PHYSOR 2004 -The Physics of Fuel Cycles and Advanced Nuclear Systems: Global Developments
Chicago, Illinois, April 25-29, 2004, on CD-ROM, American Nuclear Society, Lagrange Park, IL. (2004)

Effect of Pellet Radial Power and Temperature Distributions on Fuel Assembly Neutronics

Emily Wolters[*1], Mohamed Ouisloumen[1] and Hideki Matsumoto[2]
[1]*Westinghouse Electric Company, P.O Box 355, Pittsburgh, PA 15230-0355 USA*
[2]*Mitsubishi Heavy Industries Ltd, 3-3-1 Nishu-ku, Yokohama 220-8401, Japan*

Recently, the resonance self-shielding module of the PARAGON code has been enhanced with the capability of subdividing the fuel pellet into multi-regions. A gradient of temperature can be associated to these micro-regions to better account for the spatial temperature distribution. The purpose of this paper is to validate this module when a profile of temperature is used in the fuel pellet. Comparison to MCNP code will be performed. We will also study the effect of this gradient of temperature on reactivity and power distribution for different types of fuel pin cells and assemblies. We will compare the results to the current Westinghouse core design methodology where a flat temperature is used throughout the pellet. Since the radial temperatures depend on the radial powers and vice-versa, iteration between PARAGON and the fuel rod design code PAD will be performed.

KEYWORDS: PARAGON, lattice code, fuel temperature profile, space dependent resonance self-shielding.

1. Introduction

The exact and natural way of accounting for the temperature of the fuel pellet, in neutronics calculations, is to use a temperature profile during the generation of the assembly multi-group data that are used in the reactor core calculations. Usually, these temperature profiles are obtained by specialized fuel rod design codes. For that purpose, the lattice codes should have the capability of numerically dividing the pellet into multi-regions in all the major calculational modules namely: resonance self-shielding, flux solution and depletion.

The majority of the current core design methodologies use an effective temperature that is obtained for one single region of the fuel. This approach is usually adopted because the lattice codes lack the multi-region capability in resonance self-shielding modules and/or because of the excessive computational time that such methods can require. Many ways may be used to define an effective temperature, from simple volume average to more sophisticated one that can preserve the reaction rates. The current Westinghouse core design methodology uses a model in FIGHTH [1] code that can produce the effective fuel pellet temperature for one region by preserving the reaction rates for the major absorbing isotopes like U238 or Pu240. The advantage of this method is mainly the running time of the lattice code. The disadvantage is that the method is tied to the type of fuel and can become cumbersome because of the isotopic table that should be handled, consequently each time a new type of fuel is considered (like Thorium) new studies and qualifications are to be carried out to define new models that preserve the reaction rates.

Recently, the resonance self-shielding module of the PARAGON [2] code has been enhanced with the capability of subdividing the fuel pellet into multi-regions. A gradient of temperature can be

[*] Summer Student from University of Michigan, Ann Arbor, MI, USA, E-mail: ewolters@engin.umich.edu

associated to these micro-regions to better account for the spatial temperature distribution. The theory behind this new self-shielding module is described in reference [3]. The purpose of this paper is to study the effect of the gradient of temperatures on the assembly reactivity prediction. In section 2 we will describe the mechanism of this study. Section 3 describes the comparison to MCNP and the results and analysis of this study. The paper will end with conclusions given in section 4.

2. Models Description

2.1. Overview of PARAGON code modules

PARAGON [2] is the new Westinghouse neutron and photon transport code. It is mainly used to generate the multi-group fuel assembly data for reactor core calculations. PARAGON flux solution is based on collision probability and interface current methods to solve the transport equation. The coupling between adjacent cells is achieved through a discrete angular flux approximation at the cell's surfaces. The resonance self-shielding module of PARAGON is based on Dancoff method where the intermediate resonance assumption is used to approximate the flux shape at the resonance energies. This method has been recently generalized [3] to handle multi-rings in the resonant fuel regions with the capability of associating different temperatures to these rings (gradient of temperature). This new method will be referenced here as SDDM (Space Dependent Dancoff Method). PARAGON depletion module uses the Laplace transform method and predictor/corrector technique. It has the capability to deplete the detailed micro-regions specified in the user input.

