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Benchmark Calculations for U235

A report produced for Magnox Electric

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Executive Summary

American and European studies use modern computer codes with processed evaluated nuclear data to predict physics parameters for thermal reactors. The quality of prediction is checked by studying benchmark experiments. Various analyses have highlighted the need to increase resonance capture cross sections for U235 in JEF2.2 (European) and ENDF/B-VI revision 2 (American) evaluations.

Three further evaluations have been developed as a result. Firstly ENDF/B-VI revision 3 was produced by collaborative international study. This was further developed and a new file released in January 1996. Comments about the physics of this file resulted in further study culminating in a new file being developed in December 1996 at Oak Ridge National Laboratories.

This paper uses all five evaluations to predict the criticality ($k_{effective}$) of ten experimental benchmarks. These have been selected to cover a range of systems described as having intermediate and thermal neutron spectra. All nuclear data other than U235 are based on JEF2.2.

We conclude that the MONK7 Monte Carlo code, with Hyper-fine group data, predicts trends effectively. Six of the seven thermal systems have improved predictions of k with the latest ORNL U235 evaluation compared with JEF2.2 and all except TRX are within 200 pcm (mN) of unity. Two of the three intermediate spectra systems have much improved results when calculated with the January 1996 evaluation. Current predictions with the December data are up to 1.5% high. We note that further U235 data evaluation is required to achieve satisfactory results for three of the ten systems.

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1 Introduction

The JEF2.2 and ENDF/B-VI Benchmark Programmes have suggested that the JEF2.2 and ENDF/B-VI revision 2 nuclear data evaluations contain too little resonance capture for U235[1,2]. As a result, new evaluation work is underway to produce a file for the Joint Evaluated Fission and Fusion library version 3 (in its Test status) JEFF-3.T. (This will be released for formal benchmarking as JEFF3.0.) The evaluation work is organised by Sub-Group 18 of the OECD NEA Working Party on Evaluation Co-operation. Various U235 evaluations have been released in revisions of ENDF/B-VI. The file proposed for ENDF/B-VI revision 4 was considered for inclusion in JEFF-3.T. The file is described in JEF/DOC 552[3]and was issued, in January 1996, to international evaluators for comment.

Moxon examined the January 1996 Leal, Derrien et al evaluation using his REFIT[4] code and issued a paper proposing improvements[5]. These were discussed at the July 1996 JEF meeting. As a result a collaborative evaluation exercise took place at Oak Ridge National Laboratory, USA (ORNL). An evaluation was produced in December 1996 but was not made available in Europe until March 1997[6]. The file is noted to be preliminary.

This paper describes the use of these U235 evaluations in suitable benchmark studies.

2 Computer Codes and Methods

All benchmark calculations used the Monte Carlo codes MONK7[7] and the MONK5W option of WIMS7[8]. For each assembly three calculations were run. Each used different initial random numbers to predict k_{eff} to within a standard deviation (σ) of 100mN (pcm). No other physics parameters were considered in this study.

3 Applications Libraries

Standard nuclear data libraries for MONK7[9] and WIMS7[10] are produced from JEF2.2 evaluated nuclear data. All nuclide data on the 1996 DICE library for MONK are modelled in 13,193 hyper-fine energy groups. A pre-shielding treatment is also applied for major fuel isotopes and structural materials. This treatment includes fitting shielded data averaged over 4 groups for U238 and 2 groups for U235. The 172 group WIMS library was used throughout the broad group work. Resonance shielding is included for major fuel isotopes and absorbers in the form of tabulated resonance integrals in the energy range 4eV to 9KeV.

The JEF2.2 U235 data were already present on the libraries. The NJOY Code[11] had been used to generate these data and has also been used to process all other U235 evaluations. All processed data were added to the libraries as extra nuclides.

4 U235 Evaluations

This benchmark testing uses five versions of U235 evaluated nuclear data. JEF2.2 and ENDF/B6 revision 2 were the starting points for the benchmarking programmes in Europe and the USA respectively. Studies using these evaluations indicated problems attributed to too little resonance capture in U235[1,2]. Attention has been concentrated on the resolved resonance (and thermal) range(s) .

ENDF/B-VI revision 3[12] was the first attempt to rectify the situation. In this revision the mean capture width was increased from ~33meV to ~37meV. The resolved resonance range remained sub-divided into 11 bands with extra unphysical resonances inserted; allowing a continuous cross section to be generated from reasonably quick NJOY processing.

The next proposed evaluation was issued in January 1996[3]. The main European evaluator was H Derrien. The mean capture width was ~45meV but there was considerable variation in individual resonances. A single energy band was used in the resolved range. This removes the unphysical resonances but significantly increases the NJOY processing time.

A preliminary evaluation[6] has resulted from the ORNL study completed in December 1996. Limitations have been placed on the variation of the capture width in the range 4 to 100eV by setting widths smaller than 30meV and larger than 60meV to 40meV. However several (~7) resonance widths had to be reset in order to obtain suitable fits to experiment when the SAMMY[13] code was used. At higher energies a mean width of 40meV was used with a 2% constraint.

