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Validation of WIMS9

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The WIMS lattice cell and burnup code has been established as a standard reactor physics code for a wide range of reactor types for the last 30 years, the latest version of which, WIMS8 [1], was issued in 1999. WIMS is continuously under development within Serco Assurance ANSWERS Software Service to meet the needs of its users and the increasing accuracy demands of the nuclear industry in general. As part of this development programme, a series of detailed studies were undertaken to compare the results from the deterministic WIMS modular code system with those from point data Monte Carlo calculations performed using the MONK8 code [2], a companion code in the ANSWERS code suite. Results of this investigation were outlined in a paper to the last PHYSOR conference [3]. These inter-comparisons led to the identification of the most significant method approximations remaining in WIMS8, in particular, in the resonance self shielding treatment. As a result of this, a number of improved methods have been developed and incorporated in WIMS for its next issue as WIMS9.

1 WIMS9 Overview

The WIMS lattice cell and burnup code has been established as a standard reactor physics code for a wide range of reactor types for the last 30 years, the latest version of which, WIMS8 [1], was issued in 1999. WIMS is continuously under development within Serco Assurance ANSWERS Software Service to meet the needs of its users and the increasing accuracy demands of the nuclear industry in general. As part of this development programme, a series of detailed studies were undertaken to compare the results from the deterministic WIMS modular code system with those from point data Monte Carlo calculations performed using the MONK8 code [2], a companion code in the ANSWERS code suite. Results of this investigation were outlined in a paper to the last PHYSOR conference [3]. These inter-comparisons led to the identification of the most significant method approximations remaining in WIMS8, in particular, in the resonance self shielding treatment. As result of this, a number of improved methods have been developed and incorporated in WIMS for its next issue as WIMS9. The areas of improvement in WIMS9 [3], relative to WIMS8 are summarised below:

- Extension of the energy range treated as the resonance region by WIMS into the unresolved energy region with an upper energy of 183 KeV.

- Modification of the single nuclide independent fission spectrum used in WIMS8 to include nuclide dependence.

- Modelling of the interactions between resonances at lower resonance energies.

- Improvements to the correction factor for the broad group out-scatter cross-sections due to the presence of resonances.

- Introduction of resonance scattering theory in addition to the resonance absorption theory currently used in WIMS8.

- Current rather than flux energy weighting for the condensation of the transport and P_1 moment of the scatter cross-section.

WIMS9 can treat resonance absorption and scatter either using equivalence theory or, to include a better treatment of geometrical effects, sub-group theory. Equivalence theory for both homogeneous and heterogeneous geometries is implemented in the HEAD module. The HEAD module calculates absorption, scatter, fission and broad group removal cross-sections for the resonance nuclides. It also calculates a nuclide dependent correction for broad group removal for all nuclides. This correction caused by the presence of resonance absorption and scatter is called the f(p) correction.

In the WIMS9 version of HEAD a fine group calculation is now performed to provide a better evaluation of the interaction effects between the resonances of different nuclides. In addition, average currents in the fuel are also evaluated to allow current rather than flux weighting of the transport and P_1 scatter cross-sections. This fine group calculation uses 100 fine groups within a broad group and is performed for broad groups 70 to 92 (55.5 eV to 4 eV) of the WIMS 172 group library. At high resonance energies the WIMS8 statistical overlap interaction model between resonances is sufficiently accurate. For groups 70 to 92 the resonances are broad enough that the use of 100 fine groups, of equal energy width, can model them sufficiently well. Both methods suffer some inaccuracy at mid range resonance energies and for these groups the WIMS8 method has been retained.

2 Modelling Methods

The standard suite of validation cases for WIMS include a wide range of experimental benchmarks covering different thermal power reactors types. These benchmarks were re-calculated using WIMS9 and the results were compared with those from previous WIMS8 analyses.

