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A new UK fission yield evaluation – UKFY3.7

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Summary of talk

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- New fission yield Evaluation UKFY3.7
  - ★History of UK evaluations
  - ★Evaluation process
  - ★New data
  - ★New models
- Initial testing of the new library
  - ★ ν_d
  - ★Fission “pulse” decay heat
  - ★PWR fuel assemblies decay heat
  - ★Conclusions
- Future work
  - ★Uncertainties/covariance
  - ★New measurement types
  - ★Energy dependence
- Acknowledgements

UK Fission Yield Library History

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- Fission yield libraries for computer calculations were pioneered in the UK by Eric Crouch in the 1960’s resulting in the C1, C2, C3, C4 libraries.

- Following his retirement, the work continued with

- UKFY1 1986 (JEF-1) Banai, James and Weaver.
- UKFY2 1993 (JEF-2.2) Mills, James and Weaver.

  …
- UKFY3.6A 2005/7 (JEFF-3.1.1) Mills

UK evaluation process

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- Six steps
  - ★Collect measurements and analyse to give recommended values and uncertainties.
  - ★Fill gaps in fission yield mass and charge distributions with model calculations for important fissioning systems.
  - ★Adjust independent yields for physical constraints; mass, charge, complementary fragment yields …
  - ★Split independent yields to isomeric states (Madland and England)
  - ★Calculate cumulative yields from independent yields and using experimental cumulative yields calculate uncertainties.
  - ★Produce data in ENDF format.

Important fissioning systems

Max. Fraction of Fission Rate			
>10%	1-10%	0.1%-1%	Spont. fission
nuclides: 5	2	12	3
*^{233}U TFH *^{235}U TFH *^{238}U FH *^{239}Pu TF *^{241}Pu TF	*^{240}Pu F ^{245}Cm TF	*^{232}Th FH ^{234}U F ^{236}U F ^{237}Np TF ^{238}Np TF ^{238}Pu TF ^{242}Pu F ^{241}Am TF ^{242m}Am TF ^{243}Am TF ^{243}Cm TF ^{244}Cm TF	^{252}Cf Sp ^{242}Cm Sp ^{244}Cm Sp

* Nuclides in UKFY1 and previous UK libraries.
T Thermal fission.
F Fast fission.
H 14Mev Fission.
Sp Spontaneous fission.

New data

- Existing data for JEFF-3.1.1 frozen around 2000.
- JEFF community and literature search identified 10 new important references suitable for evaluation.
- In 2016 one new fast reference published and included.
- Included these in the database and reanalysed.

Dataset	Absolute	Relative	"ratio of ratio"	Total
UKFY3.6A	11887	1352	1471	14710
UKFY3.7	12924	1442	1471	15837

New data

- New data split into systems:

Neutron spectra	Fissioning nuclide	UKFY3.6	New data	UKFY3.7
Thermal	Th229	337	72	409
Thermal	U233	757	188	945
Thermal	U235	2390	151	2541
Thermal	Np238	115	63	178
Thermal	Pu239	861	225	1086
Thermal	Pu241	334	63	397
Thermal	Cm245	161	219	380
Thermal	Cf249	305	239	544
Fast	U235	724	5	729
Fast	Pu239	390	5	395
Fast	Pu241	111	5	116

- Fast yields refer to Neodymium cumulative yields.

New data

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- Effect of new fast yields on Nd148 cumulative yields.

Fissioning nuclide	UKFY3.7	UKFY3.6A
U235	1.677 ± 0.020	1.696 ± 0.019
Pu239	1.700 ± 0.029	1.699 ± 0.025
Pu241	1.943 ± 0.041	1.946 ± 0.045

Results of new data- U233 Thermal neutron fission

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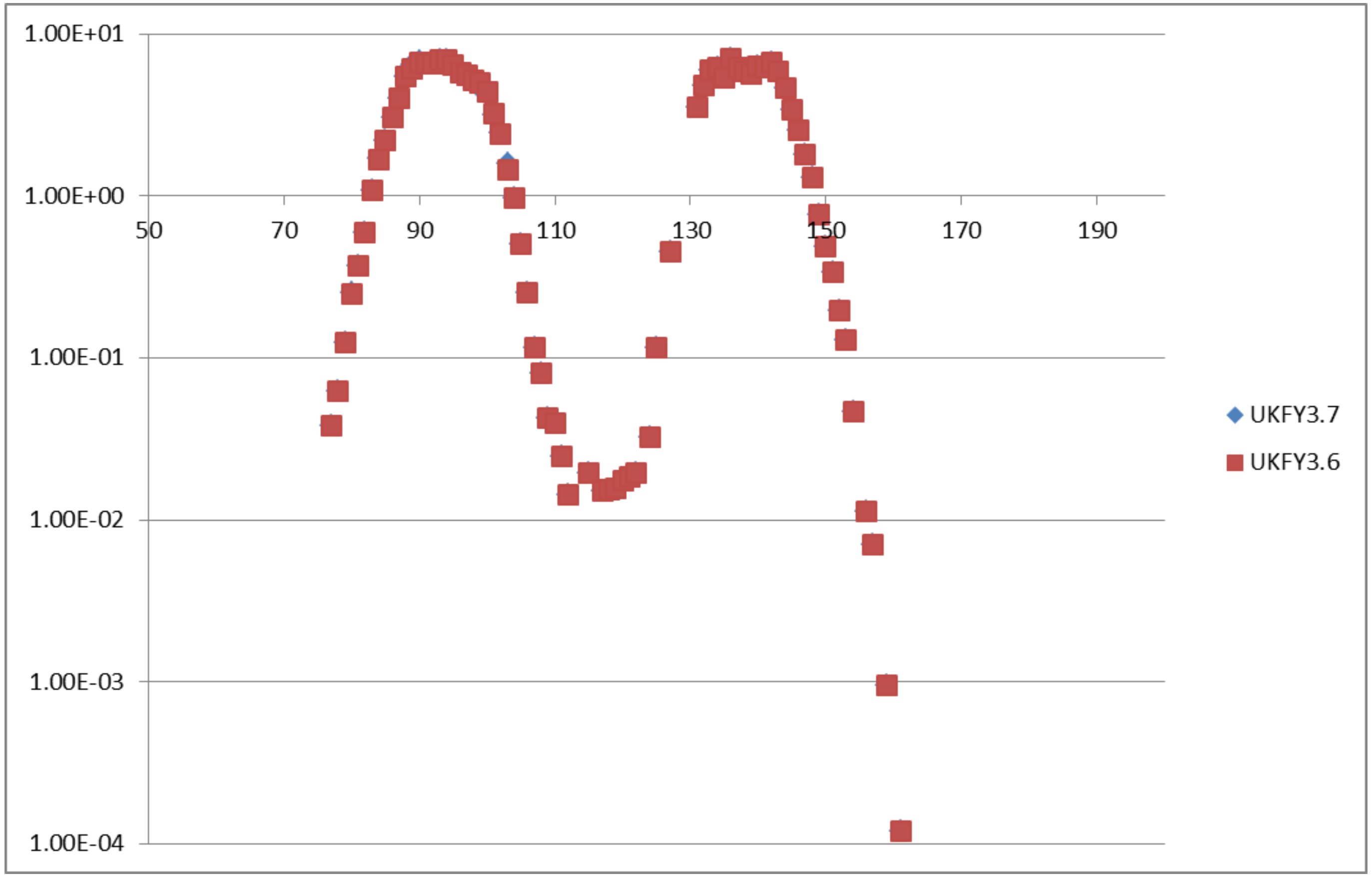

Results of new data- U233 Thermal neutron fission

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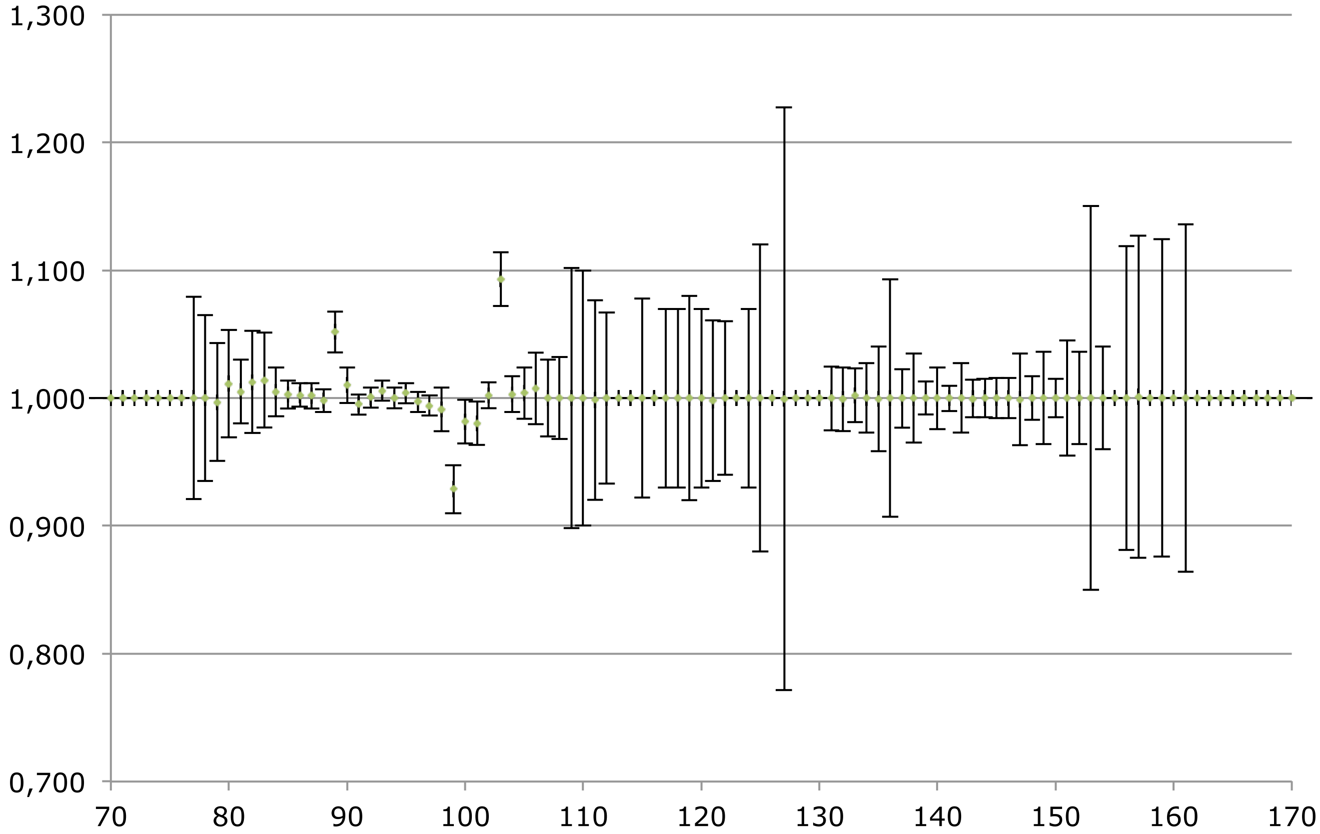
Ratio to UKFY3.6A