PARAGON has been designed with great flexibility in geometry handling and data editing. It has been recently qualified and it is being used in the routine design calculations by Westinghouse and Mitsubishi Heavy Industries and their customers.

2.2. Modeling description

At the level of the assembly, the temperature of the fuel pellet plays a significant role in resonance cross-section calculations. Although the assembly data is tabulated as a function of assembly average temperature, the pin wise detailed radial temperature is very important at this level of calculation, especially in case of a heterogeneous assembly where pin powers significantly differ from pin to pin. On the other hand, the fuel rod thermal mechanics design codes depend on the radial power distribution in the pellet produced by neutron transport codes like PARAGON. The purpose of this paper is to study the effect of the radial temperature distribution produced by the Westinghouse fuel rod design code PAD [4] on the reactivity and relative powers computed by PARAGON. Since PAD depends on radial powers from PARAGON and PARAGON results depend on radial temperatures from PAD the iteration between the two codes is necessary. We will also study the results of the case when an effective temperature is used rather than space dependent temperature profile. For that, the FIGHTH code [1] will be used to generate the effective temperature by preserving the isotopic reaction rates. By using two fuel rod design codes PAD and FIGHTH, we will measure the effect on predicted reactivity due to the thermal mechanics models used to get the radial temperature profiles. The study will be carried out for different fuel types. We will first start by studying single pin cells. The following cells will be considered: IFBA, MOX and annular pellets. Fresh and burned pin cells will be considered as well as different uranium enrichments. Then, various assemblies will be considered such as 17x17 assemblies with gadolinia and IFBA rods.

The following scheme will be used to iterate between PAD and PARAGON. The initial temperature from FIGHTH will be used by PARAGON to generate initial power distribution to input to PAD. The resulting temperature will then be used by PARAGON to compute new

radial pin power distribution that will be put back to PAD. The cycle will be repeated till the temperatures and radial pin power converge. The following figure illustrates the iteration process:

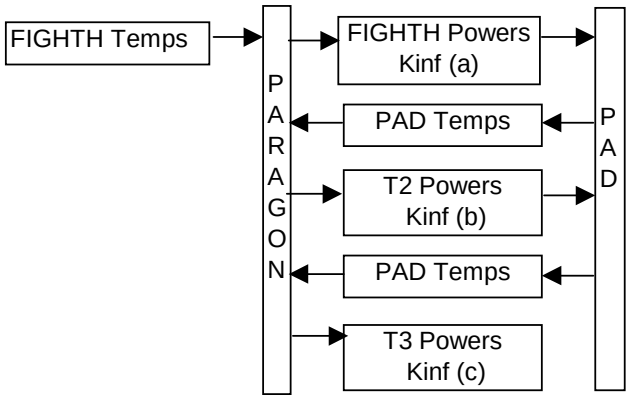

Fig.1 Iteration diagram between PAD and PARAGON

In a first step we will compare the radial power distribution against Monte Carlo code MCNP [5] calculations to benchmark the accuracy of the SDDM method. A special cross section library for MCNP has been created to reflect the temperature profile in the pellet.

3. Results and analysis

3.1. Comparison to MCNP

The aim of comparing PARAGON to MCNP results is to make sure that the new self-shielding module gives appropriate results mainly in terms of reactivity and flux distribution in the fuel pellet. For this particular study, we will consider the following typical fuel pin cells: a 17x17 IFBA (Integrated Fuel Burnable Absorber) cell, a MOX pin cell, a burned 17x17 pin cell and an annular 17x17 type of fuel cell. The fuel part of these cells will be divided into 10 equal volume rings. The following temperature profile (in degree Kelvin): [1120, 1075, 1040, 1000, 960, 920, 885, 815, 780] will be associated to these micro-regions (this profile is from a typical design case). A new cross-section library at the above temperatures has been generated for MCNP runs using NJOY code [6]. To simulate the burned fuel pin, a typical isotopic composition was taken from depleting the same pin cell in PARAGON but using a flat temperature for all ten rings. We have eliminated the fission products and kept only the uranium and plutonium isotopes in order to eliminate the burden of generating too many cross-section libraries for MCNP run. All MCNP runs are in continuous energy.

