylinder and in particular slab geometry. There seems to be a trend. For PuNH there are serious overestimations (non-conservative) of the minimum critical geometry values. A likely cause is the density method used. Many of the values are similar to those given in ARH-600. The water fraction of the solution appears to be underestimated. This explains why the concentration limits are conservative. This is based on speculation, looking at the results, not on an investigation of the method.

EMS: MCNP5 with ENDF/B-V cross-sections

There are two methods for plutonium systems, one with an early cross-section set for ^{239}Pu (.50c) and the other with a final version (.55c). The difference is dramatic for fast systems but not for thermal, something that is probably familiar to frequent users of this library. For UO_2, all values seem to be slightly conservative. For UNH, the cross-sections give the same trend but the density method makes a comparison of the overall methods complicated. The densities for UNH and PuNH were determined using density relationships in SCALE 5 at 300K. For PuO_2, both sets are conservative for mass systems while the final version seems quite accurate on fast systems (the early set is conservative). For PuNH, the behaviour should be similar as for thermal PuO_2. The two sets do seem to be very similar for all PuNH systems. However, the density issues for solutions make it more complicated to find weak trends.

EMS: MCNP5 with ENDF/B-VI.2 cross-sections

The results for UO_2 systems are very consistent. There is a strong trend with the ^{235}U enrichment or rather with the presence of ^{238}U. Without this nuclide, for $U(100)O_2$ systems, the results appear very accurate. For low enrichments, the reference values are highly non-conservative. The same trend is seen for the UNH systems. If the best-estimate values for PuO_2 are correct, this method is consistently very accurate. This conclusion is supported by the small bias-corrections as well. For PuNH systems, the accuracy is good for mass systems (over-moderated) while giving consistent overestimations for geometry-controlled systems (near optimum infinite system moderation). For both hydrated nitrate systems (U and Pu) the quality of the values depends on the nuclide density methods. The densities were taken from SCALE 5 calculations at 300K.

EMS: MCNP5 with ENDF/B-VI.6 cross-sections

The ^{238}U trend from the previous release VI.2 cross-section library is absent; all uranium systems are calculated with consistency and good accuracy. Errors due to nuclide densities are not considered in this conclusion. For the plutonium systems, good results were obtained, similar to those for ENDF/B-VI.2 cross-sections. The overestimations for some thermal Pu systems are lower than for release VI.2.

EMS: MCNP5 with ENDF/B-VI.8 cross-sections

The changes from release VI.6 seems to be small. Both the uranium and the plutonium values are close for almost all systems.

EMS: MCNP5 with ENDF/B-VII.P cross-sections

For uranium with 100 or 20% by mass of ^{235}U, there is a clear trend for some overestimation of the reference values. For low-enriched uranium the values are good and similar to the releases VI.6 and VI.8. The only plutonium isotope, ^{239}Pu does not seem to change much compared with release VI.8.

EMS: MCNP5 with JEF-2.2 cross-sections

The uranium values are consistently near the best-estimate, excluding density effects. The behaviour seems similar to ENDF/B-VI.6 but with a negative trend (conservative) for slab, cylinder and maybe volume control. For plutonium systems there is a consistent and very strong underestimation (conservative) of the PuO_2 mass and all geometry-constrained PuNH system values. This underestimation is found by the verification and corrected for. The concentration values seem to be slightly high, while the fast systems are close to the best-estimate (excluding density effects).

EMS: MCNP5 with JEFF-3.0 cross-sections

For uranium systems, the behaviour is quite similar to JEF 2.2. There appears to be spectrum-related trends with slightly higher (less conservative) values for JEFF 3.0 for near optimum moderated leakage systems (geometry control) and lower for over-moderated leakage systems (mass). For plutonium there is a drastic improvement for moderated leakage systems while retaining the good qualities of JEF 2.2 for other systems. This is also detected by the verification process, leading to small biases for JEFF 3.0.

EMS: MCNP5 with JENDL-3.2 cross-sections

There is a very strong conservative bias for all uranium systems. Moderated PuO_2 and PuNH system values show the same trend. Fast plutonium systems are calculated about the average.

EMS: MCNP5 with JENDL-3.3 cross-sections

The uranium systems are now calculated with what appears to be small biases. The improvement from JENDL-3.2 is significant. The moderated PuO_2 and PuNH system values show the same trend as for JENDL-3.2, a conservative bias. Fast plutonium systems are also similar to JENDL-3.2; about the average.

EMS: SCALE 1 and KENOV with 27 group cross-sections from SCALE 3

The calculations of UO_2 mass reference systems with this method all resulted in high overestimations of the critical mass (non-conservative). This was expected from earlier experience but is not consistent with SCALE 5 and the same (or very similar) cross-section library. The reason for the differences is not known but may be related to incompatibility between an old code version (NITAWL in SCALE 1 as opposed to NITAWL-II) with revised data (the 27-group library in SCALE 3 was changed from the SCALE 1 version).