Results of new data- U235 Thermal neutron fission

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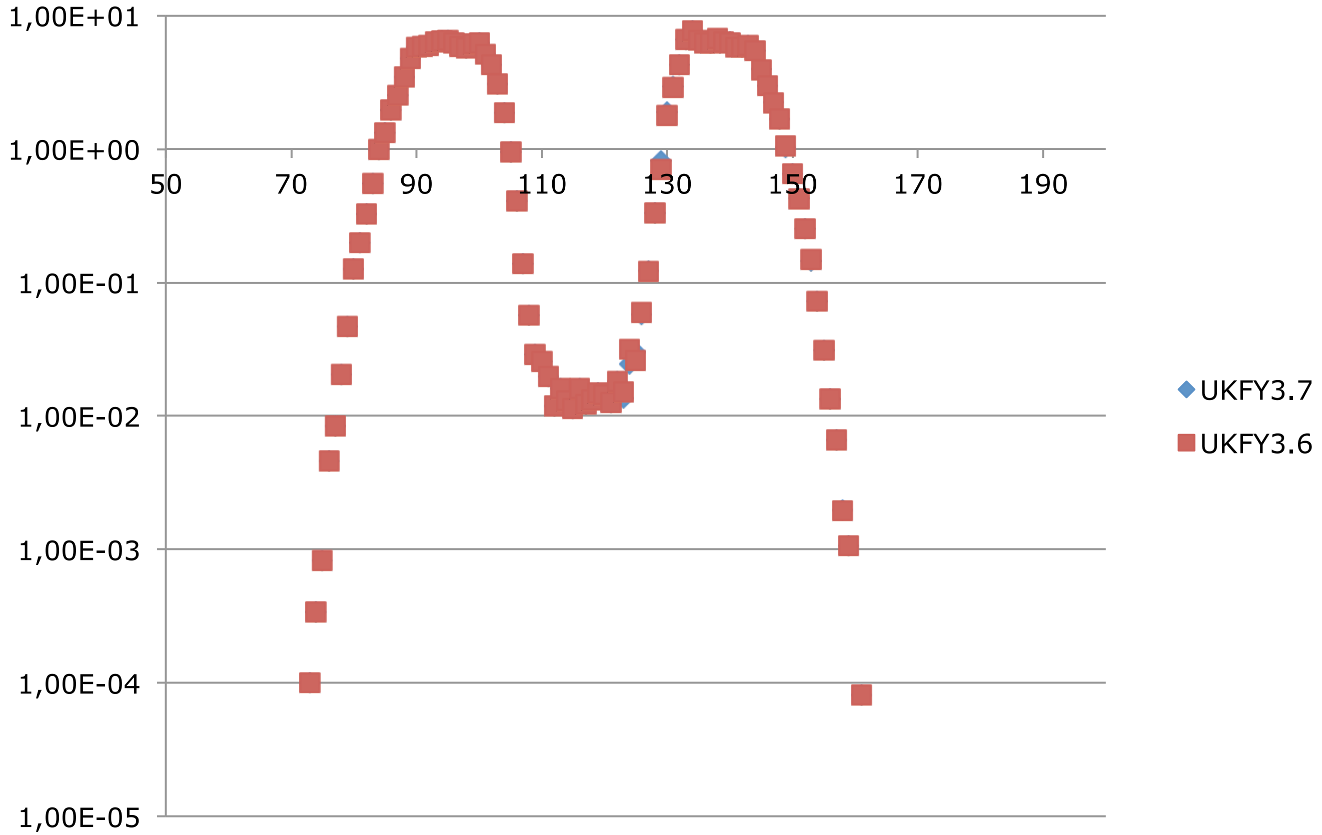

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Results of new data- U233 Thermal neutron fission

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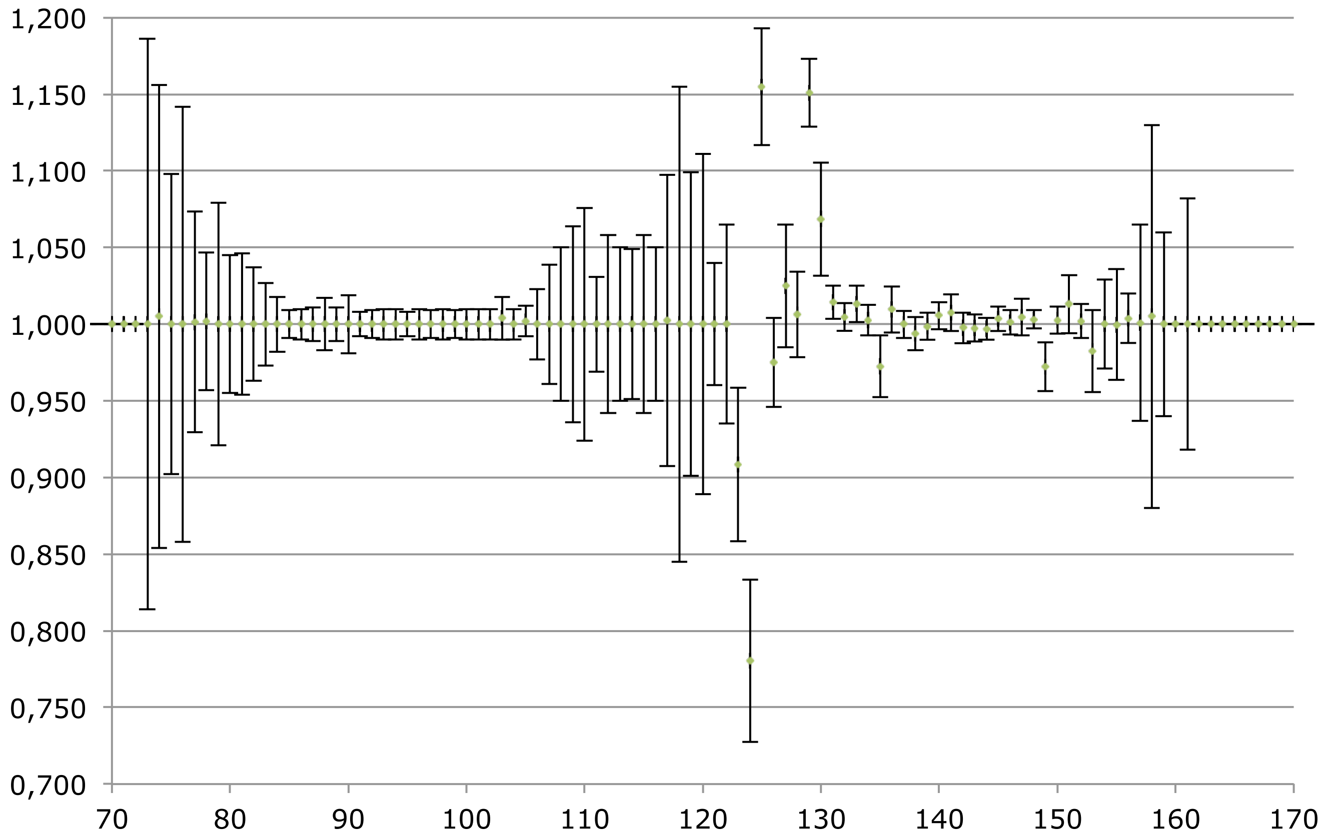
Ratio to UKFY3.6A



Results of new data- Np238 Thermal neutron fission

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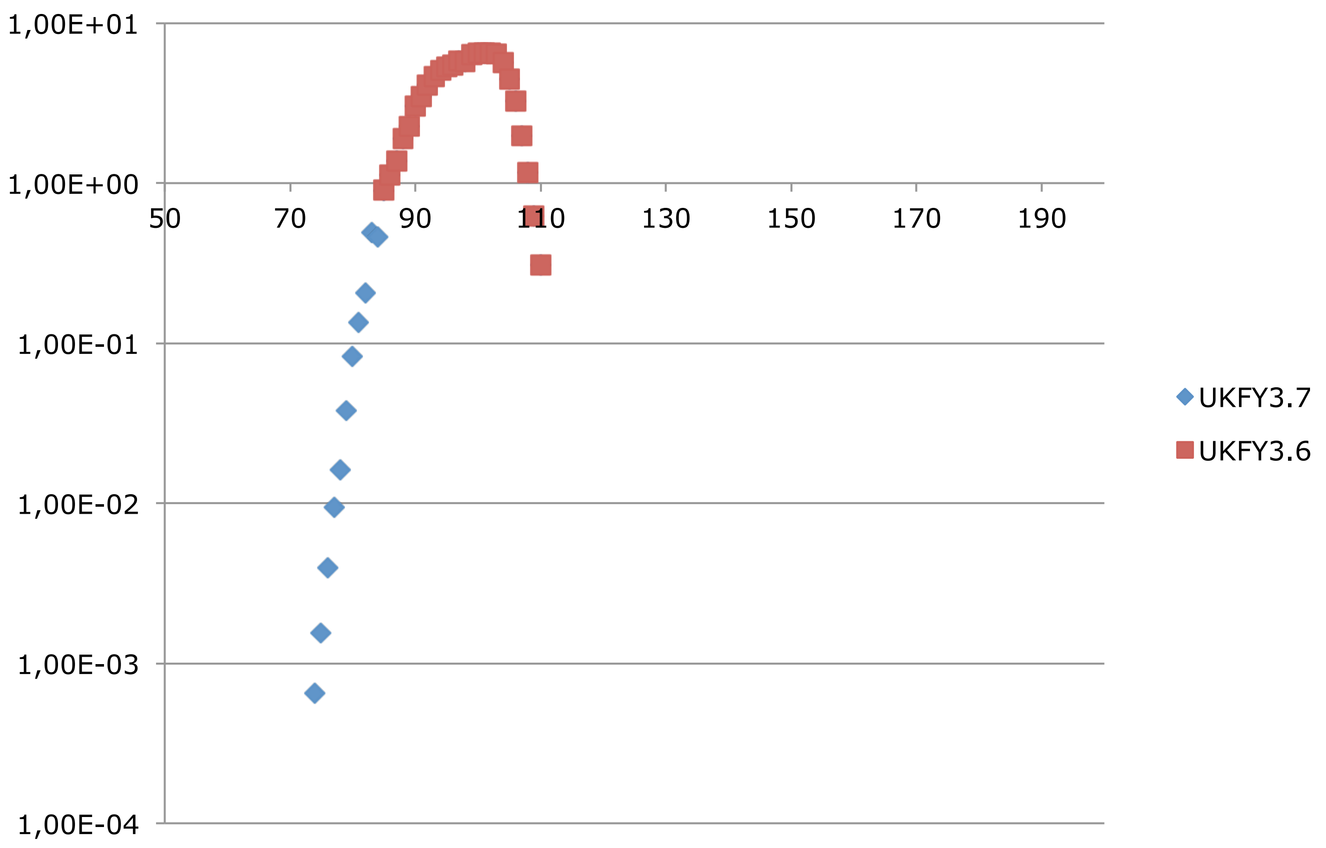