The nuclear data libraries employed for both the WIMS8 and WIMS9 studies were generated from the JEF2.2 data base [4]. However, the processing of the data for the WIMS9 library has been modified to accommodate the changes described in Section 1. Both libraries contain cross sections tabulated in 172 energy groups.

Unless otherwise stated in the following sections, the modelling methods for the repeat validation cases employed the following assumptions.

- The experiments were modelled as pincells with experimental radial and axial bucklings used to calculate leakage. The bucklings were applied in a B_1 edit.

- Equivalence theory was employed to evaluate resonance shielding effects. For WIMS9, treatment of resonance scatter was included.

- The flux calculation was performed in the 172 library group energy structure.

- Collision probabilities were used to carry out the flux calculation.

3 Description of Validation Test Cases

The benchmark cases reported here are summarised in Table 1.

Benchmark	No. of Expts	Moderator	Fuel Type
TRX	2	H_20	U Metal
Brookhaven	11	H_20	UO_2
DIMPLE	5	H_20	UO_2
KRITZ-2	2	H_20	UO_2
KRITZ-2	1	H_20	MOX
ESADA	11	H_20	MOX
BICEP	26	Graphite	U Metal
Hanford	5	Graphite	U Metal

Table 1 : **Description of Benchmarks**

Below a brief description is given of the experiments and the results obtained in each case.

3.1 BICEP/Hanford

The BICEP [5] and Hanford [6] stacks were series of exponential experiments (31 experiments in total) using graphite moderator with low enriched uranium metal fuel with enrichments ranging from 0.418 - 1.141 weight % ^{235}U. The experiments were configured into vertical and horizontal stacks with variations in fuel pin size and pitch, fuel can diameter and air channel diameter. The experimental value of k-effective is unity in each case.

These experiments were modelled using subgroup theory for resonance shielding. k-effective values for the individual BICEP experiments, analysed using both WIMS8 and WIMS9, and plotted against moderator to fuel ratio are presented in Figure 1.

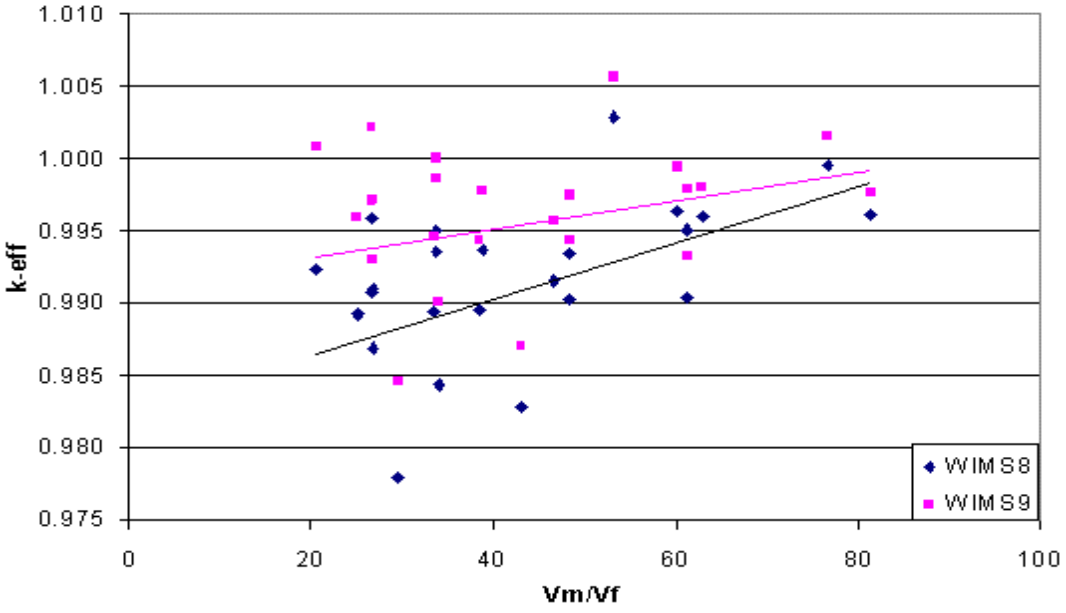

Fig. 1 : **k-effective versus Moderator to Fuel Ratio for the BICEP Cores**

The mean k-effective value, averaged over all the analysed BICEP experiments, is given in Table 2 .