Table 1 Pin cell comparison of k_∞ for a gradient of temperature in the pellet

Cell type	k_∞		Δk_∞ (pcm)
	PARAGON	MCNP	PARAGON - MCNP
17x17 IFBA	0.89466	0.89502 (0.00056)	-36
MOX	1.14157	1.14200 (0.00070)	-43
17x17 burned fuel	1.14667	1.14831 (0.00075)	-164
17x17 Annular fuel	1.29084	1.29121 (0.00064)	-37

In the table above, PARAGON predicted reactivity results agree very well with the Monte Carlo reference. Another parameter of interest is the pin power. Fig. 2 shows the comparison of the radial pin power between MCNP and PARAGON. Note that the relative error in the MCNP tallies is less than 1%.

The difference between PARAGON and MCNP relative powers is within one standard deviation.

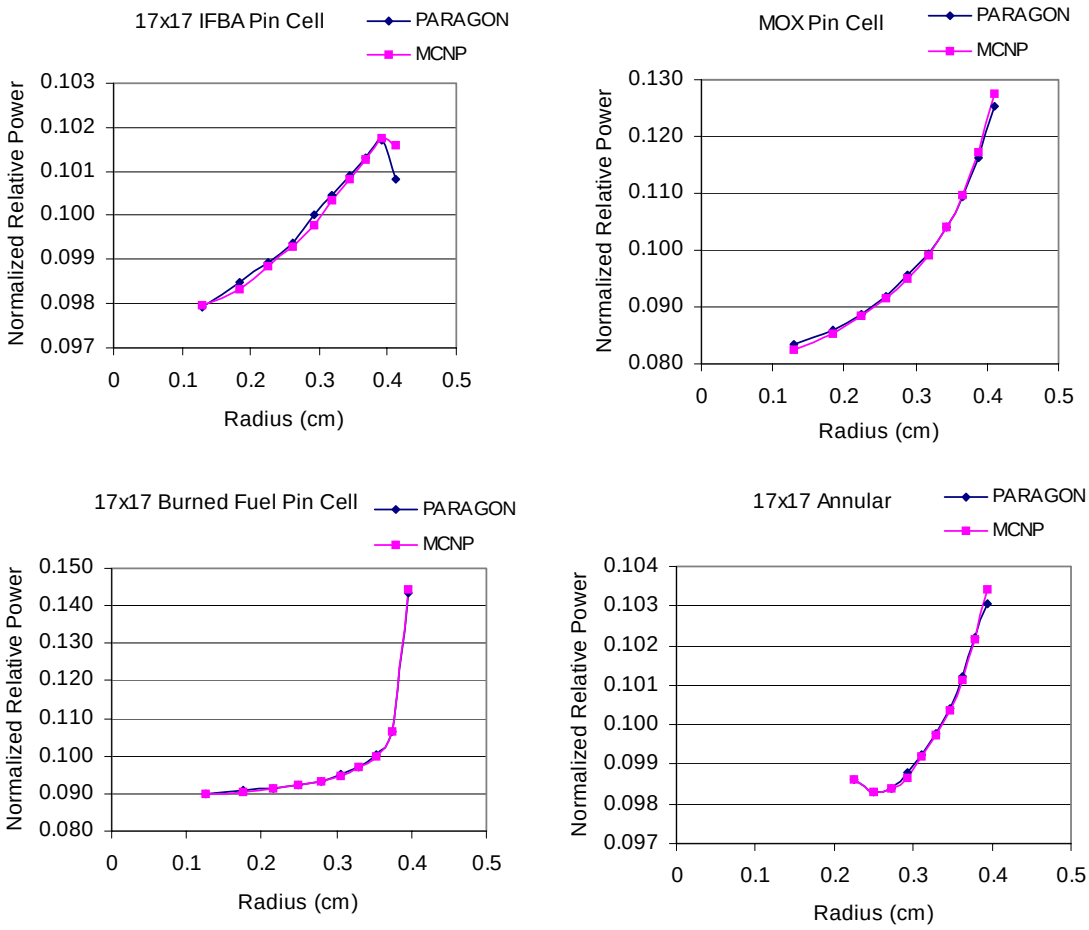

Fig. 2 Comparison of PARAGON and MCNP radial power distributions for the temperature gradient case.