Results of new data- Np238 Thermal neutron fission

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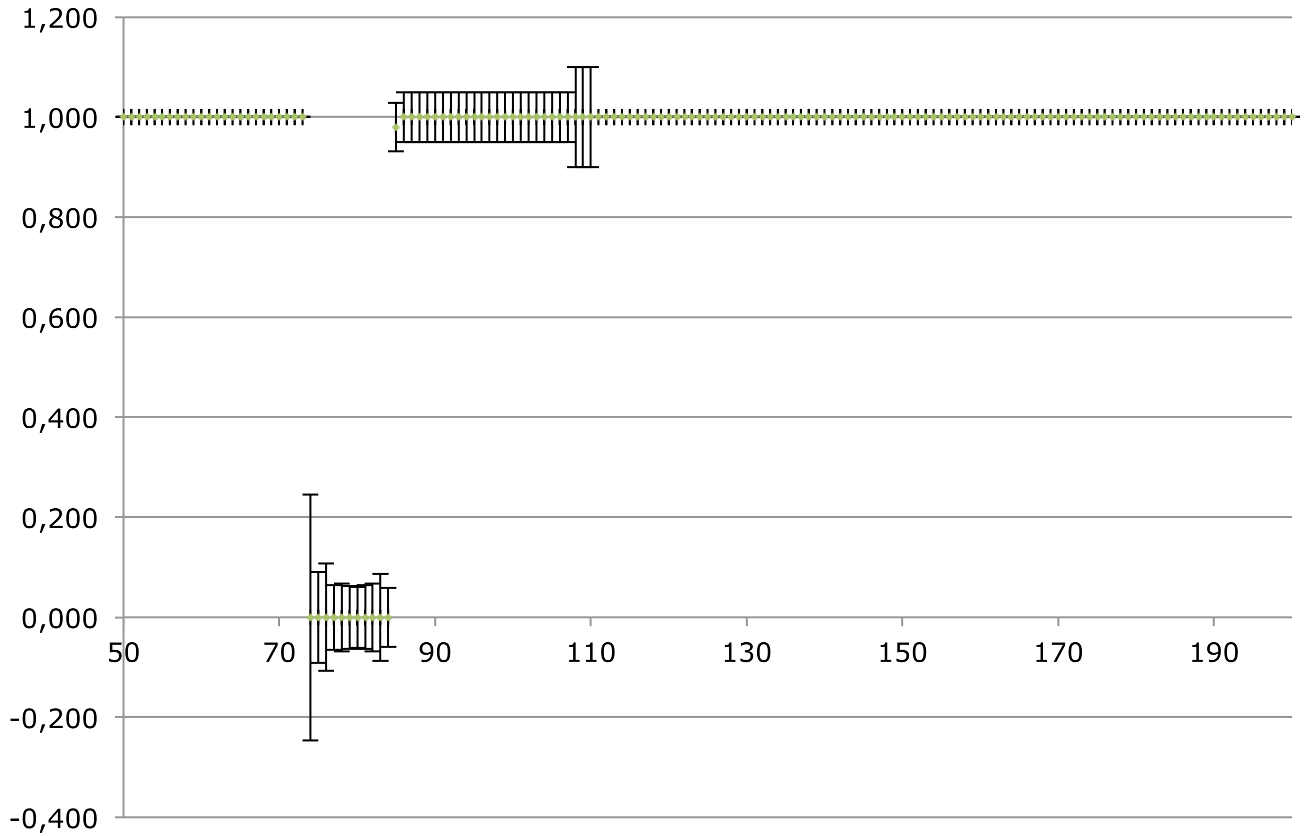
Ratio to UKFY3.6A



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Results of new data- Pu239 Thermal neutron fission

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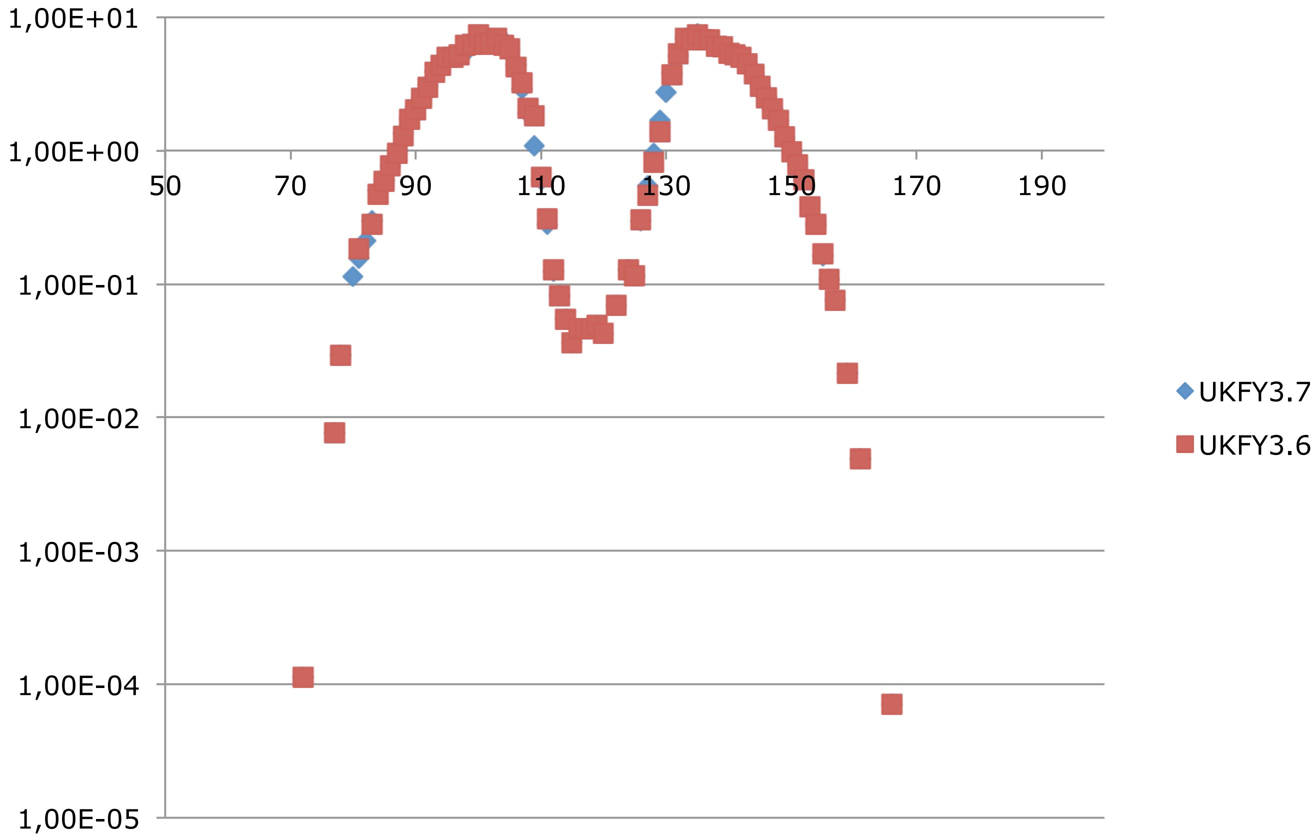