Further evaluation work is proposed by Sub-Group 18. Both REFIT and SAMMY will be used.

5 U235 Benchmarks

The effect of using the January 1996 U235 evaluation[6] instead of JEF2.2 for more than 60 experiments was studied by S. Cathalau, P. Blaise[14]. Surprisingly they found JEF2.2 gave better agreement with experiment. However, when the same experiments used in Cathalau's initial study[1] were considered, the January 1996 evaluation gave improved results! The JEF meeting concluded that it was important to carefully select experiments and always to use reference codes (Monte Carlo if possible).

Rowlands considered the problem of benchmark selection[15]. Based on his selection ideas and taking account of cases considered in the USA, ten benchmarks have been selected in an attempt to cover a full range of intermediate and thermal neutron spectra systems. Benchmarking in the USA had used the HISS Uranium assembly from the Hector reactor at Winfrith[16] together with the two Topsy reflected Uranium hydride assemblies UH3Ni and UH3UR[17] . All three have hard spectra. The hardest and softest ORNL spheres[18] are included together with the hardest and softest Uranium fluoride critical experiments: UF1 and UF6[19] .

DIMPLES01[20] and TRX[18] are both Uranium fuelled lattice benchmarks with good specification data in the public domain. A single VALDUC UO_2 lattice[21] criticality case is also considered.

6 Results

Results consist entirely of k_{eff} predictions from the two Monte Carlo codes. At this stage we have not performed analysis of experimental and modelling errors since we are viewing trends with respect to the changing U235 evaluations.

Results of the MONK5W broad group calculations are given in Appendix 1. k_{eff} predictions from each of the three runs are given together with the "1 σ " standard deviation. The mean result, plus its deviation, are then listed noting the improved accuracy. The experimental result is then compared and values of Calculation minus Experiment relative to Experiment ((C-E)/E) are given in terms of pcm ($\times 10^5$). Results are given for the five evaluations: J2U235 indicates JEF2.2; E6DU235 indicates the January 1996 evaluation of Derrien et Al, E6R2U235 refers to revision 2 of ENDF/B-VI, E6R3U235 specifies ENDF/B-VI revision 3 and finally E6ORU235 indicates the December 1996 preliminary evaluation from the ORNL study .

Appendix 2 contains results from the hyper-fine group MONK7 calculations. These are provided in the same structure.

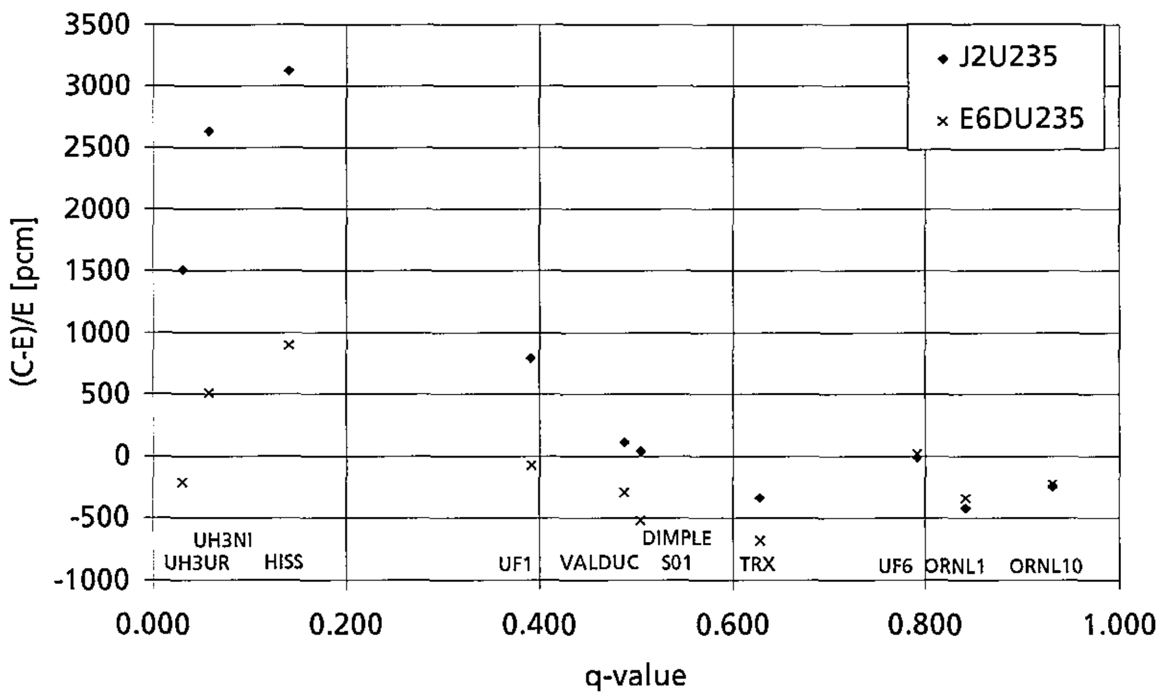
In order to compare (C-E)/E values from various countries, the JEF project suggests results be tabulated against "q":- the number of fission neutrons reaching 2.6eV. (Sometimes 4eV is used but it makes little difference.) A low value of "q" represents a hard spectrum; the softest system, with no resonance absorption, has a "q" of 1. The values of "q" used in the rest of the report were calculated from the J2U235 MONK7 results. We tabulate all further results accordingly.