The benchmarks performed above give us confidence that the new SDDM self-shielding method of PARAGON is accurate and has been implemented properly.

3.2. Effect of spatial temperature profile on PARAGON results

The iteration between PAD and PARAGON codes described in 2.2 will be considered in this section. The basic idea behind the iteration was to input PARAGON radial powers into PAD to produce a radial temperature distribution that could be put back into PARAGON.

The following models, denoted by **(a)**, **(b)**, etc, have been used to study different effects:

1. Model **(a)**: The temperature used is from FIGHTH code. An isotopic effective temperature will be used throughout all the regions in the fuel rod.
2. Model **(b)**: The temperature profile used by PARAGON is from the first iteration with PAD code.
3. Model **(c)**: The temperature profile used by PARAGON is from the second iteration with PAD code.
4. Model **(d)**: In this case a simple volume weighted average temperature (after convergence) is used for all fuel regions in PARAGON runs. This case was

introduced to compare simple average to the model **(a)**.

5. Model **(e)**: In this case, the PAD temperature model has been implemented in FIGHTH. PARAGON calculations are using effective isotopic temperature as in case **(a)**. This study will show the effect of thermal mechanics models on PARAGON reactivity prediction.

Different types of pin cells will first be considered. Some assembly results will then be presented. We found that the results converge just after one or two iterations between PAD and PARAGON. This means that with a good radial power profile it is possible with one run to generate the temperature table to be used in lattice calculations.

3.2.1. Single pin cell Results

In Fig. 3, a 17x17 IFBA pin cell (pitch is 1.26 cm and fuel radius is 0.39 cm) has been modeled. The objective is to study the impact of different temperature models described above on the reactivity predicted by PARAGON. The "(c)-(b)" case (and the overlapping of (b)-(a) and (c)-(a) curves) shows that only one iteration between PAD and PARAGON is sufficient to converge on a temperature profile for all the burnup range. The "(c)-(a)" case measures two effects. One is the differences between the PAD and FIGHTH thermal mechanics models used to generate the temperature profile, the other effect is the explicit gradient of temperature used with PAD results versus the effective temperature used in FIGHTH. The difference is quite appreciable. To separate these two effects, the case "(c)-(e)" measures the exact effect of the explicit gradient of temperature compared to an effective temperature. This case shows that an effective temperature almost reproduces the results at the BOL, but the difference become non-negligible with the burnup. This case also points to the fact that it is difficult to really define an effective temperature that can be valid for all types of fuel material composition and all spectra. The simple average of temperature is far from reproducing the results of the gradient profile of temperature as shown by the comparison in "(d)-(a)" case.

Fig.4 shows similar effects for fuel without IFBA, but with a slight bigger magnitude. For the annular fuel in Fig.5, one can see that the simple average temperature may be acceptable. Fig.6 and Fig.7 are cases for 16x16 (pitch is 1.24 cm and fuel radius is 0.41 cm) and 14x14 (pitch is 1.41 cm and fuel radius is 0.44 cm) type of fuel pins. Same shapes and higher magnitudes are obtained for these cases compared to the previous 17x17 example.

3.2.2. Fuel enrichment and temperature profile

Fig.8 shows the difference between the calculations with a temperature gradient and an effective temperature for different enrichments. The effect of the gradient of temperature in reactivity becomes more significant with the enrichment. At low enrichments, the effective temperature is giving good results. High enrichment brings in the effects of interference between U235 and U238 and that is mainly why we see big dependency on the enrichment in Fig.8. Same behavior has been observed for other type of fuels (14x14 and 16x16).

3.2.3. Assembly cases

Fig.9 is for a typical 17x17 Westinghouse assembly with same IFBA fuel rods used in Fig.3 and the standard fuel pins used in Fig.4. From that figure, one can see that all the observations for the single pin cell apply for the assembly.