Results of new data- Pu239 Thermal neutron fission

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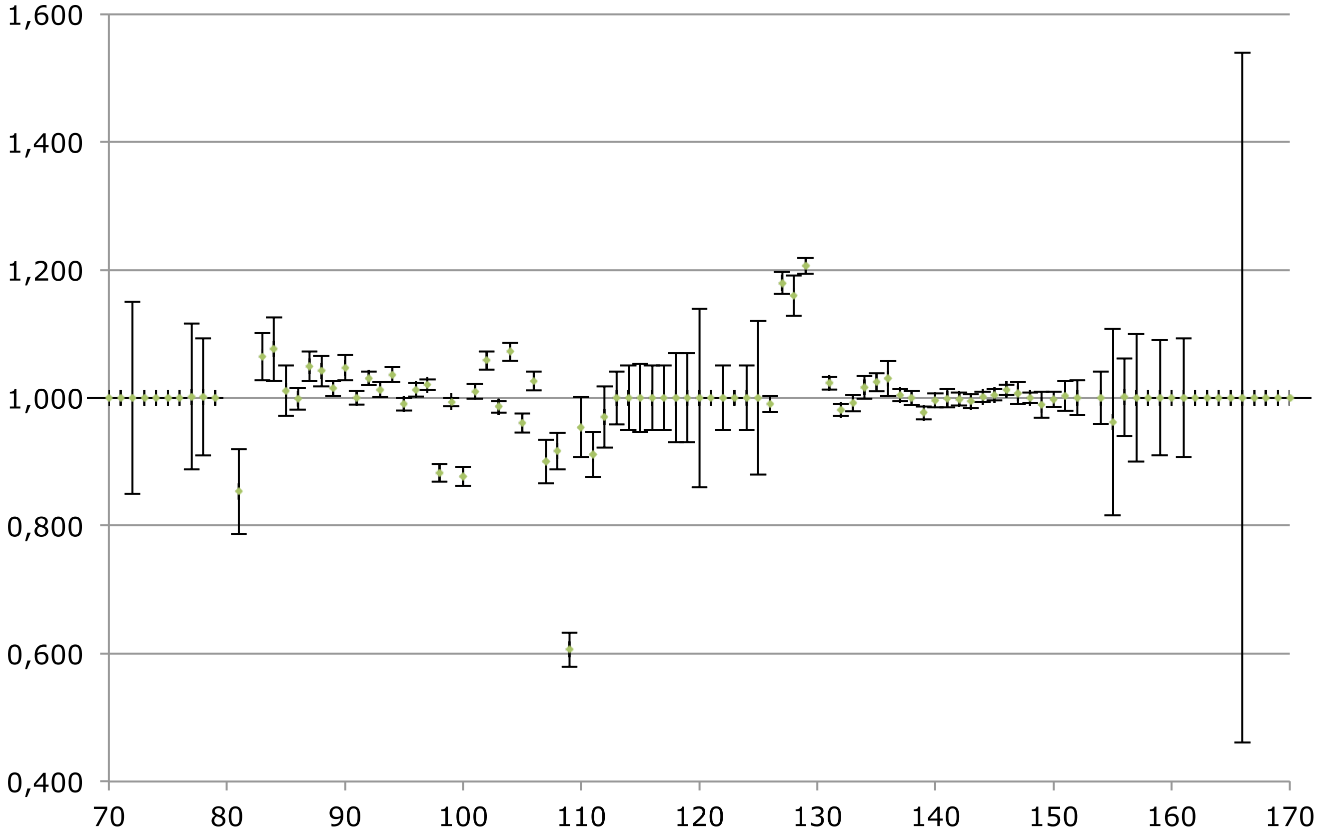
Ratio to UKFY3.6A



Results of new data- Pu241 Thermal neutron fission

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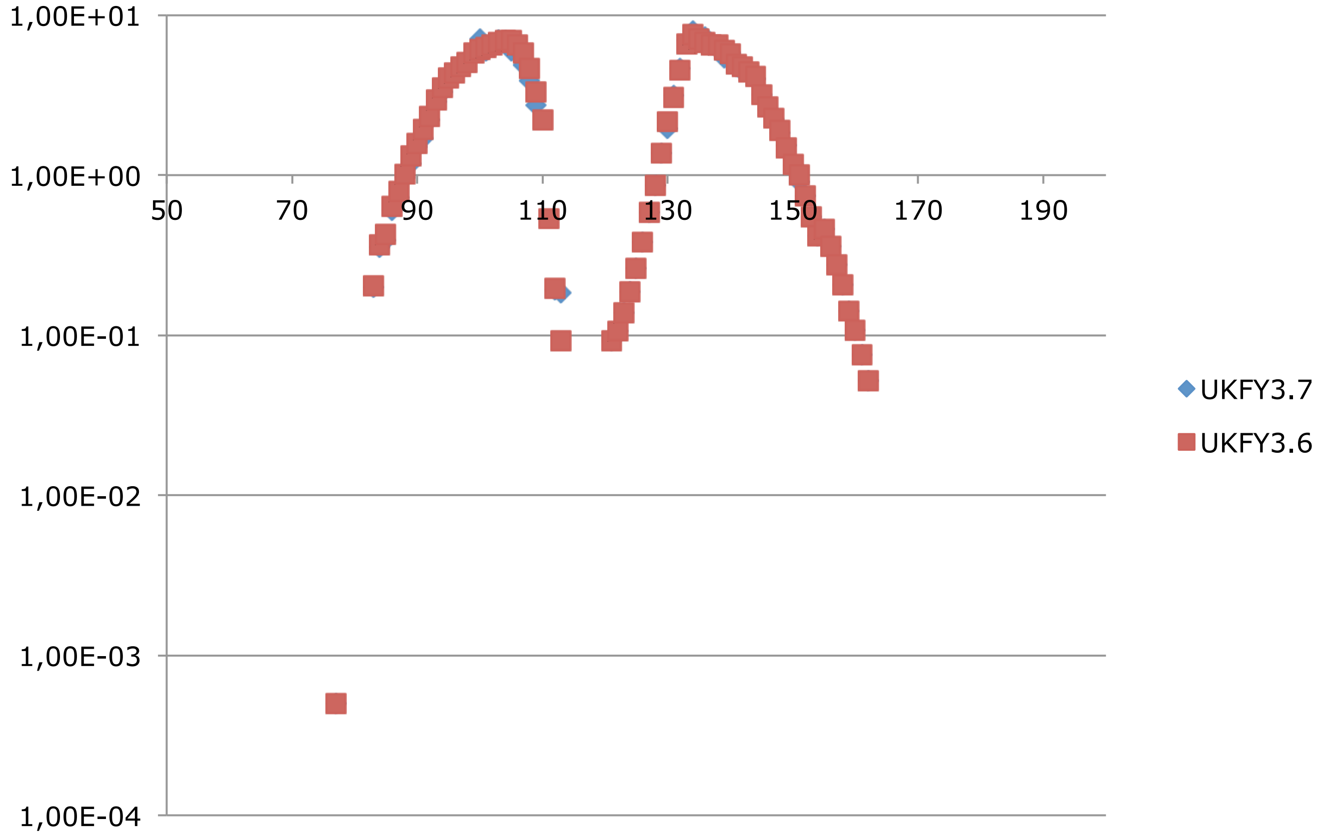

Results of new data- Pu241 Thermal neutron fission

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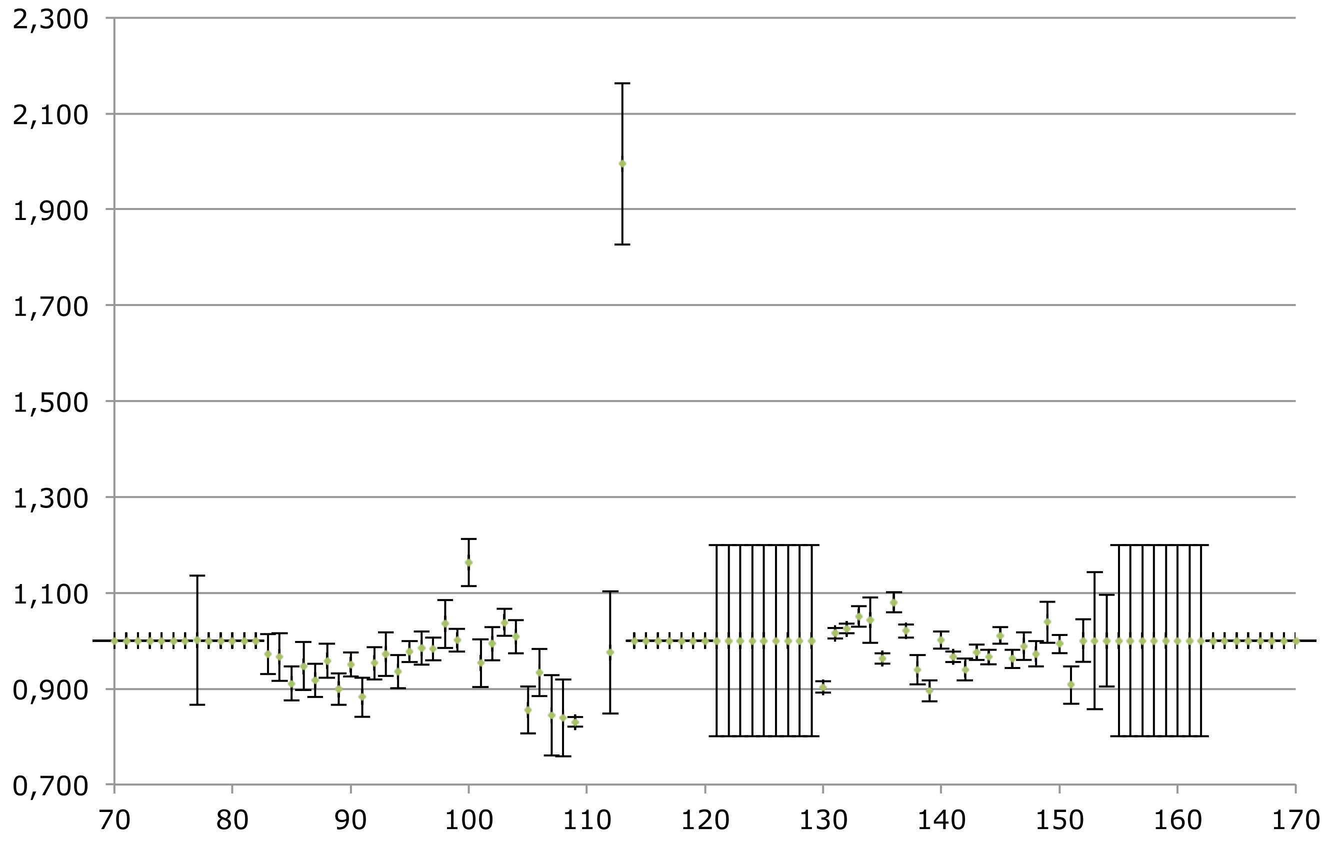
Ratio to UKFY3.6A