The first table, below, compares broad and hyper-fine group results as predicted using JEF2.2.

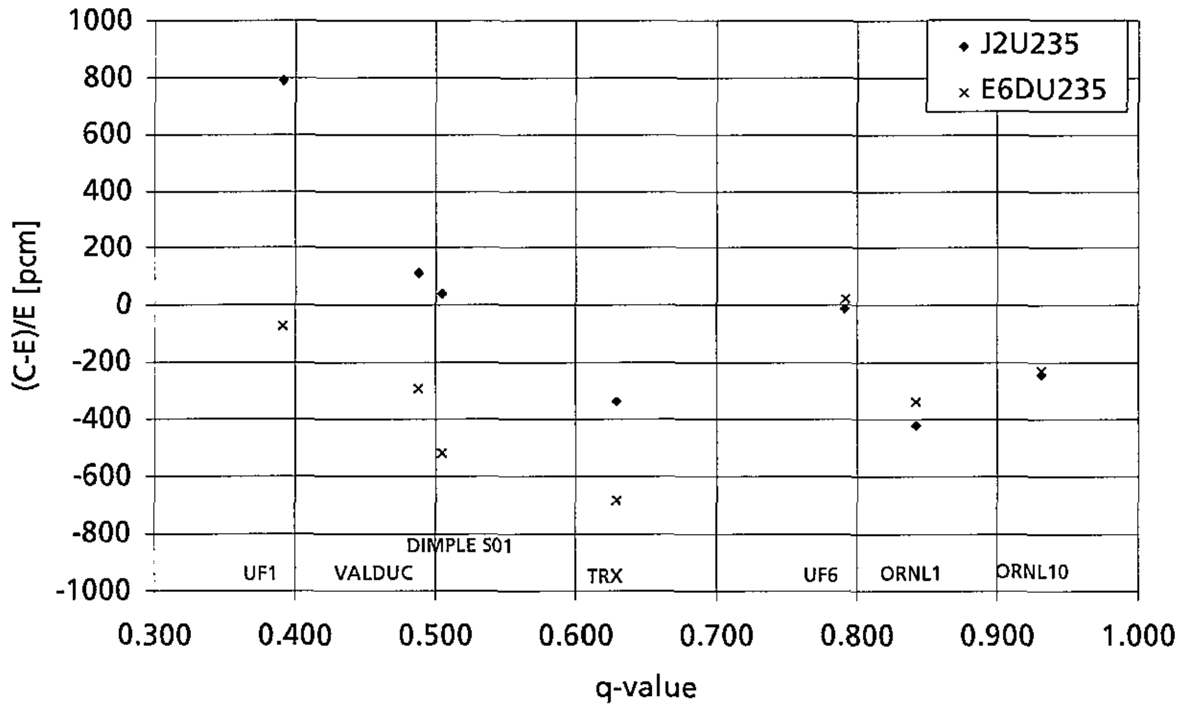
Case	q-value	MONK7 (C-E)/E	MONK5W (C-E)/E	Δ
UH3-UR	0.031	1506	1533	-27
UH3-NI	0.058	2630	6030	-3400
HISS (HUG)	0.140	3127	2847	280
U flouride 1	0.391	790	687	103
Valduc	0.488	110	170	-60
DIMPLE Assembly S01	0.504	37	53	-17
TRX1	0.629	-340	-523	183
U flouride 6	0.791	-13	-113	99
ORNL1	0.842	-423	-393	-30
ORNL10	0.931	-243	-300	57

The first two columns describe the case and spectrum softness. Hyper-fine group (MONK7) relative predictions of k_{eff} are followed by broad group results (MONK5W). Both are given in terms of pcm. Differences are also listed. If we consider an overall convergence to be within 100pcm, all but two cases compare with experiment within 2 σ. The HISS result may indicate a slight loss of accuracy in broad groups with hardening spectrum. The need to use fine group data for this assembly has been suggested in a private communication from C Durlston. However the Ni reflected Topsy result indicates that broad group methods cannot be applied due to the high energy resonance structure. Even if resonance shielding were applied, it would be very difficult to model, due to large variation over short distances at the inside edge of the reflector . Our conclusion is that fine group data are needed. Since this assembly is used in the USA we did not wish to find a substitute due to a method restriction.