	WIMS8	WIMS9	Δk (pcm)
Mean k-eff.	0.99071	0.99535	464
s.d.	0.00772	0.00715	-

Table 2 : **Mean k-effective Values for the BICEP Lattices**

The k-effective values for the individual Hanford Lattices, plotted against moderator to fuel ratio are presented in Figure 2.

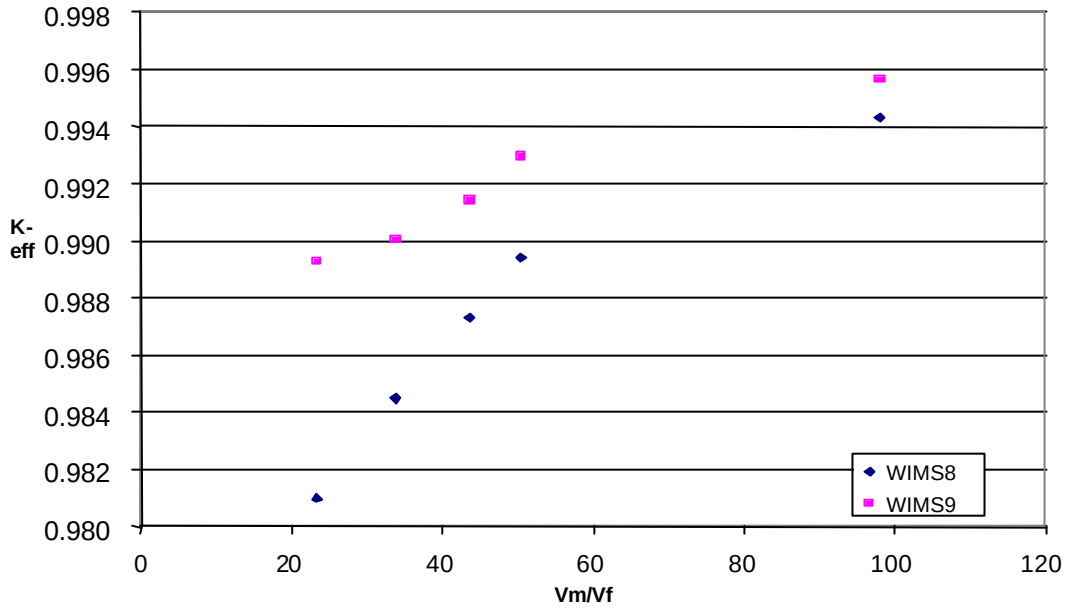

Fig. 2 : **k-effective versus Moderator to Fuel Ratio for the Hanford Cores**

It is observed that the enhanced methods in WIMS9 significantly improve the agreement both on absolute reactivity and the trend with moderator to fuel ratio with respect to WIMS8. It should be noted that the large discrepancy between WIMS9 and experiment for the Hanford Lattices is also found for point energy Monte Carlo Calculations.

3.2 KRITZ-2

The KRITZ cores [7] comprised three light water moderated critical lattice experiments using UO_2 (2:1 and 2:13) and MOX fuel (2:19) with nominal temperatures of 20^{o}C and 245^{o}C.

These experiments were modelled using equivalence theory calculations in 6 energy groups. A 2D whole core model with axial buckling was employed. The calculated k-effective values and isothermal temperature coefficients (defined as $\Delta K/\Delta T$) are presented in Table 3.

