The Resonance Interference Model for PARAGON

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ABSTRACT

A new interference model is implemented in the self-shielding module of PARAGON lattice physics code in order to accurately compute the background cross section in resonance region for major resonant isotopes. This new "heterogeneous-heterogeneous" equivalence procedure is based on the two heterogeneous situations: one is the self-shielding module of PARAGON and the other is an exact continuous heterogeneous equivalent slowing down case modeled in the RABBLE code. This equivalence generates a table that correlates the two background cross-sections as a function of other parameters like enrichment. Several set of benchmark calculations were performed to validate this method. This new model reproduces the Monte-Carlo MCNP continuous energy calculations without a need to adjust the basic cross-section library for any conditions.

INTRODUCTION

PARAGON [1] is the lattice code designed to be a part of the Westinghouse ALPHA/PARAGON/ANC (APA) nuclear design system package [2]. It is a two-dimensional transport code based on collision probability with interface current method. As in any lattice physics code, PARAGON generates the self-shielded cross-sections in an iterative way for a mixture of resonant isotopes. During each iteration, the isotopes are self-shielded one by one assuming the other isotopes are not resonant, but their latest self-shielded cross-section (from previous iteration) are used as a "source" to that particular isotope. This procedure and other assumptions used in the resonance self-shielding theory do not seem to take into account correctly the interference between different isotopes. To reproduce the continuous Monte Carlo calculations and to better predict the critical experiments, we usually apply a reduction to the U-238 absorption cross-sections – in the magnitude of 3.4% [5] - in the multi-group lattice physics calculations. On the other hand the continuous Monte Carlo does not show a need for further U-238 reduction.

A new interference model, based on "heterogeneous-heterogeneous" equivalence, for resonance self-shielding is developed to better account for spatial and energy resonance interactions in a mixture of isotopes and consequently eliminates the need for any adjustment of the basic data in the cross-section library. This paper describes the technique that has been applied to develop this methodology.

DESCRIPTION OF THE MODEL

The basic idea behind this new model is to define a relation between the isotopic background (dilution) cross-section in two heterogeneous situations (heterogeneity is in both composition and space): one is the exact continuous slowing down calculation and the other is the current model used in the lattice codes like PARAGON with coarse mesh energy groups. A table of "heterogeneous-heterogeneous" equivalent background cross section is generated for major resonant isotopes and for all epithermal groups. A program is developed to search the table for an equivalent heterogeneous-heterogeneous background cross-section and produce a new dilution cross-section that will be later used by PARAGON to compute the final multi-group self-shielded cross-sections for any isotope in a given mixture.

The equivalence table was generated using PARAGON and RABBLE [4]. RABBLE has been implemented in the NJOY [6] code as a module and uses the continuous energy data from NJOY modules. PARAGON uses 70-group cross-section library for more than 250 isotopes containing 17 epithermal groups of shielded data for resonant isotopes. It should be noted that U-238 absorption cross sections (or any other data) are not adjusted in this library. PARAGON produces σ_e values called "heterogeneous" background cross-sections for resonant isotopes. RABBLE is a continuous slowing-down code that uses a cylindrical geometry to compute different isotopic reaction rates in a coarse energy mesh. The cases are calculated in heterogeneous models. Knowing the exact reaction rates i.e. absorption and fission reaction rates from RABBLE, we can determine the $\tilde{\sigma}_e$ called "exact heterogeneous" background cross sections by searching in the PARAGON library table for values that preserves reaction rates of the reference cases.

RABBLE and PARAGON were run for a combination of different values of pitch (moderation ratio), uranium enrichment (U), plutonium content (W) and fuel temperature (T_f) covering the range of the core operations and cold conditions. The table was constructed with 4 parameters for all uranium and plutonium nuclides and for all 17 epithermal groups: uranium enrichment ranging from 0.10 to 8.0 w/o, plutonium content ranging from 0.0% to 54.0%, fuel temperature ranging from 296.0 K to 2000.0 K and background cross section (σ_e) ranging from 10 to 1.0E+10 barns. The relation can be written as the function given in Eq. 1. Figures 1 through 4 illustrate the "exact heterogeneous" background cross sections of U-238 as a function of uranium enrichment, fuel temperature, plutonium content, and "heterogeneous" background cross sections, respectively.