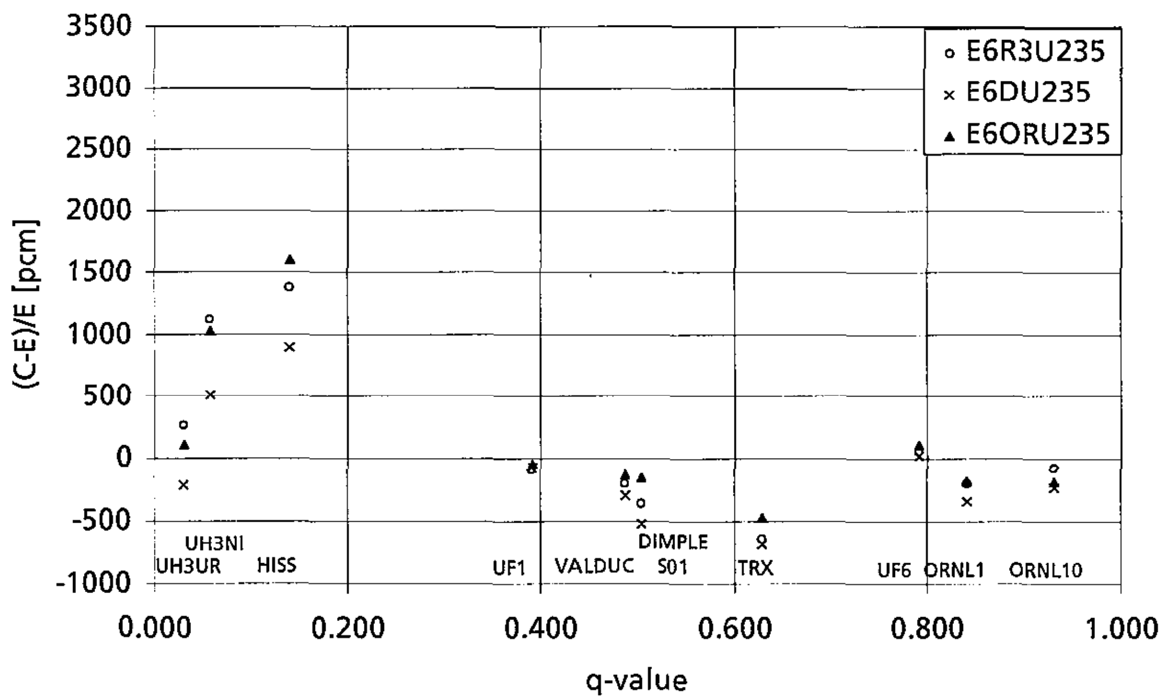
All further analysis in this report will use the hyper-fine group results.



The first figure compares JEF2.2 (J2U235) results with those from the January 1996 evaluation(E6DU235). This comparison shows the most radical change in the prediction of k_{eff}. It is worth noting that two gaps can be seen in the range of experiments studied as well as some overlap between DIMPLES01 and VALDUC. We could improve the analysis by finding a system with a "q" of about 3. However, the main trend is that the increased capture in the January 1996 evaluation has significantly improved the three hard spectra assemblies. It is important to question whether the new shape is random or indicative that systems similar to HISS are still predicted at about the 1% super-critical level. We have noted in section 4 that throughout the U235 evaluation work, the unresolved data have remained unchanged. This is hardly considered likely due to the radical changes made in the resolved range. It may be worth optimising an evaluation at these energies and investigating the impact on the hard assemblies before continuing with more in-depth analysis at lower energies.



The next figure above "zooms in" on the previous one to show the effect on the softer assemblies. i.e. when the three hard assemblies are removed. All calculations predict k_{eff} within ~0.5% (500pcm) except with the following experiments:- UF1 and DIMPLES01 with JEF2.2 and TRX with the January 1996 evaluation. There is little difference between evaluations for the soft assemblies (q above 0.8). Unfortunately DIMPLES01 is very important being similar to a PWR in terms of neutron spectrum.