EMS: SCALE 4.4, XSDRNPM with 238 group cross-sections

The SCALE 4 default values for convergence, mesh and angular quadrature in XSDRNPM calculations were used in 2000 and 2001. Already at that time it was understood that this may not be sufficient for fast systems. Further, the verification was based on a too wide selection of benchmarks. The biases are not reliable. The calculated UO_2 values all appear quite good, with small deviations from

the best-estimate values. The UNH and PuNH values reflect the nuclide density methods. SCALE 4 results don't seem very different to SCALE 5 results. The verification indicates conservative cross-section biases for Pu systems.

EMS: SCALE 5, XSDRNPM and KENOVa with 238-group cross-sections

Better default values and improving them for some systems (in particular fast systems) lead to some changes in reference values compared with SCALE 4 and the same cross sections. The new density method for solutions in SCALE 5 does not seem to change the reference values much as long as the actinide densities are below the solubility limits. Overall, the 238-group library holds very well for all systems and the verification seems to work well.

EMS: SCALE 5, XSDRNPM and KENOVa with 27-group cross-sections

In spite of the statistical fluctuations, the Monte Carlo Code KENOVa is in practice more reliable and often more accurate than the deterministic code XSDRNPM. Reasons are that it is easier to validate the KENOVa method (more benchmarks) and that the cost of high precision (many neutron histories) has been reduced significantly during the years. Comparison of early XSDRNPM calculations of reference values with KENOVa calculations showed that there were several cases of insufficient convergence, mesh and/or angular quadrature in the XSDRNPM calculations. Improving such input has led to almost identical results.

The 27 group library has been used in Sweden since 1978 when the specifications and the 218-group library that it is collapsed from were published. It is not the most accurate library today but the limitations are quite well understood and predictable. Many safety reports and licenses have been issued based on calculations with this library. For this reason it will remain to be important. As is shown in the study, different combinations of codes and different versions of the 27-group library may result in quite different reference values. The results reported here may not be representative of older calculations.

For high-enriched uranium systems (both thermal and fast), the results are clearly conservative. For low-enriched uranium the results appear quite accurate with no strong trends. This is contradictory to experience from the 1980's, when the results were often non-conservative for low-enriched uranium. Changes in the structure and in the NITAWL resonance processing code may have improved the situation.

All calculations of plutonium systems lead to very conservative results, at least as far as the cross-sections are concerned. The verification reveals this behaviour but the fast systems are not corrected sufficiently. A reason may be that the 27-group library was never designed or intended for fast systems. If the physics of such systems are not simulated well enough, it is not easy to correct for the deviations through bias corrections. For thermal systems, it is surprising to see how well the bias corrections correct for the errors in the plutonium cross-sections.

EMS: SCALE 5, XSDRNPM and KENOVa with 44-group cross-sections

The 44-group library has not been used as much in Sweden as the 27- and 238-group libraries. However, it is used widely internationally in transport safety reports and in publications. Information on its behaviour is useful.

For high-enriched uranium systems, the results are conservative, though not as much as for the 27-group library. For low-enriched uranium systems the accuracy is better. Compared with the 44-

group library, the 27-group library leads to less conservative, sometimes non-conservative results for the low-enriched uranium. This is seen in the verification results.

For plutonium, the thermal system results are very conservative, though not as much as the for the 27-group library. For fast systems, the group-structure was not designed or intended for such simulations. The results are conservative but the verification cannot correct for it appropriately. For PuNH systems, the density effect makes it more complicated to evaluate the cross-section influence.

GRS: The German criticality safety handbook

The first (1970) version of this handbook has been the most popular in Sweden since it covers many of the solutions common in fuel fabrication (wet UF_6 conversion process and recovery of scrap). There have been some revisions in the mid 1980s and in 1998. The methods used to derive the values are described but the density determination methods are not always clear.

The tables and curves in the handbook don't always agree with each other. This can be confusing.

The handbook is, like most other safety handbooks, intended to be used together with verification and other steps to assure that the application is safe. The purpose has never been to give exact values.

The handbook does not cover all reference systems. The high-enriched (20, 100% ^{235}U) uranium system results seem to be scattered around the best-estimate values. The low-enriched UO_2 results are consistently non-conservative. The low-enriched UNH results are even more consistent, though in the opposite, conservative direction. The table and the curves give different values for the same system.

For UNH with the enrichments 3, 4 and 5% by mass of uranium, there is another peculiarity. The U(5)NH mass parameter (485 kg U) that was given in the tables on the NAIS web page and distributed to participants during meetings is based on a an editorial error in the 1985 version of the handbook. This was corrected to 445 kg U in the 1998 release of the handbook. Of the 12 mass and geometry values for these systems, the corrected U(5)NH mass value is the only one that is different from the IRSN Standard de Criticité from 1978. The GRS results were obtained with GAMTEC/DTF-IV calculations while the IRSN results were obtained with a combination of literature search and calculations with DTF/IV, MORET and APOLLO. The values seem to have a common origin but it is not easy to find.