Fig.10 is a typical MHI 17x17 assembly with 16 gadolinia cells (8 w/o gadolinia enrichment). The same behavior is observed as in the case of Fig.8 with a slight increase in the magnitude.

It is worth mentioning that the pin powers prediction is not sensitive to the temperature profile.

3.2.4. Effects of iterations on temperature profile generation.

During the iteration between PAD and PARAGON, there are slight changes in the magnitude of the temperature profile at the convergence of the results compared to the ones obtained by the built in radial

powers. The other important parameters did not manifest any appreciable changes in this iteration process. There is no effect on EOL ZrO_2 thickness and the rod internal pressure did not change significantly.

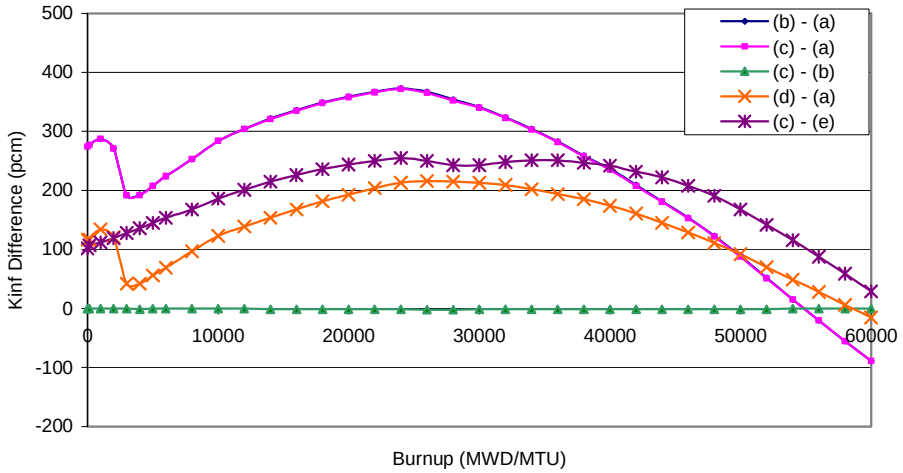

Fig. 3 17x17 IFBA pin cell with 4.7% w/o enrichment

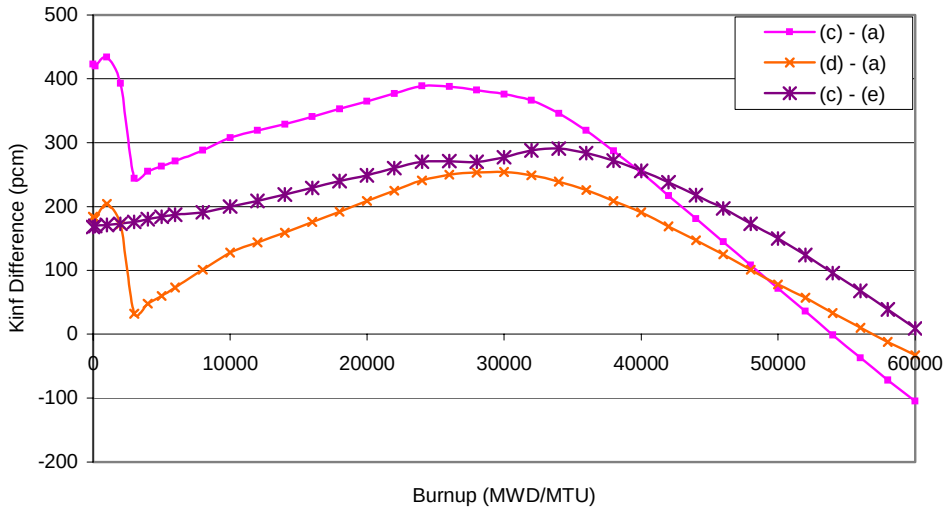

Fig. 4 17x17 Standard fuel cell (without IFBA) with 4.7% w/o enrichment

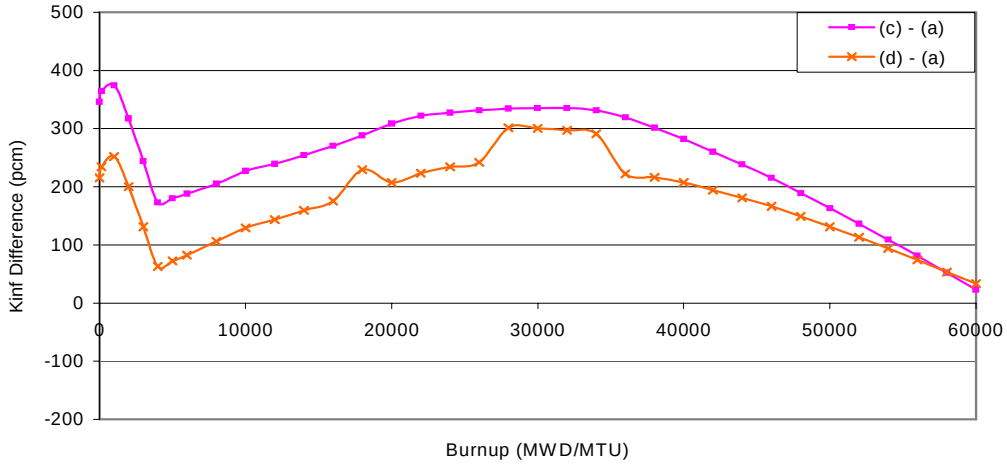