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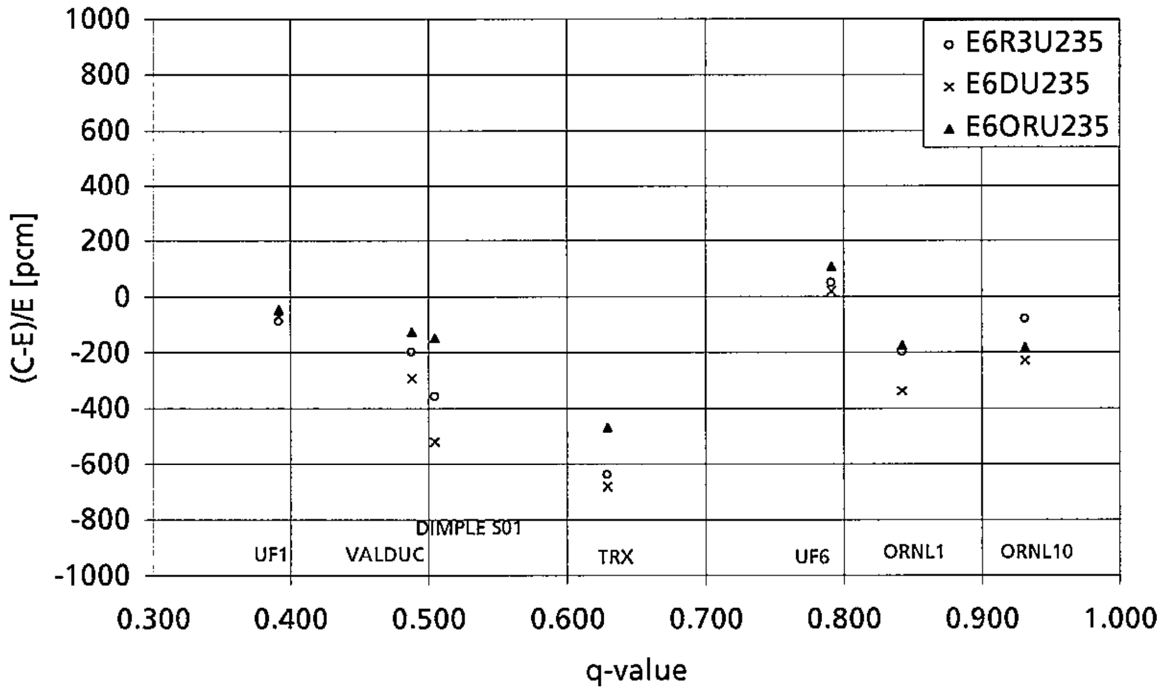
This figure above compares results for the three new evaluations which have been developed since the benchmarking of JEF2.2 and ENDF/B-VI revision 2 indicated the need to increase U235 resonance capture. The overall improvement from JEF2.2 can be seen by the lack of points above ~1500pcm. (The scale is the same as the first figure showing JEF2.2 data compared with the January 1996 evaluation.) The trend observed with the December 1996 ORNL evaluation is back towards ENDF/B-VI revision 3 results. Although it is often said the hard spectra assemblies are still over-predicted, this is indicated by only two out of the three assemblies. The results for UH3UR are now VERY good! The question raised earlier regarding the hard spectra is even more valid now that HISS results are ~1600 pcm high.



The figure above again excludes the results from the three hard assemblies and is plotted on the same scale as the previous "zoom" figure. Apart from TRX, all results with the new December 1996 ORNL evaluation are within 200 pcm. There is overall improvement over JEF2.2 results even in this range of "q".

7 Conclusions

1. A study of the impact of new U235 evaluations has been completed.
2. The use of selected benchmarks is required.
3. The use of MONK7 with hyper-fine group data predicts trends effectively.
4. Broad group analysis is not suitable for Ni reflected assemblies and possibly HISS.
5. Broad group trends are similar to fine group trends for other systems.

6. The impact of changes to data in the unresolved ranges should be considered.

7. The latest, preliminary, U235 evaluation leads to results similar to ENDF/B-VI revision 3.

8. The improvement to hard spectra HISS and UH3-Ni assemblies by using the January 1996 evaluation is lost in the December 1996 ORNL version.

9. Very good results are now obtained for the other hard system - UH3-UR.

10. Results with the 1996 ORNL evaluation are within 200 pcm for seven of the ten assemblies.

11. Improvements are still needed to the U235 evaluations.

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Appendices

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Appendix 1
WIMS7(MONK5W) Broad Group Results

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DIMPLE Assembly S01

Run	U235 k-eff	U235 Standard Deviation	U235E6D k-eff	U235E6D Standard Deviation	U235E6R2 k-eff	U235E6R2 Standard Deviation	U235E6R3 k-eff	U235E6R3 Standard Deviation	U235E6OR k-eff	U235E6OR Standard Deviation
1	1.0002	0.0014	0.9952	0.0014	0.9974	0.0014	0.9994	0.0014	1.0013	0.0015
2	1.0005	0.0014	0.9968	0.0014	0.9979	0.0014	0.9967	0.0014	0.9993	0.0014
3	1.0009	0.0014	0.9949	0.0014	0.9997	0.0014	0.9955	0.0014	0.9991	0.0014
Mean	1.0005	0.0008	0.9956	0.0008	0.9983	0.0008	0.9972	0.0008	0.9998	0.0008
(C-E)/E	53	81	-437	81	-167	81	-280	81	-16	83

HISS (HUG)

Run	U235 k-eff	U235 Standard Deviation	U235E6D k-eff	U235E6D Standard Deviation	U235E6R2 k-eff	U235E6R2 Standard Deviation	U235E6R3 k-eff	U235E6R3 Standard Deviation	U235E6OR k-eff	U235E6OR Standard Deviation
1	1.0283	0.0004	1.0065	0.0004	1.0272	0.0004	1.0109	0.0004	1.0136	0.0004
2	1.0288	0.0004	1.0062	0.0003	1.0271	0.0004	1.0110	0.0004	1.0132	0.0004
3	1.0283	0.0004	1.0061	0.0003	1.0269	0.0004	1.0112	0.0004	1.0132	0.0004
Mean	1.0285	0.0002	1.0062	0.0002	1.0271	0.0002	1.0110	0.0002	1.0133	0.0002
(C-E)/E	2847	23	623	19	2707	23	1103	23	1333	23

