

COMPARISON OF NEUTRONIC BEHAVIOUR OF TRIANGULAR LATTICE AND CIRCULAR ARRAY DESIGNS IN A SMALL FLUORIDE SALT-COOLED HIGH-TEMPERATURE REACTOR

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ABSTRACT

This work aims to provide better understanding on the neutronic performances of two fuel assembly designs, namely triangular lattice and circular array, in order to improve fuel utilization of a UC_2 pin-type fuel assembly in a Small modular Advanced High Temperature Reactor (SmAHTR). In addition, this paper investigates whether a circular array arrangement can be simply modeled with a triangular lattice design or vice versa while still getting the closest neutronic performance, which then offers simplification in modeling using a three-dimensional Monte Carlo neutronic code, Serpent. Two parameters are introduced, namely pitch, p , for the triangular array and radial distance, \bar{d}_{rad} , for the circular array. For the circular array design, \bar{d}_{rad} is varied with respect to p of the triangular lattice design, creating six test cases. The infinite multiplication factor, k_{inf} , and flux spectrum of each test case are then compared. Results show that the triangular lattice design has better neutron economy compared to the circular array cluster for the case where $p = \bar{d}_{rad}$. The neutronic performance of the circular array design is improved when the radial distance is incrementally decreased from the original pitch and the interpolated decrement percentage is found to be approximately 8% when the reactivity difference is 0 pcm. The circular array design has to concede smaller radial distance and tighter spacing between pins to achieve similar neutronic performance of the triangular lattice arrangement.

ABSTRAK

Kerja-kerja ini bertujuan untuk memberi pemahaman yang lebih baik mengenai prestasi neutron dua reka bentuk pemasangan bahanapi, iaitu kisi segi tiga dan pekeliling, untuk meningkatkan penggunaan bahan api daripada bahan api pin-jenis UO_2 dalam Reaktor Suhu Tinggi Modular Tinggi (SmAHTR). Di samping itu, makalah ini menyiasat sama ada susunan tatasusunan pekeliling hanya boleh dimodelkan dengan reka bentuk kisi segitiga atau sebaliknya sementara masih mendapat prestasi neutron yang paling dekat, yang kemudiannya menawarkan penyederhanaan dalam pemodelan menggunakan kod neutron Monte Carlo tiga dimensi, Serpent. Dua parameter diperkenalkan, iaitu pitch, p , untuk pelbagai segitiga dan jarak radial, \bar{d}_{rad} , untuk pelbagai pekeliling. Untuk reka bentuk pelbagai pekeliling, \bar{d}_{rad} diubah berikutan dengan p reka bentuk kekisi segi tiga, mewujudkan enam kes ujian. Faktor pendaraban tak terhingga, k_{inf} , dan spektrum fluks setiap kes ujian kemudiannya

dibandingkan. Keputusan menunjukkan bahawa reka bentuk kisi segitiga mempunyai ekonomi neutron yang lebih baik berbanding dengan kluster pelbagai pekiling untuk kes di mana $p = drad$. Prestasi neutron reka bentuk array pekiling bertambah baik apabila jarak radial secara bertahap menurun dari pitch asal dan peratusan penurunan interpolasi didapati kira-kira 8% apabila perbezaan kereaktifan ialah 0 pcm. Reka bentuk tatasusunan bulatan harus mengakui jarak jejari yang lebih kecil dan jarak yang lebih tegas antara pin untuk mencapai prestasi neutron yang serupa dengan susunan kekisi segitiga.

Keywords: Triangular lattice, circular array, fluoride salt-cooled high-temperature reactor (FHR), Small modular Advanced High Temperature Reactor (SmaHTR), neutron economy, UO_2 pin-type fuel assembly.

INTRODUCTION

This study explores various possible fuel pin configurations that can be implemented in a fuel assembly of the Small Modular Advanced High Temperature Reactor (SmaHTR) [1], which is a variant of fluoride salt-cooled high-temperature reactors (FHRs). The main requirement is the arrangement needs to be fitted in the circular coolant channel of the assembly that has a radius of 16.94 cm as shown in Figure 1. Common pin arrangements in a pin-type fuel assembly are square lattice in PWRs, triangular lattice in VVERs and circular array in AGRs or CANDU reactors (Figure 2). Since the studied SmaHTR fuel assembly is a hexagonal prism, the preferable options are narrowed down to two arrangements, namely triangular lattice and circular array. This assessment is intended to provide better understanding of which arrangement can give better neutron economy as well as the much needed improved fuel utilization for a pin-type fuel assembly.