Fig. 5 17x17 annular pin cell with 4.6% w/o enrichment

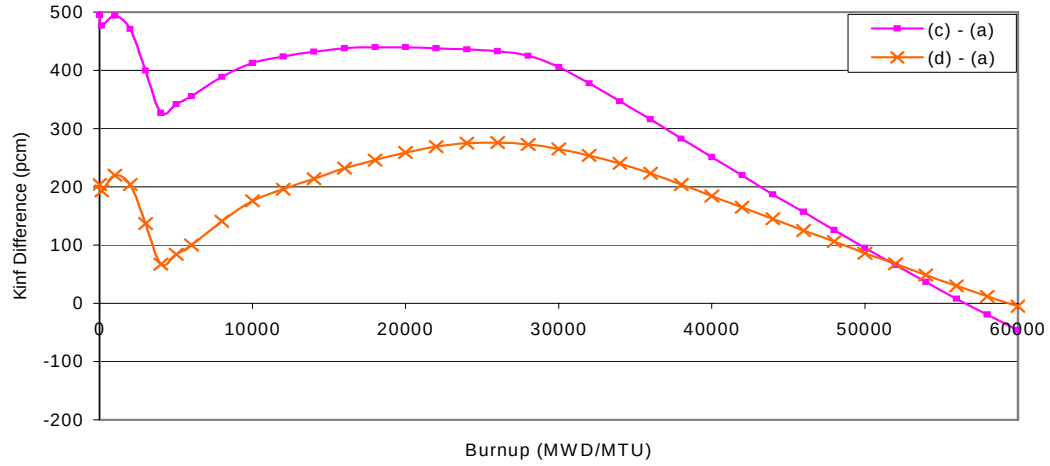

Fig. 6 16x16 standard pin cell with 4.3% w/o enrichment

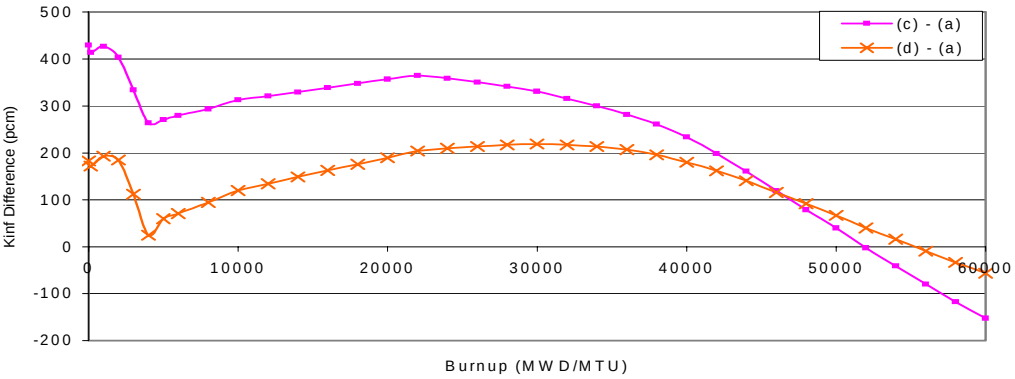

Fig.7 14x14 Standard fuel cell with 4.6% w/o enrichment

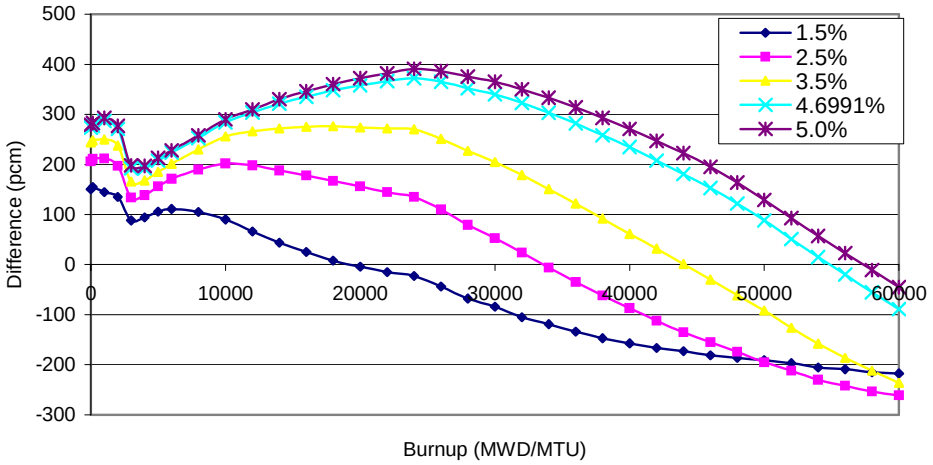

Fig.8 Case of 17x17 IFBA pin cell model "(c)-(a)" reactivity for various enrichment.

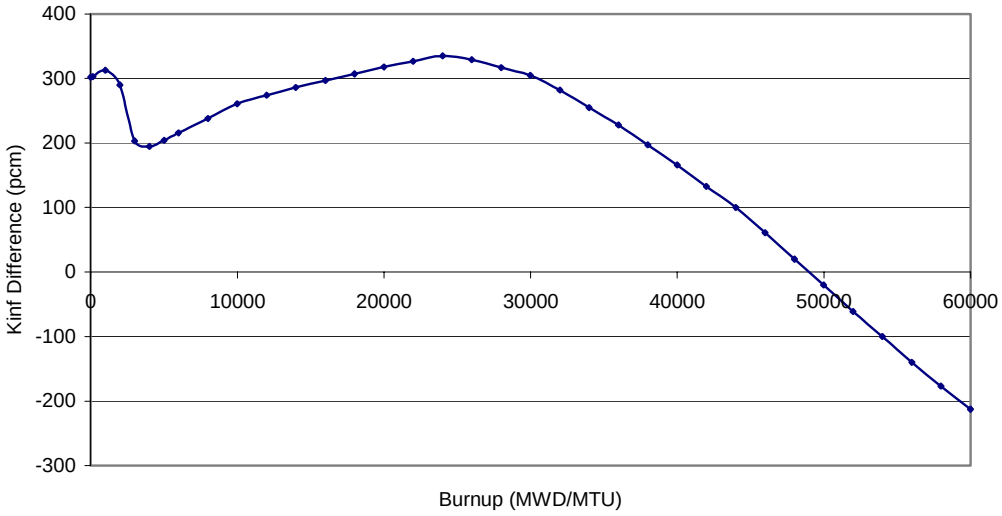

Fig.9 17x17 assembly case model "(c)-(a)" reactivity results.