$$\tilde{\sigma}_e = f(\sigma_e, U, W, T_f) \qquad (1)$$

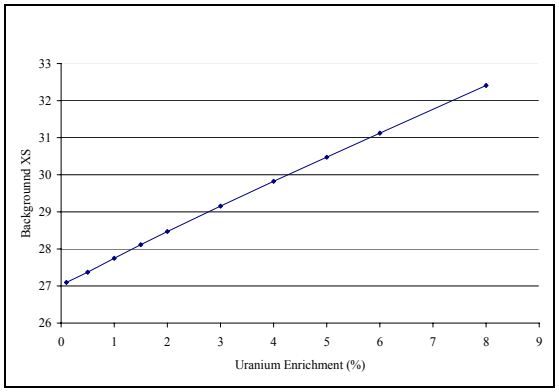

Figure1:U-238 background XS at W=3%,T=922K

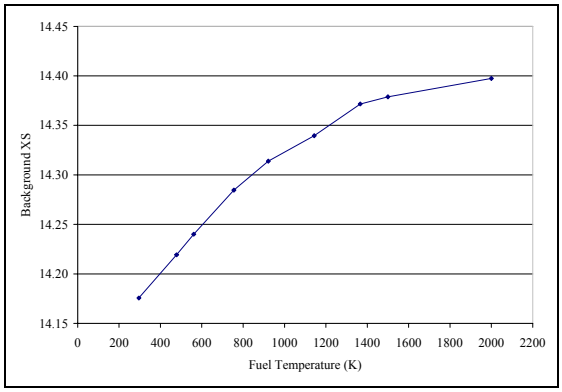

Figure2: U-238 background XS at W=0%,U=3%

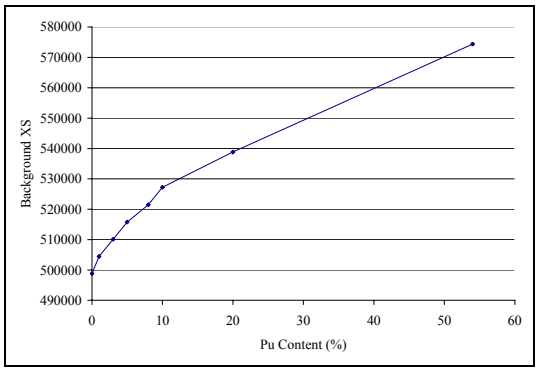

Figure3: U-238 background XS at U=3%,T=922K

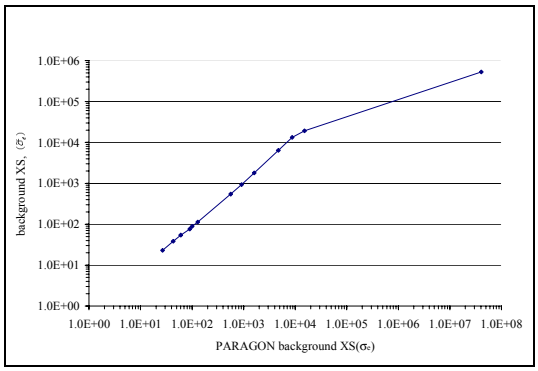

Figure4:U-238 background XS at U=4%,T=922K,W=10%

A module based on the model described above was developed and implemented in PARAGON. This module interpolates linearly in the equivalence table to determine the exact isotopic background cross-section for the geometry and mixture treated. PARAGON calculates the final self-shielded cross-sections for a given mixture based on the new background cross sections, which are considered to be more accurate.

NUMERICAL RESULTS

In order to test this new method, three different sets of benchmarks were analyzed: the fuel pin cells, the Doppler benchmark, and the assembly cases. PARAGON with the new interference module and the 70-group background cross-section table are used for calculations. The calculations were performed with single region or multi-regions in fuel and moderator as needed. The obtained results are compared to continuous Monte Carlo models. The MCNP results are within 30 pcm standard deviation for a 5 million neutron sampling (1000 cycles and 5000 particles/cycle). It should be noted that the 70-group cross-section library used in this study has self-shielded cross sections for Zr isotopes. Both MCNP and PARAGON cross-section libraries are based on ENDF/B6.3 version.