Expt.	Cold			Hot			$\Delta k/\Delta t$ (pcm/^oC)	
	WIMS8	WIMS9	Δk (pcm)	WIMS8	WIMS9	Δk (pcm)	WIMS8	WIMS9
2:1	0.99185	0.99413	228	0.98919	0.99065	146	-1.16	-1.52
2:13	0.99289	0.99539	250	0.98924	0.99198	274	-1.65	-1.54
2:19	0.99431	0.99750	319	0.98758	0.99191	433	-3.13	-2.60
Mean k-eff.	0.99302	0.99567	265	0.98867	0.99151	284		
s.d.	0.00101	0.00139		0.00077	0.00061			

Table 3 **: k-effective Results for the KRITZ Cores**

The WIMS9 k-effective values are closer to the experimental value of unity than those for WIMS8. However the trend on isothermal temperature coefficient is less clear: a significant improvement is observed for the Pu fuelled lattice (2:19), however for the UO_2 lattices one WIMS9 result is slightly better and one slightly worse than WIMS8. These changes for the UO_2 lattice are not very large, in fact they tend to improve the consistency of the results from the two different experiment. The overall picture is that the WIMS9 UO_2 lattice results for temperature coefficient are unchanged relative to WIMS8 whilst the Pu fuelled lattice results are improved.

3.3 Brookhaven

The Brookhaven lattices were a series of 11 light water moderated, critical lattice experiments with 3% enriched UO_2 fuel in stainless steel cans. They included variations in lattice pitch (1.6cm - 2.3cm) and dissolved boric acid concentrations (0 - 7.8 grams/litre). The results of these analyses are given in Table 4.

Vm/Vf	Boric Acid (g/l)	WIMS8	WIMS9	Δk (pcm)
1.3	0.0	1.00096	1.00392	296
1.6	0.0	0.99516	0.99874	358
2.1	0.0	0.99425	0.99816	390
2.9	0.0	0.99538	0.99911	372
4.1	0.0	0.99560	0.99837	277
4.1	0.999	0.99890	1.00074	184
4.1	1.487	0.99915	1.00055	140
4.1	2.231	0.99636	0.99715	79
4.1	3.085	0.99752	0.99757	6
1.3	3.826	1.00317	1.00508	191
1.3	7.8	1.00147	1.00241	94
Mean k-eff.	-	0.99799	1.00016	217
s.d.	-	0.00282	0.00252	-

Table 4 : **k-effective Results for the Brookhaven Lattices**

Taking the mean values over the suite of experiments, the WIMS9 agreement has improved

by around 200 pcm with respect to WIMS8. There is also a tendency for the consistency of the results to improve with WIMS9 as noted by the reduced standard deviation.

3.4 ESADA

The ESADA Experiments [8] were a series of 11 light water moderated, critical lattices with MOX fuel in zirconium cans. They included variations in lattice pitch (1.75 - 3.5cm) and dissolved boron concentration (261 & 526 ppm). k-effective values for the ESADA lattices are presented in Table 5.

Fuel $\%^{240}Pu$	Vm/Vf	Boron (ppm)	WIMS8	WIMS9	Δk (pcm)
8	1.125	0	0.98988	0.99367	379
8	1.557	0	0.98785	0.99272	487
8	3.500	0	1.00529	1.01008	479
8	4.366	0	1.00640	1.01058	418
8	8.257	0	1.00203	1.00210	7
8	1.125	261	0.99634	0.99984	350
8	3.500	261	0.99707	1.00108	401
8	1.125	526	0.99335	0.99663	328
8	3.500	526	0.99424	0.99747	323
24	3.500	0	1.00390	1.00794	404
24	4.366	0	1.00359	1.00702	343
Mean k-eff.			0.99818	1.00174	
s.d.			0.00614	0.00610	

k-effective values corrected for Pu grain shielding effects.