ORNL1

Run	U235 k-eff	U235 Standard Deviation	U235E6D k-eff	U235E6D Standard Deviation	U235E6R2 k-eff	U235E6R2 Standard Deviation	U235E6R3 k-eff	U235E6R3 Standard Deviation	U235E6OR k-eff	U235E6OR Standard Deviation
1	0.9970	0.0008	0.9966	0.0008	0.9953	0.0011	0.9963	0.0008	0.9979	0.0008
2	0.9960	0.0008	0.9976	0.0007	0.9962	0.0008	0.9970	0.0008	0.9999	0.0008
3	0.9952	0.0008	0.9968	0.0008	0.9972	0.0007	0.9980	0.0008	1.0011	0.0008
Mean	0.9961	0.0005	0.9971	0.0004	0.9965	0.0005	0.9971	0.0005	0.9996	0.0005
(C-E)/E	-393	46	-294	44	-351	48	-290	46	-37	46

TRX1

Run	U235 k-eff	U235 Standard Deviation	U235E6D k-eff	U235E6D Standard Deviation	U235E6R2 k-eff	U235E6R2 Standard Deviation	U235E6R3 k-eff	U235E6R3 Standard Deviation	U235E6OR k-eff	U235E6OR Standard Deviation
1	0.9950	0.0008	0.9922	0.0009	0.9919	0.0008	0.9942	0.0008	0.9938	0.0009
2	0.9928	0.0009	0.9928	0.0009	0.9927	0.0008	0.9945	0.0008	0.9934	0.0009
3	0.9961	0.0008	0.9942	0.0009	0.9929	0.0008	0.9915	0.0009	0.9947	0.0008
Mean	0.9948	0.0005	0.9931	0.0005	0.9925	0.0005	0.9935	0.0005	0.9940	0.0005
(C-E)/E	-523	48	-693	52	-750	46	-646	48	-597	50

U flouride 6

Run	U235		U235E6D		U235E6R2		U235E6R3		U235E6OR	
	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation
1	1.0009	0.0007	0.9992	0.0008	1.0003	0.0008	1.0013	0.0011	1.0023	0.0008
2	0.9984	0.0008	1.0005	0.0008	0.9970	0.0008	0.9984	0.0008	1.0012	0.0008
3	0.9967	0.0008	0.9966	0.0011	0.9999	0.0008	1.0015	0.0008	0.9997	0.0008
Mean	0.9989	0.0004	0.9992	0.0005	0.9991	0.0005	1.0002	0.0005	1.0011	0.0005
(C-E)/E	-113	44	-83	50	-93	46	23	50	107	46

Valduc

Run	U235		U235E6D		U235E6R2		U235E6R3		U235E6OR	
	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation
1	1.0003	0.0016	1.0003	0.0017	1.0010	0.0016	0.9989	0.0016	1.0032	0.0016
2	1.0017	0.0016	0.9979	0.0017	0.9979	0.0017	1.0004	0.0016	1.0028	0.0016
3	1.0031	0.0016	0.9964	0.0016	0.9978	0.0016	0.9996	0.0016	1.0008	0.0016
Mean	1.0017	0.0009	0.9981	0.0010	0.9989	0.0009	0.9996	0.0009	1.0023	0.0009
(C-E)/E	170	92	-187	96	-106	94	-37	92	227	92

UH3-NI

Run	U235		U235E6D		U235E6R2		U235E6R3		U235E6OR	
	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation
1	1.0614	0.0016	1.0423	0.0016	1.0577	0.0017	1.0440	0.0016	1.0463	0.0016
2	1.0608	0.0016	1.0400	0.0016	1.0574	0.0016	1.0466	0.0016	1.0454	0.0016
3	1.0587	0.0016	1.0401	0.0016	1.0612	0.0016	1.0450	0.0016	1.0451	0.0016
Mean	1.0603	0.0009	1.0408	0.0009	1.0588	0.0009	1.0452	0.0009	1.0456	0.0009
(C-E)/E	6030	92	4080	92	5881	94	4520	92	4560	92

UH3-UR

Run	U235		U235E6D		U235E6R2		U235E6R3		U235E6OR	
	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation
1	1.0173	0.0014	0.9991	0.0015	1.0159	0.0015	1.0028	0.0014	1.0000	0.0015
2	1.0138	0.0015	0.9984	0.0015	1.0143	0.0015	1.0058	0.0014	1.0008	0.0014
3	1.0146	0.0015	0.9968	0.0015	1.0133	0.0014	0.9976	0.0014	1.0016	0.0014
Mean	1.0153	0.0008	0.9981	0.0009	1.0144	0.0008	1.0021	0.0008	1.0008	0.0008
(C-E)/E	1533	85	-190	87	1444	85	207	81	84	83