Pin cell benchmarks

Under hot full power conditions (HFP) (fuel at 900K, clad and moderator at 600K), the eigenvalues calculated by MCNP and PARAGON for pin cell benchmarks are presented in Table 1. The obtained results show very good agreement between MCNP continuous energy and PARAGON calculations. The wide variety of benchmarks presented in this case demonstrates the robustness of the methodology for the real core applications both for PWR and BWR reactors.

Table 1: MCNP and PARAGON eigenvalues for pin cells

Case	MCNP(σ in pcm)	PARAGON	Delta (pcm) PARAGON-MCNP
17X17 Westinghouse OFA pin cell – no void	1.28739 (±29)	1.28837	119
17X17 Westinghouse OFA pin cell – 50% void	1.20413 (±29)	1.20288	-125
17X17 Westinghouse OFA pin cell – 80% void	1.03117 (±25)	1.03190	73
14X14 Westinghouse pin cell with 4 w/o Enrichment	1.27805 (±28)	1.27703	-102
15X15 pin cell - No BA 3.9 w/o Enrichment	1.27294 (±30)	1.27234	-60
16X16 Westinghouse pin cell - 4 w/o Enrichment	1.25617 (±29)	1.25629	12
17X17 Standard pin cell - 5 w/o Enrichment with IFBA	0.95114 (±29)	0.95196	82
14X14 CE pin cell - 4.3 and 3.8 w/o Enrichment containing Erbia	0.97247 (±28)	0.97188	-59
17X17 pin cell with MOX	1.16550 (±30)	1.16642	92
17X17 pin cell with MOX	1.12369 (±29)	1.12400	31

Doppler benchmarks

In this benchmark, the effect of changes of temperature was studied for 17x17 standard (STD) pin cells. The enrichment is ranging from 0.71 to 4.8 w/o in three conditions; cold zero power (CZP) (fuel, clad and moderator are at 296K), hot zero power (HZP) (fuel, clad and moderator are at 600K), and HFP. The eigenvalues calculated by MCNP and PARAGON using the 70-group cross-section library for Doppler benchmarks are compared in Table 2.

At high enrichment (> 1.6 w/o) the agreement between MCNP and PARAGON is very good for all conditions. For low enrichment (below 1.6 w/o) a relatively larger error is obtained (~ 300 pcm). This large discrepancy is due to the low number of groups used by PARAGON at high energy range where the fast fission (mainly from U-238) became more important in the case of low enrichment. A new optimized energy mesh is under development that will solve this problem. At the core level, the low fuel enrichment is usually used in the blanket (for PWR). Hence, the differences seen here will be insignificant in the core level.

Table 2: MCNP and 70-group PARAGON eigenvalues for 17x17 Standard pin cell

Enrichment (w/o)	MCNP(σ in pcm)	PARAGON	Delta (pcm) (PARAGON-MCNP)
CZP Temperatures (fuel, clad, moderator = 296K)			
0.711	0.70320(±20)	0.70031	-289
1.600	0.99062(±25)	0.98795	-267
2.400	1.12060(±28)	1.11951	-109
3.100	1.19376(±28)	1.19282	-94
3.900	1.25208(±29)	1.25200	-8
4.200	1.26928(±28)	1.26933	5
4.500	1.28535(±29)	1.28522	-13
4.800	1.29943(±30)	1.29956	13
HZP Temperatures (fuel, clad, moderator = 600K)			
0.711	0.68755 (±19)	0.68477	-278
1.600	0.97438 (±25)	0.97193	-245
2.400	1.10583 (±27)	1.10406	-177
3.100	1.17862 (±29)	1.17788	-74
3.900	1.23763 (±28)	1.23762	-1
4.200	1.25488 (±29)	1.25539	51
4.500	1.27116 (±29)	1.27143	27
4.800	1.28511 (±29)	1.28586	75
HFP Temperatures (fuel=900K, clad = 600K, moderator = 600K)			
0.711	0.68029 (±19)	0.67689	-340
1.600	0.96463 (±24)	0.96215	-248
2.400	1.09495 (±28)	1.09326	-169
3.100	1.16778 (±28)	1.16694	-84
3.900	1.22664 (±30)	1.22652	-12
4.200	1.24388 (±29)	1.24427	39
4.500	1.25980 (±29)	1.26032	52
4.800	1.27377 (±28)	1.27481	104