Table 5 : **k-effective Values for the ESADA Experiments**

The use of WIMS9 causes an increase in mean k-effective of around 350 pcm. However, WIMS9 tends to slightly over-predict k-effective while WIMS8 tends to under-predict k-effective by the same magnitude. It should be noted that the relatively large uncertainty associated with these experiments reduces the precision of any conclusion. However, it is the case that these results are consistent with results from other experiments.

3.5 DIMPLE

The DIMPLE cores [9] were a series of 5, critical lattice experiments with 3% enriched UO_2 fuel in stainless steel cans. Three pitches of 1.32cm, 1.25cm and 1.87cm were used at temperatures of 20^oC and 80^oC. k-effective values for the DIMPLE lattices are shown in Table 6.

The use of WIMS9 causes an increase in mean k-effective of around 280 pcm. Again, WIMS9 tends to over-predict k-effective while WIMS8 tends to under-predict k-effective by the same magnitude. The results also illustrate two further effects. The change in k-infinity is relatively small on average which indicates that the increase in reactivity is mainly due to changes in leakage. This is due to the different method used to calculate the transport cross section. Also the WIMS8 results exhibit a small trend with pitch or moderator to fuel ratio, a

trend which is significantly reduced by WIMS9, giving results that are more consistent. This is also shown by the reduction in the standard deviation associated with the differences between experiment and theory.

Core	Vm/Vf	Temp (^oC)	K-infinity			K-effective		
			WIMS8	WIMS9	Δk (pcm)	WIMS8	WIMS9	Δk (pcm)
R1/100H	1.0	20	1.27145	1.27136	-9	0.99942	1.00227	285
R1/100H	1.0	80	1.26293	1.26269	-24	0.99740	1.00013	273
R2/100H	3.2	20	1.33684	1.33796	112	0.99594	1.00012	418
R3/100H	0.8	20	1.22534	1.22433	-101	1.00081	1.00244	163
S01/A	1.0	20	1.26688	1.26670	-19	0.99877	1.00145	268
Mean k-inf./k-eff.			1.27269	1.27261	-8	0.99847	1.00128	281
s.d.			0.03602	0.03670		0.00167	0.00100	

Table 6 **: k-effective Results for DIMPLE Lattices**

3.6 TRX

The TRX cores [10] were two light water moderated, critical lattice experiments with 1.3% enriched uranium metal fuel in aluminum cans. The results for the TRX lattices are given in Table 7.

Expt.	Vm/Vf	K-infinity			K-effective		
		WIMS8	WIMS9	Δk (pcm)	WIMS8	WIMS9	Δk (pcm)
TRX1	2.35	1.17878	1.18149	271	0.99044	0.99436	392
TRX2	4.02	1.16424	1.16601	177	0.99154	0.99458	304
Mean k-inf./k-eff.		1.17151	1.17375	224	0.99099	0.99447	348
s.d.		0.00727	0.00774		0.00055	0.00011	

Table 7 **: k-effective Results for the TRX Lattices**

As for the DIMPLE results, there is a significant effect due to leakage. In this case however, there is also a significant contribution to the changes between WIMS8 and WIMS9 from changes in k-infinity. The net result is that WIMS9 gives a reduction in the under-prediction of reactivity of around 350 pcm.

4 Discussion of Results

4.1 Mean Reactivity

Validation tests have been carried out with WIMS9 using a subset of the standard WIMS validation suite covering a range of light water and graphite moderated systems. A range of parameters have been considered including reactivity and trends with variations in lattice pitch, temperature and boron concentration. A number of improvements in results, with respect to WIMS8, have been noted. For example, mean values for k-effective for uranium pins in water, and for MOX pins in water are given in Table 8 and Table 9 respectively.