Results of new data- Cm245 Thermal neutron fission

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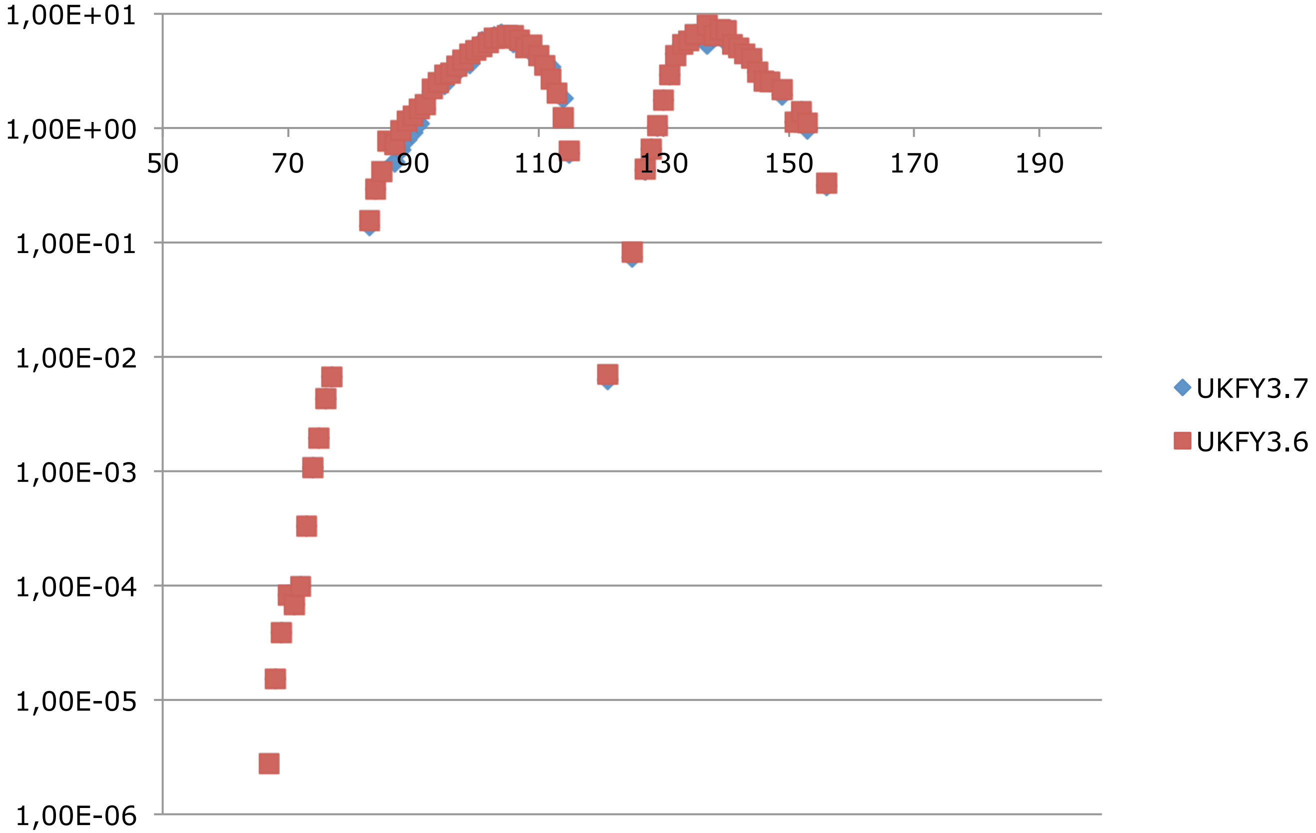

Results of new data- Cm245 Thermal neutron fission

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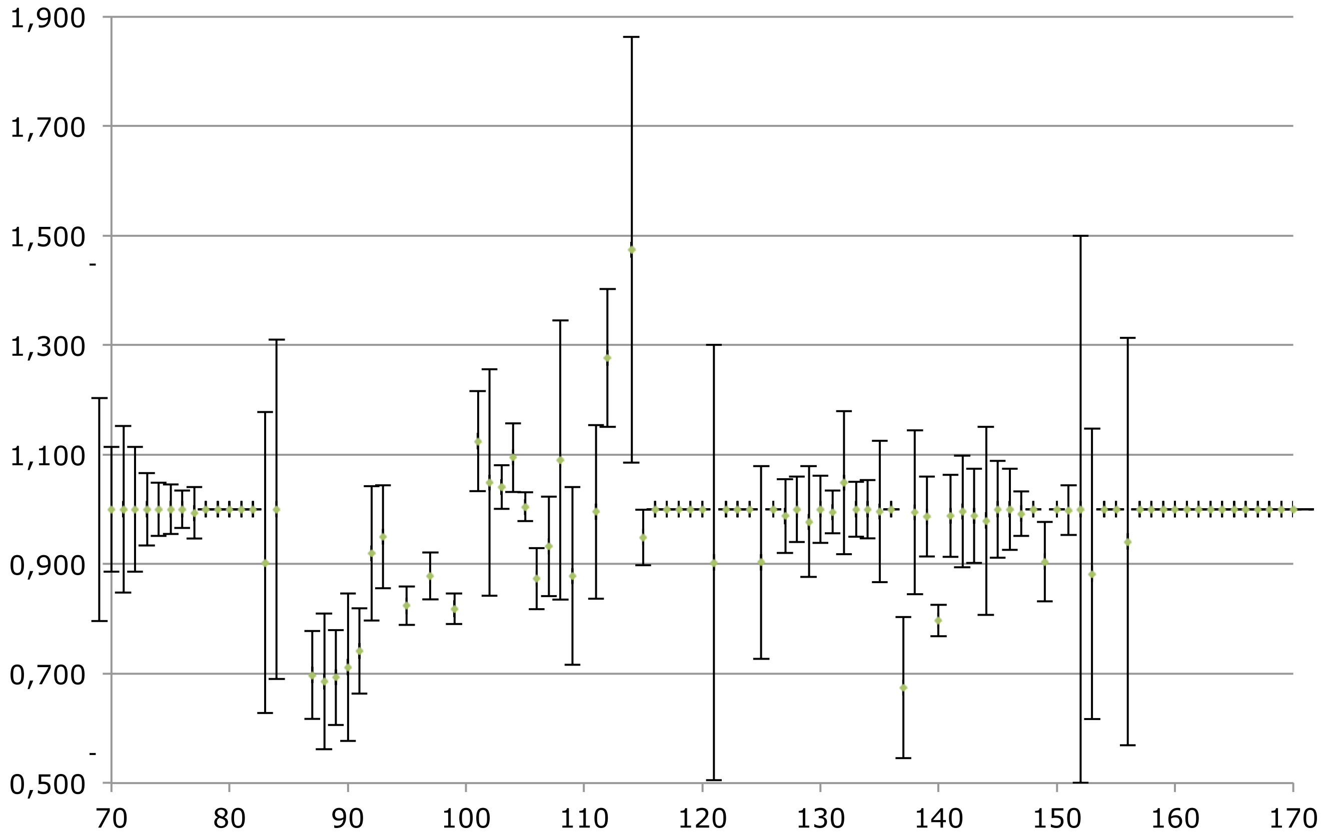
Ratio to UKFY3.6A



Results of new data- Cf249 Thermal neutron fission

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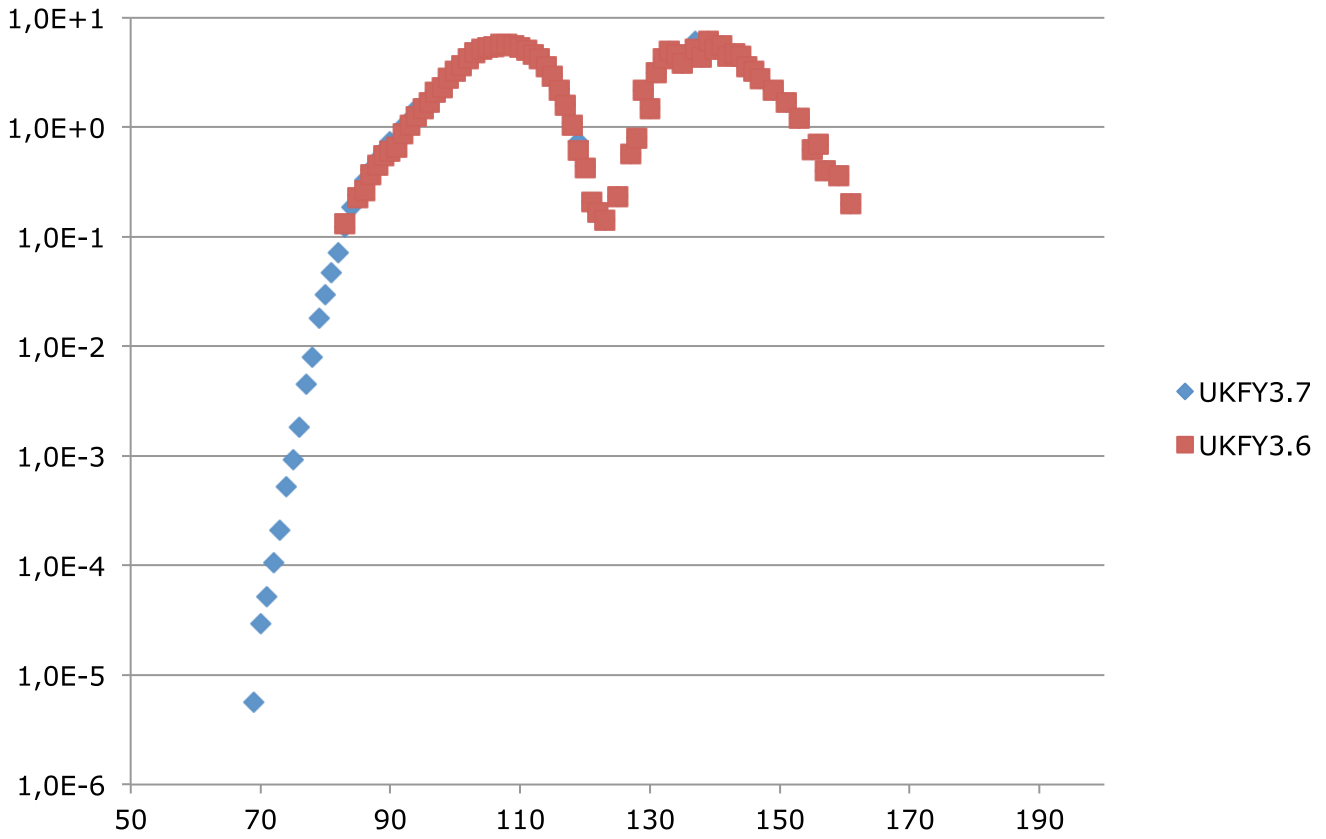