Assembly benchmark

In these benchmarks, different types of assemblies were studied in three conditions, CZP, HZP, and HFP. The eigenvalues calculated by MCNP and PARAGON (using the 70-group cross-section library) are presented in Table 3. The comparisons show very good agreement between MCNP and PARAGON. As observed in pin cell benchmarks, the large number of cases studied in the table below demonstrates that the new interference model is applicable for all assembly designs that are used in the current operating nuclear reactor cores.

Table 3: MCNP and PARAGON eigenvalues for assemblies

Case	MCNP(σ in pcm)	PARAGON	Delta (pcm) (PARAGON-MCNP)
CZP Temperatures (fuel, clad, moderator = 296K)			
15X15 No BA with 3.9 w/o Enrichment	1.28138(±27)	1.27971	-167
15X15 with 5 w/o Enrichment and 60 IFBA	1.24705(±30)	1.24792	87
17X17 Standard 2.1w/o Enrichment	1.07761(±27)	1.07750	-11
17X17 OFA 4.8w/o Enrichment	1.38062(±27)	1.38237	175
17X17 Standard 5w/o Enrichment & 128 IFBA	1.12103(±47)	1.12187	19
17X17 OFA with 4.7 w/o Enrichment & 156 IFBA	1.06089(±34)	1.06133	44
17X17 with 9 w/o Gad Fuel	1.13789(±30)	1.13844	55
17X17 MOX Fuel	1.19911(±30)	1.20015	104
HZP Temperatures (fuel, clad, moderator = 600K)			
15X15 No BA with 3.9 w/o Enrichment	1.27326(±28)	1.27327	1
15X15 with 5 w/o Enrichment and 60 IFBA	1.23962(±30)	1.23989	27
17X17 Standard 2.1w/o Enrichment	1.06556(±28)	1.06446	-110
17X17 OFA 4.8w/o Enrichment	1.36796(±29)	1.36942	146
17X17 Standard 5w/o Enrichment & 128 IFBA	1.11125±31)	1.11148	23
17X17 OFA with 4.7 w/o Enrichment & 156 IFBA	1.05191(±29)	1.05199	8
17X17 with 9 w/o Gad Fuel	1.10677(±30)	1.10809	132
17X17 MOX Fuel	1.17858(±30)	1.18002	144
HFP Temperatures (fuel = 900K, clad and moderator = 600K)			
15X15 No BA with 3.9 w/o Enrichment	1.26405(±28)	1.26404	-1
15X15 with 5 w/o Enrichment and 60 IFBA	1.23175(±30)	1.23249	74
17X17 Standard 2.1w/o Enrichment	1.05789(±28)	1.05587	-202
17X17 OFA 4.8w/o Enrichment	1.35790(±27)	1.35902	112
17X17 Standard 5w/o Enrichment & 128 IFBA	1.10423(±34)	1.10427	4
17X17 OFA with 4.7 w/o Enrichment & 156 IFBA	1.04538(±31)	1.04457	-81
17X17 with 9 w/o Gad Fuel	1.09852(±30)	1.09908	56
17X17 MOX Fuel	1.16772(±27)	1.16806	34

CONCLUSIONS

A new resonance self-shielding model based on equivalence between exact heterogeneous slowing down calculation and approximate heterogeneous calculation is developed and implemented in the PARAGON lattice code. This new model is capable of reproducing the continuous energy Monte Carlo calculations and eliminates the need to reduce the absorption resonance integral of U-238 as it is usually done to match the continuous energy and critical experiments results. This new model has been tested in a large number of assembly fuel types encountered in PWR (or BWR) nuclear reactors and seems to produce accurate results. The core modeling with the new PARAGON version is underway. The preliminary results show a consistent good prediction of the core parameters like boron, ITC, power distribution etc.

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