	WIMS8	WIMS9	Δk (pcm)
Mean k-eff	0.99685	0.99933	248
s.d.	0.00345	0.00309	-

Table 8 : **Mean k-effective Values for Uranium Pins in Water**

	WIMS8	WIMS9	Δk (pcm)
Mean k-eff	0.99785	1.00139	353
s.d.	0.00597	0.00595	-

Table 9 : **Mean k-effective Values for MOX Pins in Water**

It can be seen that for both UO_2 and MOX light water moderated systems, the WIMS9 mean k-effective values are in closer agreement with experiment. For graphite moderated systems, mean k-effective values are also in closer agreement with experiment for WIMS9, in this case the increase in reactivity was about 465 pcm.

4.2 Trend with Pitch

The WIMS9 results also show a marked reduction in the trend of reactivity against lattice pitch, relative to WIMS8. The significant trend with WIMS8 was particularly evident for graphite systems but could also be discerned for water system (see DIMPLE results). The significant reduction in trend with WIMS9 is particularly evident from the BICEP and DIMPLE results.

4.3 Leakage Effect

The DIMPLE and TRX results indicate that for these high leakage experiments there is a significant change in the leakage when calculated with WIMS9 rather than WIMS8. This effect is of the order of 280 pcm for DIMPLE and 220 pcm for TRX. As leakage contributes an effect of between 20% and 30% for these cores this amounts to a 1% decrease in leakage in WIMS9. This change in leakage is due to the new WIMS9 method of calculating transport cross-sections in the resonance region.

5 The Transport Cross Section Calculation in WIMS9

In WIMS9 a fine group calculation is performed for each of the broad energy groups between the energies of 55.5 eV and 4 eV. Each broad group is modelled using 100 fine groups using infinite dilution cross-section data held on the nuclear data library. When performing the fine group calculation, fine group cross-section data is used for both the broad group being considered as well as the broad group at immediately higher energy. This allows the modelling of changes in the neutron slowing down density due to resonances at neighboring higher energies. For energies higher than those modelled explicitly the approximation used is that the slowing down density is unaffected by the presence of resonances.

This calculation allows the currents entering the fuel to be approximated which, through the use of current weighting, allows a more accurate estimation of the transport and P_1 scatter cross-sections. Figure 3 shows the results for a flux and current calculation in the vicinity of

the 6.7eV U238 capture resonance for a 0.4 cm radius PWR fuel pin with a fuel to moderator ration of 2 : 1.