Results of new data- Cm245 Thermal neutron fission

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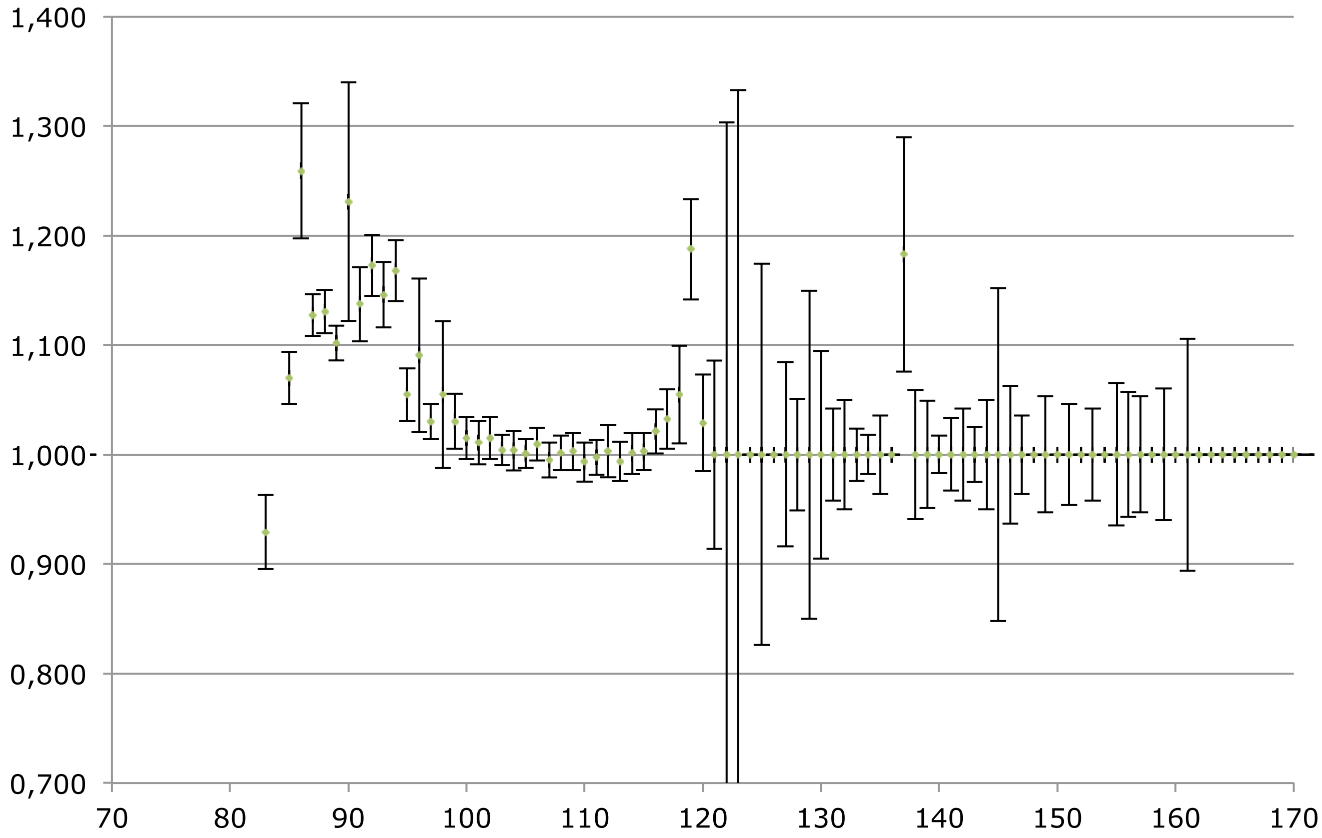
Ratio to UKFY3.6A



New models

- UKFY3.6A
  - ★Mass distribution using 5-Gaussian fitting and model parameter extrapolation.
  - ★Charge distribution using Wahl Zp model fitting and model parameter extrapolation.
  - ★Isomeric splitting using technique based upon Madland and England.
- UKFY3.7
  - ★Mass distribution using GEF.
  - ★Charge distribution using GEF.
  - ★Isomeric splitting using technique based upon Madland and England.

Initial testing

The strongest arguments prove nothing so long as the conclusions are not verified by experience. Experimental science is the queen of sciences and the goal of all speculation.

Roger Bacon,
Opus Tertium, 11th Century A.D.

Initial testing

Delayed neutron summation calculation

$$\nu_d = \sum_{i=0}^{n} C_i P_n^i$$

$$\sigma_{\nu_d}^2 = \sum_{i=0}^{n} \sigma_{C_i}^2 \, {P_n^i}^2 + \sum_{i=0}^{n} C_i^2 \, \sigma_{P_n^i}^2$$

Initial testing

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Delayed neutron summation calculation (per 100 fissions)

System	Neutron energy	UKFY3.7	JEFF-3.1.1	ν_d from experiment [4]
Th232	Fast	4.081±0.184	5.384±0.237	5.47±0.12
Th232	14MeV	2.907±0.165	3.056±0.211	2.85±0.13
U233	Thermal	0.738±0.062	0.724±0.056	0.664±0.018
U233	Fast	0.757±0.063	1.042±0.079	0.729±0.019
U233	14MeV	0.411±0.040	0.559±0.060	0.422±0.025
U234	Fast	1.079±0.082	1.342±0.169	1.06±0.12
U235	Thermal	1.471±0.083	1.477±0.079	1.654±0.042
U235	Fast	1.444±0.080	1.698±0.087	1.714±0.022
U235	14MeV	0.800±0.064	0.934±0.071	0.927±0.029
U236	Thermal	2.487±0.118		
U236	Fast	1.933±0.111	2.386±0.152	2.31±0.26
U238	Fast	3.535±0.131	4.037±0.129	4.51±0.061
U238	14MeV	2.295±0.093	2.369±0.098	2.73±0.08
Np237	Thermal	1.303±0.083	1.130±0.076	1.07±0.10
Np237	Fast	1.141±0.064	1.169±0.064	1.22±0.03
Np238	Thermal	1.658±0.202	1.419±0.135	
Np238	Fast	1.783±0.188	1.635±0.202	
Pu238	Thermal	0.376±0.035	0.319±0.038	0.456±0.051
Pu238	Fast	0.455±0.043	0.483±0.067	0.456±0.051
Pu239	Thermal	0.628±0.043	0.605±0.043	0.624±0.024
Pu239	Fast	0.605±0.044	0.675±0.046	0.664±0.013

Initial testing

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Delayed neutron summation calculation (per 100 fissions)

System	Neutron energy	UKFY3.7	JEFF-3.1.1	ν_d from experiment [4]
Pu240	Fast	0.809±0.054	0.920±0.058	0.96±0.11
Pu241	Thermal	1.306±0.059	1.232±0.058	1.56±0.16
Pu241	Fast	1.270±0.062	1.290±0.067	1.63±0.16
Pu242	Fast	1.679±0.081	1.684±0.078	2.28±0.25
Am241	Thermal	0.488±0.043	0.378±0.047	0.44±0.05
Am241	Fast	0.486±0.059	0.414±0.055	0.394±0.024
Am242	Thermal	0.712±0.111	0.582±0.106	0.69±0.05
Am242	Fast	0.714±0.048	0.567±0.075	
Am243	Thermal	1.038±0.063	0.842±0.113	
Am243	Fast	1.034±0.060	0.816±0.099	
Cm242	Spont.	0.115±0.026	0.120±0.022	
Cm243	Thermal	0.275±0.029	0.221±0.043	
Cm243	Fast	0.284±0.028	0.212±0.030	
Cm244	Spont.	0.331±0.044	0.317±0.041	
Cm244	Thermal	0.416±0.037	0.326±0.055	
Cm244	Fast	0.376±0.032	0.334±0.042	
Cm245	Thermal	0.570±0.044	0.526±0.071	0.59±0.04
Cm245	Fast	0.591±0.042	0.466±0.065	
Cf252	Spont.	0.668±0.039	0.585±0.030	0.86±0.10

Initial testing

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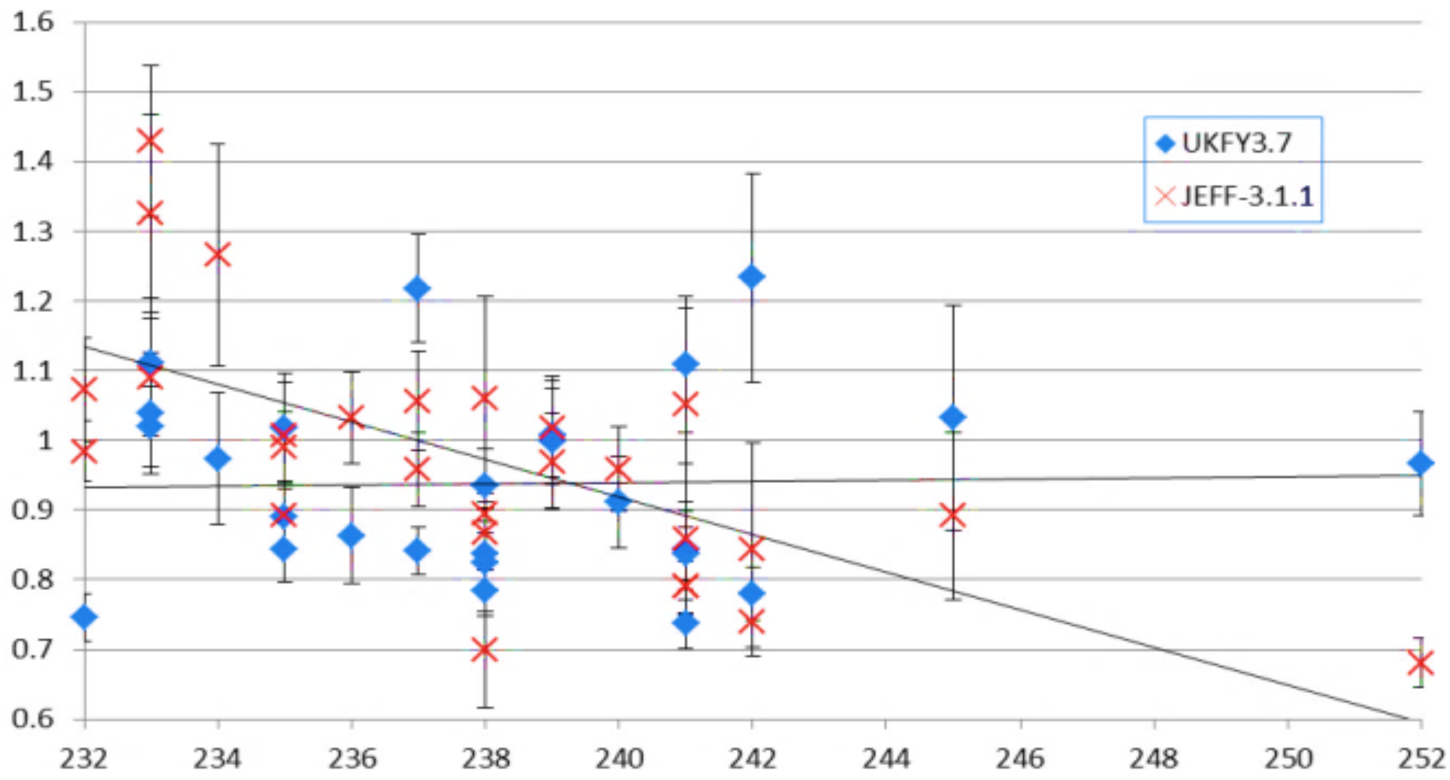
Delayed neutron summation calculation (per 100 fissions)