There are not so many values for plutonium systems, but it is apparent that the PuNH values are highly non-conservative. The density method could be a reason.

IPPE-84: Russian handbook from 1984

As seen from the description of the methods used, these values involve many large errors and uncertainties. Sometimes, they cancel out, sometimes not. The users of this handbook were informed about the uncertainties.

IPPE-ABBN93

This method is based on the ABBN93a cross section library used with either KENOVa or XSDRNPM/S. It has been used in several publications as well as in the generation of data in ICSBEP Handbook. In a very short period in late 2004, IPPE carried out reference value calculations for most systems and also reported verification results for the benchmarks listed in the report.

The simple density method for solutions used by IPPE for this project is not accurate for all densities but it seems more appropriate than other methods, except the IRSN isopiestic method. It is accurate for low and high densities, including the crystal form of the material.

The verification reported here for this method is based on the EMS selection of benchmarks. IPPE has published other verification studies that may have different conclusions.

The UO_2 results are either very close to the best-estimate average or a little bit conservative.

The UNH systems for medium and low-enriched uranium are much more conservative than the average values. They are often close to the IRSN extended isopiestic method. This is not a coincidence; the IRSN extended and the IPPE simple mixing methods are the only methods that consider the real crystal densities. For some densities, the IPPE method appears to be more conservative than the IRSN isopiestic method. This could be explained by the additional water present due to the IPPE mixing method compared with the solution simulation methods.

The PuO_2 results are very close to the best-estimate values and the bias-corrected EMS MCNP results, both for fast and thermal systems. This is a sign that the selection and evaluation of benchmarks have been successful for these applications.

For PuNH systems, the IPPE results often appear a little non-conservative. This appears to be contradictory to the experience from evaluation of UNH results. However, a look at the comparison of density methods (Appendix K) shows that the IPPE mixing gives underestimation of the water presence in PuNH while the opposite was true for UNH. Since the verification of density methods has not been reported very well, some care must be made in drawing conclusions.

IRSN – Standard de Criticité 1978

This handbook (issued by CEA which at that time included the current IRSN) has been published and is a valuable information source for criticality safety specialists. The H/X ratio to actinide density and other density relations for hydrated nitrate solutions from ARH-600 are quoted. It is not easy to find the origin of the values since they seem to be selected conservatively from a number of sources, including literature and APOLLO, DTF/IV and MORET calculations. See also the discussion above on the many identical UNH values in the German Handbook and this IRSN Standard.

An internal IRSN review of this Guide was carried out until 1996. The source [99] is not published and was not given to the Expert Group, only the values were contributed. During the final evaluation a copy was reviewed but there is no clear information on what methods were applied to obtain the values. The reported values were removed unless they can be found in the Standard, since the methods were not described very well and the results quoted in different contributions were often different.

It is not easy to directly see any trend for the UO_2 values. Some appear very conservative, other very non-conservative and some quite good. This could be related to their potentially different sources.

For UNH with low-enriched uranium, most values are identical to the German Handbook values.

For the plutonium systems that are covered, there is a wide spread of results; some are very conservative others are very non-conservative.

IRSN Pre-Isopiestic – CRISTAL and other methods using a replaced ARH-600 density relation

The values for hydrated nitrates are based on an option in CRISTAL where the older density methods based on Leroy-Jouan (UNH) and ARH-600 (PuNH) are tested against the new extended isopiestic density law. However, the ARH-600 equation comes from the 1968 ARH-600 version that was replaced in 1972. It has been used in IRSN long after that, since the 1972 ARH-600 version did not correspond to the IRSN concerns and since a method simulating the real behaviour of solutions of high actinide concentrations and high acidity was not yet available.

The only values given are for Pu(100)NH mass and volume systems. The mass values are similar while the minimum critical volume is overestimated significantly by the old method. The reason is apparent from the comparison of density methods in Appendix K.

IRSN Current methods – CRISTAL using the extended isopiestic density law

The CRISTAL system with the CIGALES graphical interface pre-processor is verified with consideration of density issues related to isotope distributions as well as to solubility and mixing of solutions and salts (crystal form). The calculated reference values are not bias-corrected and uncertainties based on verification are not given. However, the results are either more credible (density issues) or quite close to best-estimate reference values for systems where density issues are not complicating comparisons. An exception is plutonium dioxide slab systems for which IRSN reference values are a few percent higher than for other systems. The differences are within the expected uncertainty range and it is not yet obvious which values are more correct than others.