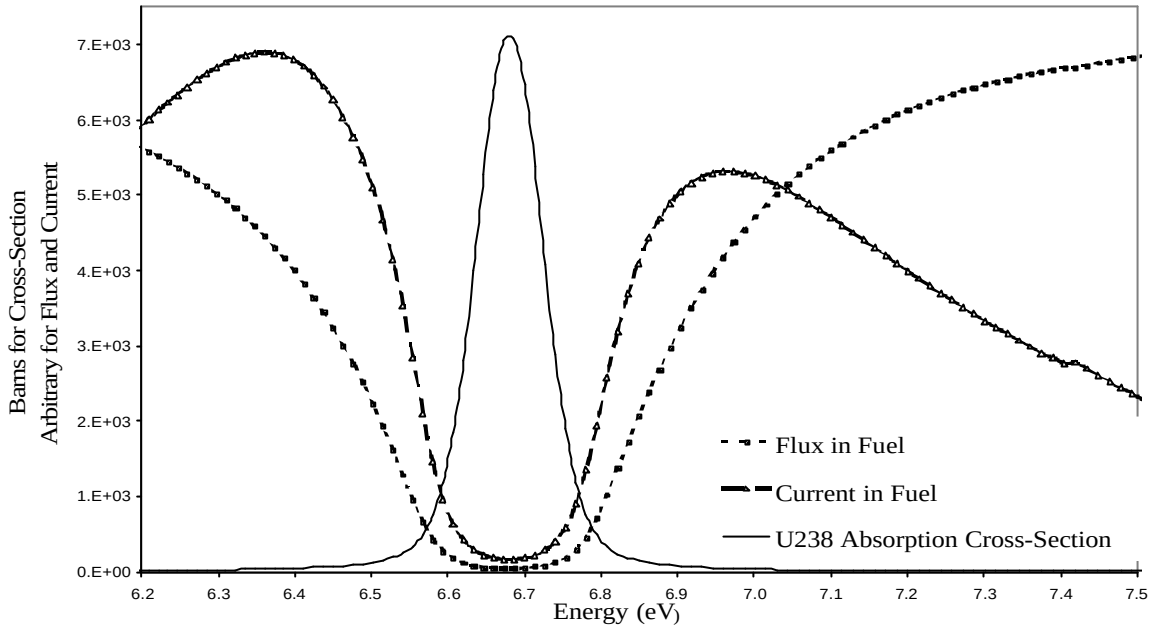

Fig. 3 : **Flux and Current Solutions Close to the U238 6.7 eV Resonance. For a 0.4 cm radius pin with Fuel : Moderator = 2 : 1**

The current is significantly larger than the flux within the resonance and in the wings of the resonance where the absorption cross-section is large. Figure 4 shows the current weighted and flux weighted absorption contributions to the transport cross-section.

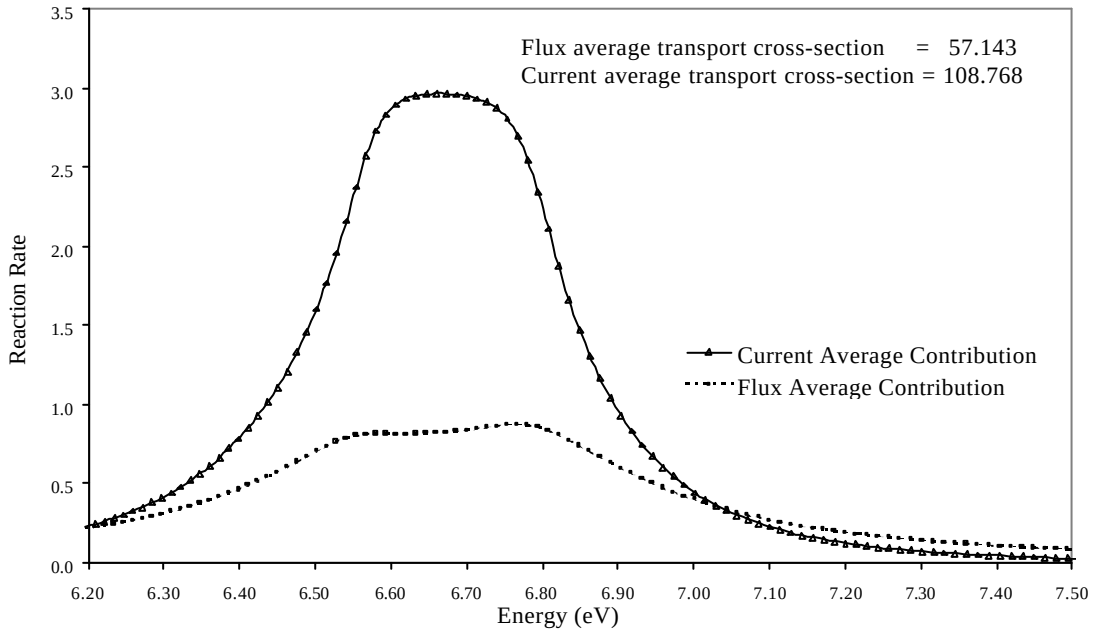

Fig. 4 : **Comparison of Contributions to the Flux and Current Average Transport Cross-Section**

The resulting current weighted transport cross-section is ~ 109 barns while the flux weighted transport cross-section is ~ 57 barns.

6 Conclusions

It can be seen from the results presented in this paper that WIMS9 improves the agreement between theory and measurement for these standard reactor physics benchmarks in a small but significant way. There is an overall improvement in reactivity prediction as well as an improvement in trends with lattice pitch and for high leakage cores.

7 Acknowledgements

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