Initial testing

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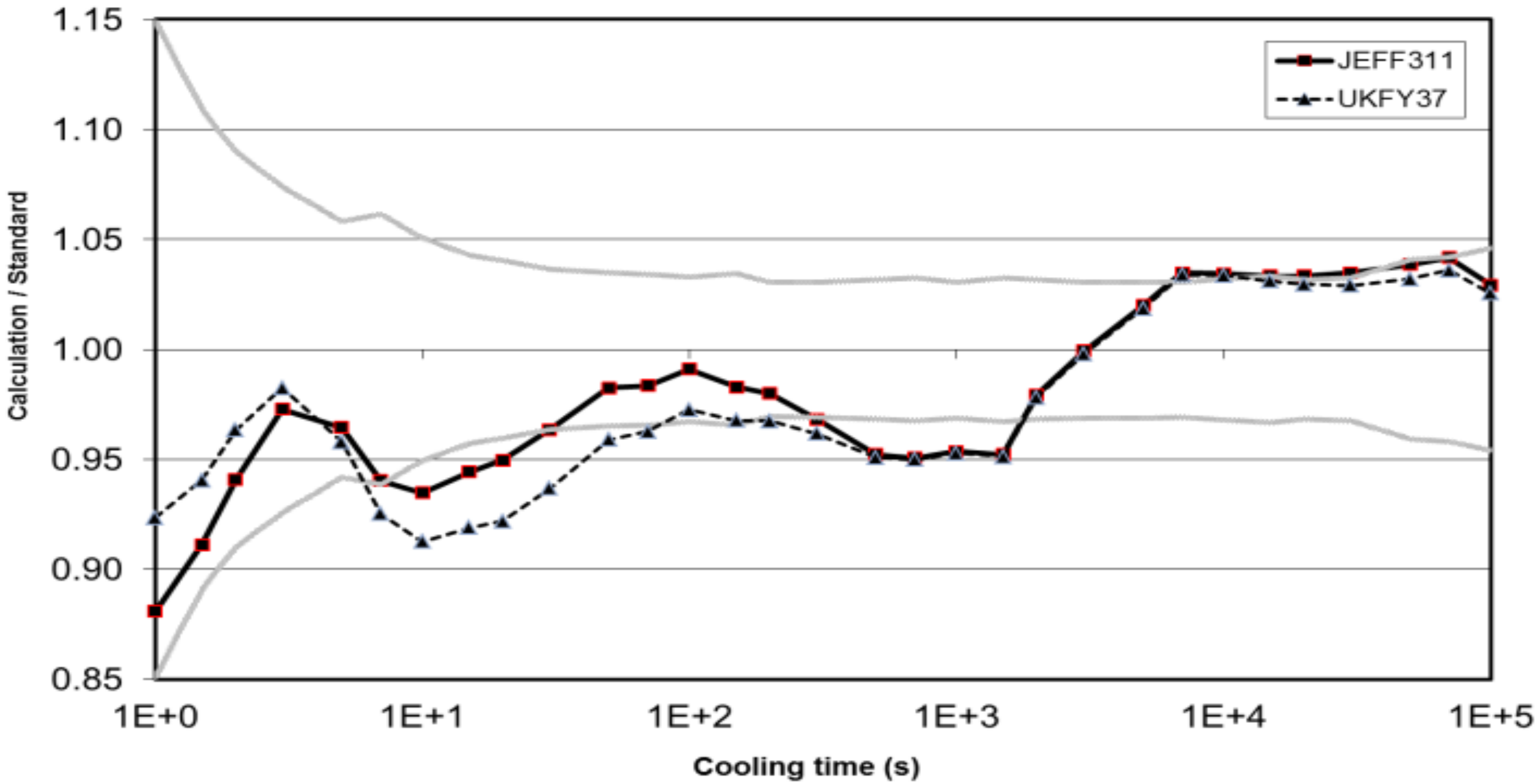
U235 Decay heat single fission "pulse" –Tobias 1989



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Initial testing

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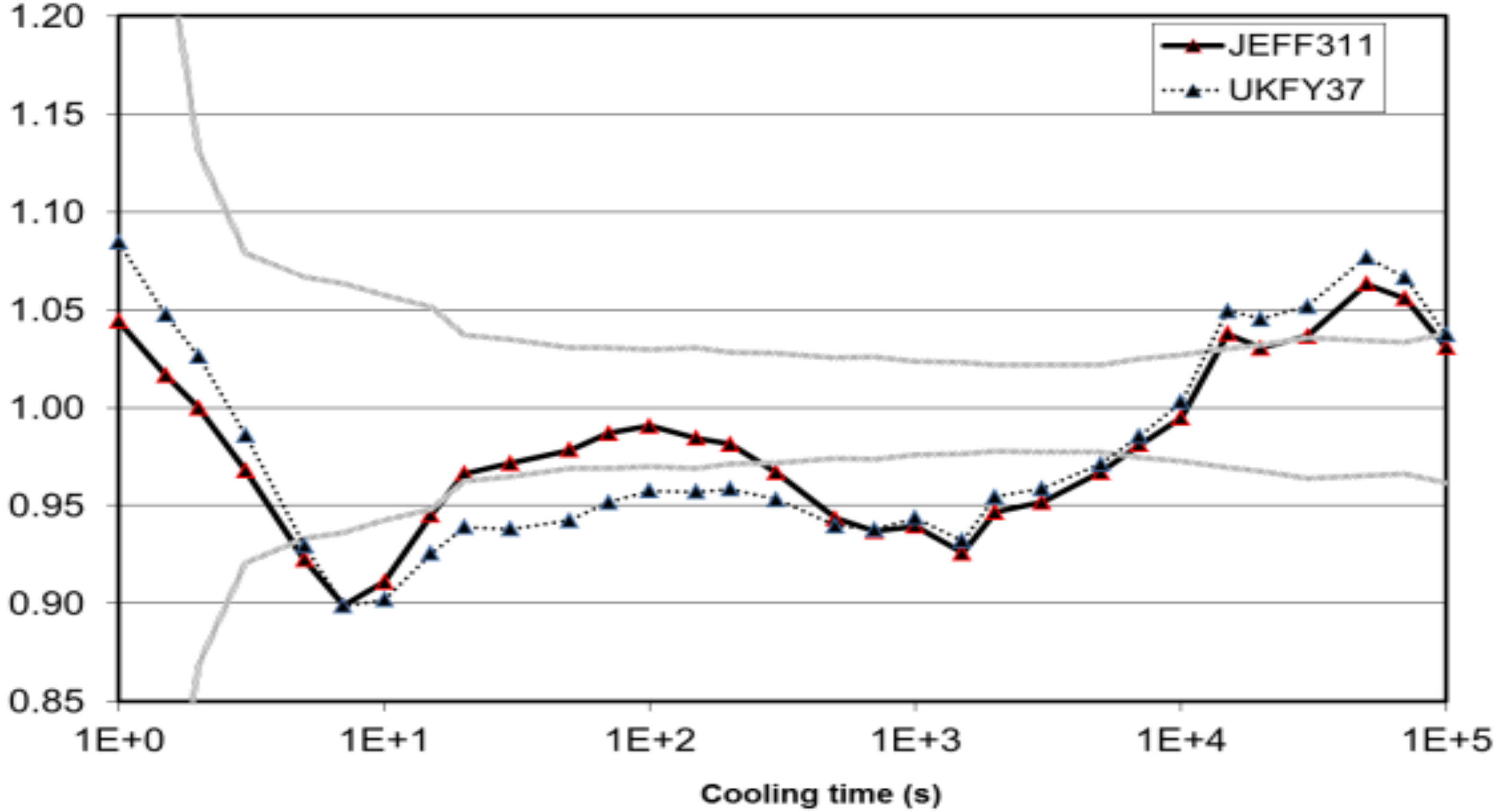
Pu239 Decay heat single fission "pulse" –Tobias 1989



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Initial testing
SKB PWR assemblies