ORNL10

Run	U235		U235E6D		U235E6R2		U235E6R3		U235E6OR	
	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation
1	0.9957	0.0000	0.9973	0.0000	0.9964	0.0000	0.9987	0.0000	0.9982	0.0000
2	0.9969	0.0000	0.9992	0.0000	0.9967	0.0000	0.9994	0.0000	0.9984	0.0000
3	0.9984	0.0000	0.9988	0.0000	0.9981	0.0000	0.9991	0.0000	0.9997	0.0000
Mean	0.9970	0.0000	0.9984	0.0000	0.9971	0.0000	0.9991	0.0000	0.9988	0.0000
(C-E)/E	-300	0	-157	0	-293	0	-93	0	-123	0

U flouride 1

Run	U235		U235E6D		U235E6R2		U235E6R3		U235E6OR	
	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation
1	1.0052	0.0018	1.0013	0.0018	1.0060	0.0017	1.0017	0.0018	1.0019	0.0018
2	1.0085	0.0018	1.0002	0.0017	1.0063	0.0018	0.9989	0.0017	1.0032	0.0017
3	1.0069	0.0017	0.9959	0.0017	1.0070	0.0017	1.0020	0.0017	1.0014	0.0018
Mean	1.0069	0.0010	0.9991	0.0010	1.0064	0.0010	1.0008	0.0010	1.0022	0.0010
(C-E)/E	687	102	-95	100	644	100	84	100	221	102

Appendix 2
MONK7 Hyper-fine Group Results

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DIMPLE Assembly S01

Run	J2U235 k-eff	J2U235 Standard Deviation	E6DU235 k-eff	E6DU235 Standard Deviation	E6R2U235 k-eff	E6R2U235 Standard Deviation	E6R3U235 k-eff	E6R3U235 Standard Deviation	E6ORU235 k-eff	E6ORU235 Standard Deviation
1	0.9997	0.0010	0.9932	0.0010	0.9982	0.0010	0.9952	0.0010	0.9978	0.0010
2	0.9997	0.0010	0.9954	0.0010	0.9980	0.0010	0.9974	0.0010	0.9998	0.0010
3	1.0017	0.0010	0.9958	0.0010	0.9989	0.0010	0.9966	0.0010	0.9979	0.0010
Mean	1.0004	0.0006	0.9948	0.0006	0.9984	0.0006	0.9964	0.0006	0.9985	0.0006
(C-E)/E	37	58	-520	58	-163	58	-360	58	-150	58

HISS (HUG)

Run	J2U235 k-eff	J2U235 Standard Deviation	E6DU235 k-eff	E6DU235 Standard Deviation	E6R2U235 k-eff	E6R2U235 Standard Deviation	E6R3U235 k-eff	E6R3U235 Standard Deviation	E6ORU235 k-eff	E6ORU235 Standard Deviation
1	1.0316	0.0003	1.0089	0.0003	1.0300	0.0003	1.0138	0.0003	1.0160	0.0003
2	1.0314	0.0003	1.0093	0.0003	1.0298	0.0003	1.0139	0.0003	1.0161	0.0003
3	1.0308	0.0003	1.0087	0.0003	1.0299	0.0003	1.0136	0.0003	1.0159	0.0003
Mean	1.0313	0.0002	1.0090	0.0002	1.0299	0.0002	1.0138	0.0002	1.0160	0.0002
(C-E)/E	3127	17	897	17	2990	17	1377	17	1600	17

ORNL1

Run	J2U235 k-eff	J2U235 Standard Deviation	E6DU235 k-eff	E6DU235 Standard Deviation	E6R2U235 k-eff	E6R2U235 Standard Deviation	E6R3U235 k-eff	E6R3U235 Standard Deviation	E6ORU235 k-eff	E6ORU235 Standard Deviation
1	0.9956	0.0010	0.9984	0.0010	0.9985	0.0010	0.9981	0.0010	0.9976	0.0010
2	0.9960	0.0010	0.9950	0.0010	0.9971	0.0010	0.9975	0.0010	0.9978	0.0010
3	0.9957	0.0010	0.9964	0.0010	0.9977	0.0010	0.9984	0.0010	0.9993	0.0010
Mean	0.9958	0.0006	0.9966	0.0006	0.9978	0.0006	0.9980	0.0006	0.9982	0.0006
(C-E)/E	-423	58	-340	58	-223	58	-200	58	-177	58