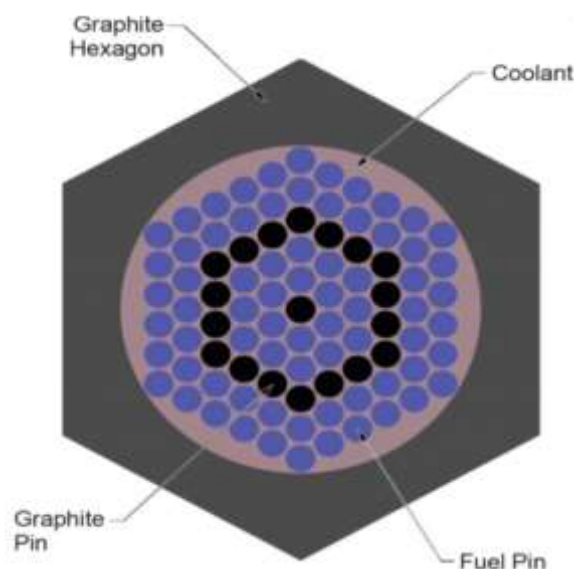


FIGURE 1. SmAHTR fuel assembly with triangular lattice fuel pin arrangement [1].

There was one previous study carried out by Szakaly et al. [2] that compares between triangular lattice and circular array designs. The study used WIMS (version 9), for analyzing triangular lattice only and MCNP

(Monte Carlo) code for comparing both triangular lattice and circular array designs. It is claimed that the triangular lattice arrangement model can be used in WIMS, to represent the circular pin arrangement because the difference in reactivity is less than 200 pcm. Nonetheless, the study does not clearly explain the geometric descriptions of both designs, such as the distance between adjacent fuel pins and the radial distance between two circular arrays. Therefore, another objective of our assessment is to find out whether a circular array arrangement can be simply modeled with a triangular lattice design or vice versa while still getting the closest (if not the same) neutronic performance, which then ultimately offers simplification in modeling.

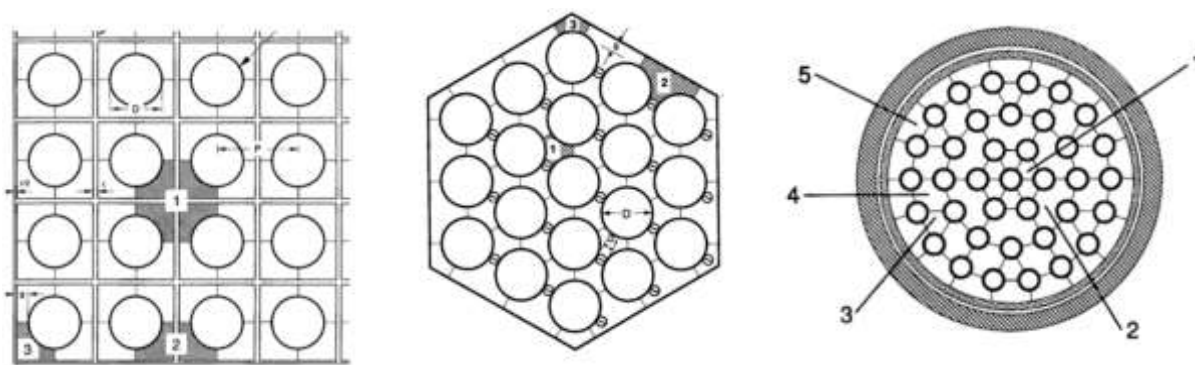


FIGURE 2. Fuel pin arrangements: (from left) square lattice, triangular lattice and circular array. The numbering denotes the different subchannel areas in the assembly. Note: Centre pin is fuelled in CANDU and unfuelled in AGR. Reproduced from Ref. [3].

METHODS

Comparing triangular lattice and circular array designs

The neutronic code used in this assessment is Serpent instead of WIMS. Serpent has been under development at the VTT Technical Research Centre in Finland since 2004 [4]. It is a three-dimensional Monte Carlo reactor physics code that can perform lattice physics calculations to estimate the criticality of a fuel assembly in an infinite lattice or in a full-core. Although, WIMS is a quick solver, it is not used here because it requires users to use different modules, other than the standard CACTUS to model the circular array of a fuel assembly [5]. CACTUS is one of the modules in WIMS that is used to calculate the multiplication factor (the criticality, k) of the model using the method of characteristics

One way to specify the circular array geometry is by using CACTUS3D, a slightly advanced module of CACTUS. This method, however, is more time consuming than using Serpent to set up as it requires placing each pin separately, using surfaces and cells definitions. Generally, to model the AGR pin cluster, the standard module used in WIMS is the PIJ module, which helps users to properly create the circular array using a shortcut parameter ‘array’ and then to calculate collision probabilities in the geometry. Subsequently, the PIJ module needs to be followed by another flux solver module named PIP, which calculates fluxes from the PIJ collision probabilities.