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Assembly	Reactor	U235 Wt%	U236 ppm	Final Irradition MWd/t	Cooling (days)	Cooling (years)	Irradiation step 1 MWd/t	Irradiation step 2 MWd/t	Irradiation step 3 MWd/t	Irradiation step 4 MWd/t	Irradiation step 5 MWd/t	Irradiation step 6 MWd/t	Measured heat (W)	JEF-2.2 C/E	JEFF-3.1.1 C/E	UKFY37 C/E
0C9	Ringhals 3	3.101	150	38442	6551	17.94	9884	8192	10350	10016			491.2	1.000	0.991	0.993
0E2		3.103	150	41628	5823	15.94	7496	13034	11308	9790			587.9	0.974	0.967	0.970
0E6		3.103	150	35993	5829	15.96	12490	13031	10472				487.7	0.986	0.975	0.977
1C2		3.101	150	33318	6559	17.96	6249	5019	11509	10541			417.7	0.999	0.988	0.990
1C5		3.101	150	38484	6593	18.05	9884	8102	10411	10087			499.2	0.983	0.974	0.977
1E5		3.103	150	34638	5818	15.93	10556	13134	10948				468.8	0.986	0.975	0.978
2A5		2.1	150	20107	7297	19.98	12228	7879					233.7	1.015	1.000	1.002
2C2		3.101	150	36577	6550	17.93	7783	8345	9932	10517			466.5	0.998	0.988	0.990
3C1		3.101	150	36572	6545	17.92	7783	8341	9931	10517			470.2	0.988	0.978	0.980
3C4		3.101	150	38447	6544	17.92	9884	8192	10354	10017			497.3	0.984	0.976	0.978
3C5		3.101	150	38373	6543	17.91	9884	8113	10343	10033			501.4	0.980	0.971	0.974
3C9		3.101	150	36560	6552	17.94	7783	8377	9876	10524			468.4	0.992	0.982	0.985
4C4		3.101	150	33333	6572	17.99	6249	4991	11030	11063			422	0.989	0.978	0.980
4C7		3.101	150	38370	6549	17.93	9884	8101	10347	10038			498.7	0.983	0.975	0.977
5A3		2.1	150	19699	6972	19.09	11696	8003					237.7	0.991	0.976	0.978
					6975	19.10							236.6	0.996	0.981	0.982
					6977	19.10							243.4	0.968	0.953	0.955
					7291	19.96							230.9	1.005	0.990	0.991
					7304	20.00							230.2	1.007	0.992	0.994
5F2		3.404	150	47308	4724	12.93	13475	6922	10337	8930	7644		714	0.976	0.971	0.974

Initial testing
SKB PWR assemblies

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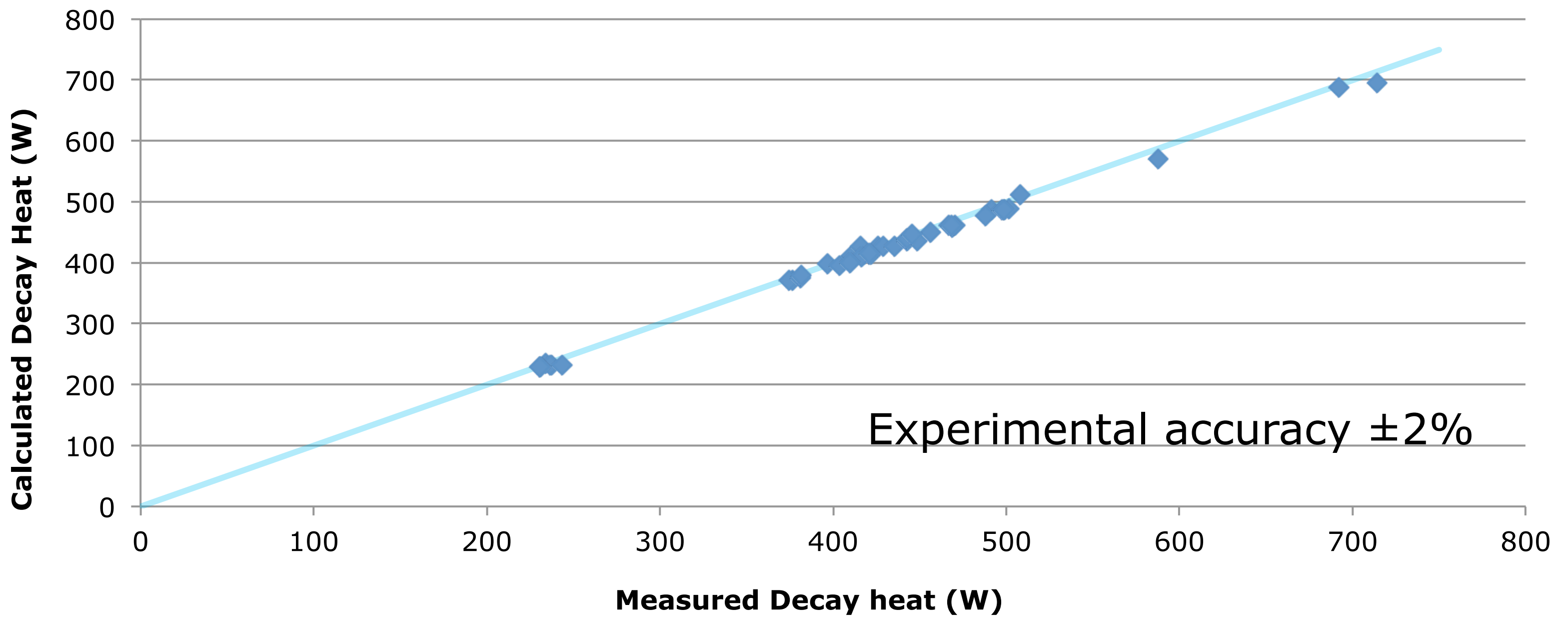
Assembly	Reactor	U235 Wt%	U236 ppm	Final Irradition MWd/t	Cooling (days)	Cooling (years)	Irradiation step 1 MWd/t	Irradiation step 2 MWd/t	Irradiation step 3 MWd/t	Irradiation step 4 MWd/t	Irradiation step 5 MWd/t	Irradiation step 6 MWd/t	Measured heat (W)	JEF-2.2 C/E	JEFF-3.1.1 C/E	UKFY37 C/E
C01	Ringhals 2	3.095	150	36688	8468	23.18	11247	9403	7569	8469			415.7	1.006	0.998	0.999
C12		3.095	150	36385	8403	23.01	11247	9318	7390	8430			410.3	1.009	1.000	1.001
C20		3.095	150	35720	6950	19.03	11247	9377	7454	7642			415.8	1.034	1.026	1.028
					6951	19.03							426.1	1.009	1.001	1.003
					6952	19.03							428.9	1.003	0.994	0.996
					6959	19.05							435.6	0.987	0.979	0.981
C42		3.095	150	35639	5803	15.89	16565	7619	8126	3329			442.3	0.991	0.983	0.985
					5804	15.89							448.4	0.978	0.970	0.972
D27		3.252	150	39676	7669	21.00	9510	12889	9267	8010			456	0.991	0.983	0.985
D38		3.252	150	39403	8005	21.92	6367	9331	7358	8701	7646		442.4	1.001	0.992	0.994
E38		3.199	150	33973	7999	21.90	7568	8458	9879	8068			376.3	0.995	0.984	0.986
					8000	21.90							374.3	1.000	0.989	0.991
E40		3.199	150	34339	8075	22.11	7705	7249	10655	8730			381.2	0.992	0.982	0.983
F14		3.197	150	34009	7722	21.14	5069	10755	9898	8287			381.8	1.003	0.992	0.994
F21		3.197	150	36273	7376	20.19	4767	6317	10046	8255	6888		420.9	0.992	0.982	0.984
F25		3.197	150	35352	7725	21.15	8307	10749	8316	7980			396.7	1.011	1.000	1.002
F32		3.197	150	50962	5860	16.04	10553	10609	8391	7761	6629	7019	692	0.994	0.990	0.994
G11		3.188	150	35463	6990	19.14	6890	10422	7868	6943	3340		416.3	0.992	0.982	0.984
G23		3.206	150	35633	6984	19.12	10268	10035	7618	7712			420.7	0.996	0.986	0.988
I09		3.203	150	40188	5849	16.01	6727	8950	9065	7568	7878		507.9	1.011	1.003	1.006
I20		3.203	150	34313	6588	18.04	8300	9010	9108	7895			403.5	0.987	0.976	0.978
I24		3.203	150	34294	6601	18.07	8245	8967	9144	7938			410	0.983	0.972	0.974
I25		3.203	150	36859	6198	16.97	5207	4991	9803	8998	7860		445.8	1.000	1.000	1.003

Initial testing
SKB PWR assemblies

Mean and Standard Deviation of C/E values

Reactor	JEF-2.2 C/E	JEFF-3.1.1 C/E	UKFY37 C/E
Ringhals 3	0.990 ± 0.012	0.979 ± 0.010	0.981 ± 0.010
Ringhals 2	0.999 ± 0.012	0.990 ± 0.012	0.992 ± 0.012
Combined	0.995 ± 0.013	0.985 ± 0.012	0.987 ± 0.012



Conclusion of Initial Testing

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- Possible improvement in trends for ν_d
- Some slight improvements and some slight worsening for U235 and Pu239 fission "pulses" against Tobias standard, but just outside one standard deviation.
- Spent PWR fuel assemblies appear to be well predicted within experimental uncertainty.

- Thus the library is suitable for further testing with the JEFF community.

Future work

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- Uncertainties estimation on engineering parameters requires fission yield covariance terms for independent yields.

  Possible methods to estimate these based upon:

  ★ Physical constraints

  ★ Perturbing underlying model parameters

  ★ LSQ or maximum likelihood approach using model parameters and experimental data

  Want to explore using measured cumulative yields to infer independent yield covariance terms.

Future work

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- Include new types of data
  - ★ Currently only include yields of specific mass, charge and isomeric state in evaluation.
  - ★ Want to include mass and charge distributions with resolution greater than one.
  - ★ Inverse reaction data
  - ★ …

- Want to give yield data as function of energy rather than for “representative” spectra
  - ★Possible now that GEF can be used as a model.

Acknowledgements

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The author would like to thank Drs. Cabellos, Diez, Hambsch, Koning, Noguere, Pigni, Rochman, Schmidt, Serot and members of the JEFF and WPEC communities for useful discussions.
Dr Frost for entering the new fission yield data into the database and Dr Mountford for extracting the GEF/GEFY model data for use in the evaluation.

This work was funded by the NNL Research and Development fund and the EURATOM FP7 project CHANDA (FP7- 605203).