TRX1

Run	J2U235 k-eff	J2U235 Standard Deviation	E6DU235 k-eff	E6DU235 Standard Deviation	E6R2U235 k-eff	E6R2U235 Standard Deviation	E6R3U235 k-eff	E6R3U235 Standard Deviation	E6ORU235 k-eff	E6ORU235 Standard Deviation
1	0.9967	0.0010	0.9929	0.0010	0.9939	0.0010	0.9940	0.0010	0.9935	0.0010
2	0.9966	0.0010	0.9934	0.0010	0.9940	0.0010	0.9935	0.0010	0.9968	0.0010
3	0.9965	0.0010	0.9932	0.0010	0.9957	0.0010	0.9933	0.0010	0.9956	0.0010
Mean	0.9966	0.0006	0.9932	0.0006	0.9945	0.0006	0.9936	0.0006	0.9953	0.0006
(C-E)/E	-340	58	-683	58	-547	58	-640	58	-470	58

U flouride 6

Run	J2U235		E6DU235		E6R2U235		E6R3U235		E6ORU235	
	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation
1	1.0001	0.0010	1.0009	0.0010	0.9986	0.0010	1.0000	0.0010	1.0019	0.0010
2	0.9992	0.0010	1.0004	0.0010	0.9993	0.0010	1.0012	0.0010	1.0011	0.0010
3	1.0003	0.0010	0.9993	0.0010	0.9988	0.0010	1.0003	0.0010	1.0002	0.0010
Mean	0.9999	0.0006	1.0002	0.0006	0.9989	0.0006	1.0005	0.0006	1.0011	0.0006
(C-E)/E	-13	58	20	58	-110	58	50	58	107	58

Valduc

Run	J2U235		E6DU235		E6R2U235		E6R3U235		E6ORU235	
	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation
1	1.0012	0.0010	0.9965	0.0010	0.9995	0.0010	0.9978	0.0010	0.9972	0.0010
2	1.0009	0.0010	0.9964	0.0010	1.0025	0.0010	0.9984	0.0010	1.0002	0.0010
3	1.0012	0.0010	0.9983	0.0010	0.9990	0.0010	0.9978	0.0010	0.9988	0.0010
Mean	1.0011	0.0006	0.9971	0.0006	1.0003	0.0006	0.9980	0.0006	0.9987	0.0006
(C-E)/E	110	58	-293	58	33	58	-200	58	-127	58

UH3-NI

Run	J2U235		E6DU235		E6R2U235		E6R3U235		E6ORU235	
	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation
1	1.0275	0.0013	1.0060	0.0013	1.0278	0.0013	1.0119	0.0013	1.0109	0.0013
2	1.0275	0.0013	1.0037	0.0013	1.0229	0.0014	1.0103	0.0013	1.0101	0.0013
3	1.0239	0.0013	1.0055	0.0013	1.0234	0.0014	1.0113	0.0013	1.0099	0.0013
Mean	1.0263	0.0008	1.0051	0.0008	1.0249	0.0008	1.0112	0.0008	1.0103	0.0008
(C-E)/E	2630	75	507	75	2486	79	1117	75	1030	75

UH3-UR

Run	J2U235		E6DU235		E6R2U235		E6R3U235		E6ORU235	
	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation
1	1.0150	0.0014	0.9977	0.0014	1.0156	0.0014	1.0004	0.0014	1.0009	0.0014
2	1.0149	0.0015	0.9983	0.0014	1.0138	0.0014	1.0032	0.0014	1.0027	0.0014
3	1.0153	0.0015	0.9976	0.0014	1.0148	0.0014	1.0042	0.0014	0.9996	0.0014
Mean	1.0151	0.0008	0.9979	0.0008	1.0147	0.0008	1.0026	0.0008	1.0011	0.0008
(C-E)/E	1506	85	-213	81	1473	81	260	81	107	81

ORNL10

Run	J2U235		E6DU235		E6R2U235		E6R3U235		E6ORU235	
	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation
1	0.9972	0.0006	0.9969	0.0006	0.9977	0.0006	0.9988	0.0006	0.9983	0.0007
2	0.9981	0.0006	0.9989	0.0006	0.9993	0.0006	0.9990	0.0006	0.9984	0.0006
3	0.9974	0.0006	0.9973	0.0006	0.9975	0.0006	0.9998	0.0006	0.9977	0.0007
Mean	0.9976	0.0003	0.9977	0.0003	0.9982	0.0003	0.9992	0.0003	0.9982	0.0004
(C-E)/E	-243	35	-230	35	-183	35	-80	35	-184	38

U flouride 1

Run	J2U235		E6DU235		E6R2U235		E6R3U235		E6ORU235	
	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation	k-eff	Standard Deviation
1	1.0081	0.0011	1.0003	0.0011	1.0055	0.0011	0.9978	0.0011	0.9996	0.0011
2	1.0082	0.0011	1.0002	0.0011	1.0050	0.0011	1.0000	0.0011	1.0002	0.0011
3	1.0074	0.0011	0.9973	0.0011	1.0052	0.0011	0.9995	0.0011	0.9988	0.0011
Mean	1.0079	0.0006	0.9993	0.0006	1.0052	0.0006	0.9991	0.0006	0.9995	0.0006
(C-E)/E	790	64	-73	64	523	64	-90	64	-47	64