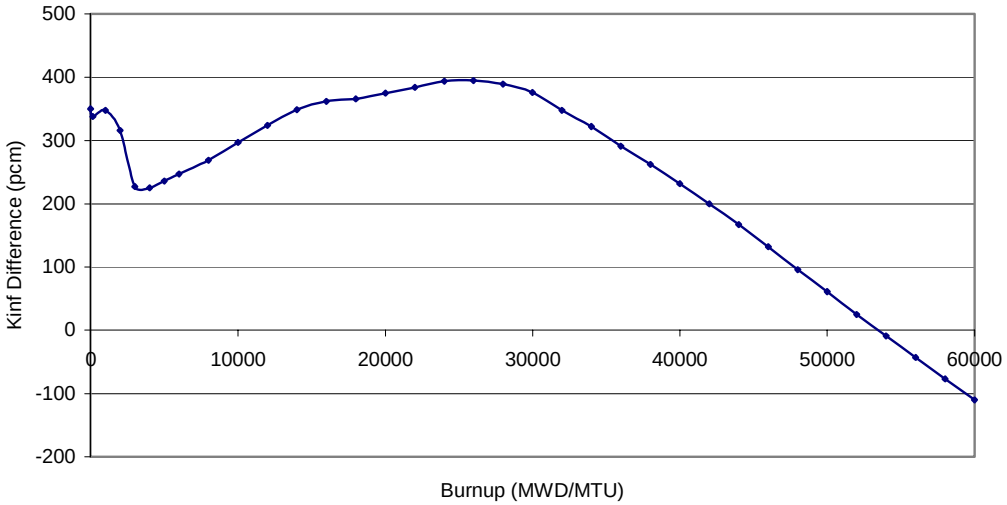

Fig.10 17x17 assembly with Gadolinia, model "(c)-(a)" reactivity results

4. Conclusions

In this paper we were interested to study the iteration between the fuel rod design code PAD and the lattice code PARAGON. PAD produces the profile of temperature that is used by PARAGON which generates the radial powers that will be used by PAD. This iteration was made possible with the new self-shielding module implemented recently in PARAGON that allows generating multi-group multi-regions temperature dependent self-shielded cross-sections.

The calculation performed both at a pin cell level as well as in the assembly level shows that accounting for the gradient profile plays a significant role in reactivity prediction. We can also conclude from this study the following:

- The new PARAGON self-shielding method predicts with a good accuracy the radial power profiles compared to MCNP.
- A simple volume average temperature used in all fuel rings may not reproduce the results of a gradient of temperature.
- The effective temperature (one temperature) used for all fuel rings reproduces the results of a gradient of temperature at BOL, but with the depletion significant differences may be obtained.
- The reactivity prediction is sensitive to the thermal mechanics model used to generate the temperature profile.

The effective temperature model is of interest in saving the calculation time in lattice code calculations. This study shows that it is difficult and cumbersome to define generic tables of effective temperature that are applicable for all types of fuels and fuel compositions.

In the future we will extend this study to cover the full core design calculations. For that one has to come with a model on how to take into account the gradient of temperature in the generation of the cross-section for core calculations within a reasonable computation time.

Acknowledgements

The authors would like to thank H.C. Huria for his help on generating the library for MCNP runs. We are also grateful to Philippe Bellanger for his help on running PAD code.

References

1) W. B. Henderson, "FIGHTH- A Simplified Calculation of Effective Temperatures in PWR Fuel Rods for Use in Nuclear Design," WCAP-9522, (1979).
2) M. Ouisloumen, et al., ANS International, Meeting on Mathematical Methods for Nuclear Applications, Sept. 2001,Salt Lake City, Utah, USA
3) H. Matsumoto, et al., Proc. Int. Conf. On The New Frontiers of Nuclear Technology: Reactor Physics, Safety and High Performance Computing, PHYSOR2002, 14A-01, Seoul, Korea, 2002.
4) Foster, J. P. et al., "Improved Performance Analysis and Design Models - PAD 4.0"WCAP-15064, November 1999.
5) "MCNP4B- Monte Carlo N-Particle Transport Code System", CCC-660, RSICC Computer Code Collection, April, 1997.
6) MacFarlane R.E., "NJOY91.118: A code System For Producing Pointwise And Multigroup Neutron and Photon Cross Sections From ENDF/B Evaluated Nuclear Data", ORNL, RSIC, PSR-171 (1994).