JAERI: The Japanese Handbooks, release 1 and 2

The Japanese handbooks contain a lot of useful information. However, the benchmarks used to establish the bias-corrected values are old, from the 1980's and earlier. This means that the biases and uncertainties in setting up benchmarks from experiment specifications and results were not as well documented as in the ICSBEP Handbook. The publication of k_{eff} biases in the handbooks could probably have been used to derive the calculated values during the evaluation. Time did not allow this but a simple adjustment of each benchmark result could have been used to modify the bias-corrections.

The evaluations used to determine values in release 2 are often identical to those for the first release. Sometimes a value is only given for release 2 even if the first release has an identical value.

There are not many values for high-enriched uranium. For low-enriched uranium in UO_2, Handbook 1 gives conservative results. The situation is more mixed for Handbook 2 though also that handbook sometimes gives very conservative results. For UNH systems, the release 2 sometimes gives non-conservative deviations. The variations from average values are often large. This is similar to the EMS SCALE 4 calculations that were bias-corrected using general ORNL safety verification.

There are not many values for plutonium systems. For PuNH volume, cylinder and slabs, values are given and they appear to be identical in both releases. The values are severely overestimated (non-conservative). This could be a density effect.

As mentioned elsewhere in the report, the minimum critical mass for $U(20)O_2$ is overestimated by 40%. This is more of an editorial error than an evaluation error but it is still very serious.

ORNL: SCALE 4.3, XSDRNPM/S and the 238 group library

This method is essentially identical to the EMS method with SCALE 4.4 and the same library. Differences could be caused by better convergence criteria used by ORNL and better interpolation in finding the optimum densities by EMS.

ORNL refers to the same verification report used by EMS in 2001 and that has been rejected by EMS for this study. It is a verification report intended for general safety application and with very large uncertainties. A more focused evaluation is preferable when a best-estimate value is requested.

ORNL also makes comments on the question of solubility limits for hydrated nitrate densities. The reported values include densities below real crystal density but with crystal density composition as well as lower densities using the same solution equation as in ARH-600 (revised 1972).

The same conclusions apply as to the EMS methods based on this cross-section library.

SERCO: MONK 8A and 8B with JEF 2.2 continuous energy cross-sections

For UO_2 systems, the values are quite close to the best-estimates and the bias-corrections based on Serco verification are small. Some slab values appear to be non-conservative.

For UNH systems, many values appear to be strongly non-conservative. The density methods are questionable (as for many other contributors) and it is difficult to see any cross-section related trends.

For PuO_2 thermal systems, the trends are interesting. The bias-corrections are opposite to those for EMS methods and reverse the trends for "raw" data results. It is not easy to say which verification works best. The IRSN isopiestic method is more often closer to the EMS values but not always.

For PuNH the bias corrections due to cross-sections are large. However, the density methods seem to be just as important. Until such verification is carried out, it is difficult to evaluate other trends.

Appendix M
NUMERICAL AND STATISTICAL CONSIDERATIONS

This appendix collects a number of issues related to precision, accuracy, convergence, interpolation, extrapolation, etc. that determine the quality of the results.

Precision of reference values

A reasonable target for the numerical and statistical values obtained from deterministic and Monte Carlo codes is a k_{eff} with a precision of 0.001. Better precision is achievable but may not be meaningful at this stage. This k_{eff} target is translated into units of reference values by taking the logarithm of the reference value unit to changes in k_{eff} (Appendix D). This is how the least significant digit before (positive logarithmic value) or after the decimal point (negative logarithmic value) is obtained. The precision in the reference value will thus correspond to between 0.0001 and 0.001 in k_{eff}.

The useful precision in biases and uncertainties depends on the application and whether systematic effects are to be evaluated. As proposed in [69], at least two significant digits are motivated in each standard deviation. However, the recommendation that a measured value should have the same precision is not clear. Systematic effects could motivate much better precision in the standard deviation than in the measured value. A coverage factor larger than one may motivate a higher precision of the standard deviation.

Accuracy of reference values

Unlike the precision, a requested accuracy may be difficult to achieve. It depends on many error sources. The availability and quality of adequate benchmarks (for cross-sections, nuclide densities and other data) is of particular importance. The propagation of uncertainties from various error sources, using results of verification to a total uncertainty related to an overall validation is often very complicated. There are not many benchmarks that cover validation in one step.

Linearity of relations, normality of statistical distributions

Many equations and other relations are based on approximations that require linearity or normal distribution. The treatment of uncertainties is an example where linear relations are often required. Normal distribution of statistical data is another requirement related to uncertainty treatment that is sometimes taken for granted.

A combination is found where the statistical distribution near the mean is more or less symmetrical while it becomes very asymmetrical further away from the mean. This is one of the reasons why the uncertainty allowance is better represented by a 95% rather than a 66% limit of confidence. In criticality safety, even a 99.9% limit of confidence is required by many authorities.