Having different modules means different methods in solving for the multiplication factor, k , of a system. Hence, the concern is that this will provide inconsistencies and unknown discrepancies that may largely come from the distinct solver modules used in WIMS and not exactly from the difference in pin arrangements. Moreover, internal parameters with respect to each module will also be different. For example, in CACTUS module, to get better k estimation, one of the parameters used is ‘azimuthal’, which needs to be manipulated or increased in order to increase the solver accuracy by changing the track spacing. On the other hand, in the PIJ

module, one of the central parameters is ‘lines’ which needs to be set for determining the number of lines used to integrate collision probabilities. Additionally, if using two different modules, it would be prudent to take special care to make sure both simulations had converged as any errors due to, for example, insufficient tracking angles, could be different in the different cases which could bias results.

For those explained reasons, Serpent is selected as the most suitable code for this study because it offers consistency as it will always use the same Monte Carlo method, regardless of the fuel pins configurations. This is also a similar issue that was faced by Szakaly et al., in which they have to use MCNP code instead of WIMS [2]. Since the Monte Carlo method is inherently known to require longer computational time, our assessment evaluates the UO₂ fuel with the minimum enrichment required for supercritical, which is 7 wt.% as estimated from our preliminary analysis. The minimum fuel enrichment is chosen because it has the shortest burnup steps, significantly reducing Serpent computational time. The Serpent analysis is carried out for a 2-dimensional infinite fuel assembly lattice for 1600 burnup days. Additionally, in order to achieve source convergence and maintain good statistical accuracy, a total of 20 million neutron histories are used in Serpent. The statistical error is found to be small, approximately 11.31 pcm.

To easily model and compare the triangular lattice and circular array configurations, some important parameters are introduced. For triangular lattices, the important variable is the center to center distance between fuel pins, also known as pitch, p . On the other hand, for the circular array, the significant parameter is radial distance, d_{rad} . It is defined as the distance between two adjacent rings or circular arrays as presented in Figure 3. The circular array configuration is modified by changing the value of the radial distance, d_{rad} . Another related parameter is the edge distance, d_{edge} , which is defined as the radial distance between the outermost ring and the edge of a coolant channel in a circular array fuel assembly.

The reference test case is the fuel assembly with triangular lattice arrangement (Figure 4a). There are additional five test cases with circular array configurations as displayed in Figure 4. They all have similar number of fuel and graphite pins as the baseline fuel assembly has (reference test case), preserving the proportions of all materials (coolant, fuel, cladding and graphite) in the assembly. The first test case is labeled as case A as shown in Figure 4b, in which the pitch, p , is made equal to the radial distance of the circular array fuel assembly ($p = d_{rad} = 3.08$ cm). To further understand the effect from varying the radial distance, cases B, C and D are created for the sensitivity analysis of the radial distance where the distance between fuel pin rings of the pin is modified by -5% , -1% and $+1\%$ of the original pin radial distance from case A (3.08 cm). The last test case (case E) is simply changing the radial distance by equally spacing the fuel pin rings within the coolant channel inside the assembly, including the edge distance. The radial distance, d_{rad} and edge distance d_{edge} for case E are then calculated to be 2.823 cm. Table. 1 tabulates the d_{rad} and d_{edge} of all the test cases fuel assembly configurations.

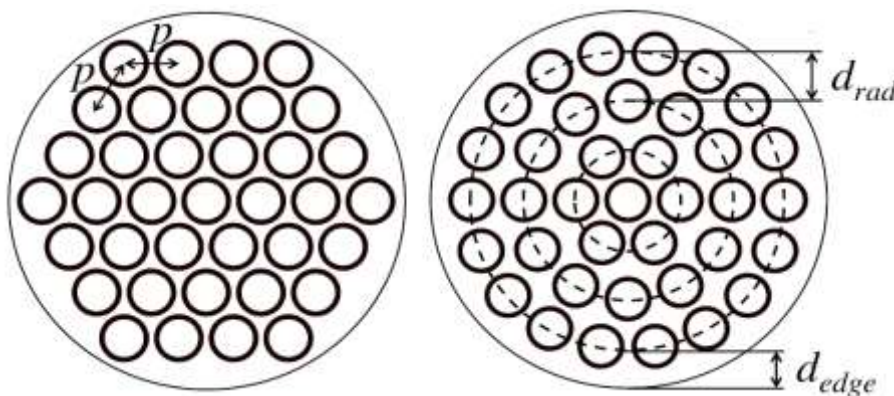


FIGURE 3. (Left) Pitch, p in a triangular lattice and (right) the radial distance, d_{rad} between two adjacent fuel pins rings in a circular array cluster.

TABLE 1. Variations of d_{rad} and d_{edge} for all test cases.

Parameter	Reference Case	Case A $p = d_{rad}$	Case B -5%	Case C -1%	Case D +1%	Case E Equally spaced
p or d_{rad} (cm)	3.08	3.08	2.93	3.05	3.11	2.82
d_{edge} (cm)	-	1.54	2.31	1.69	1.4	2.82

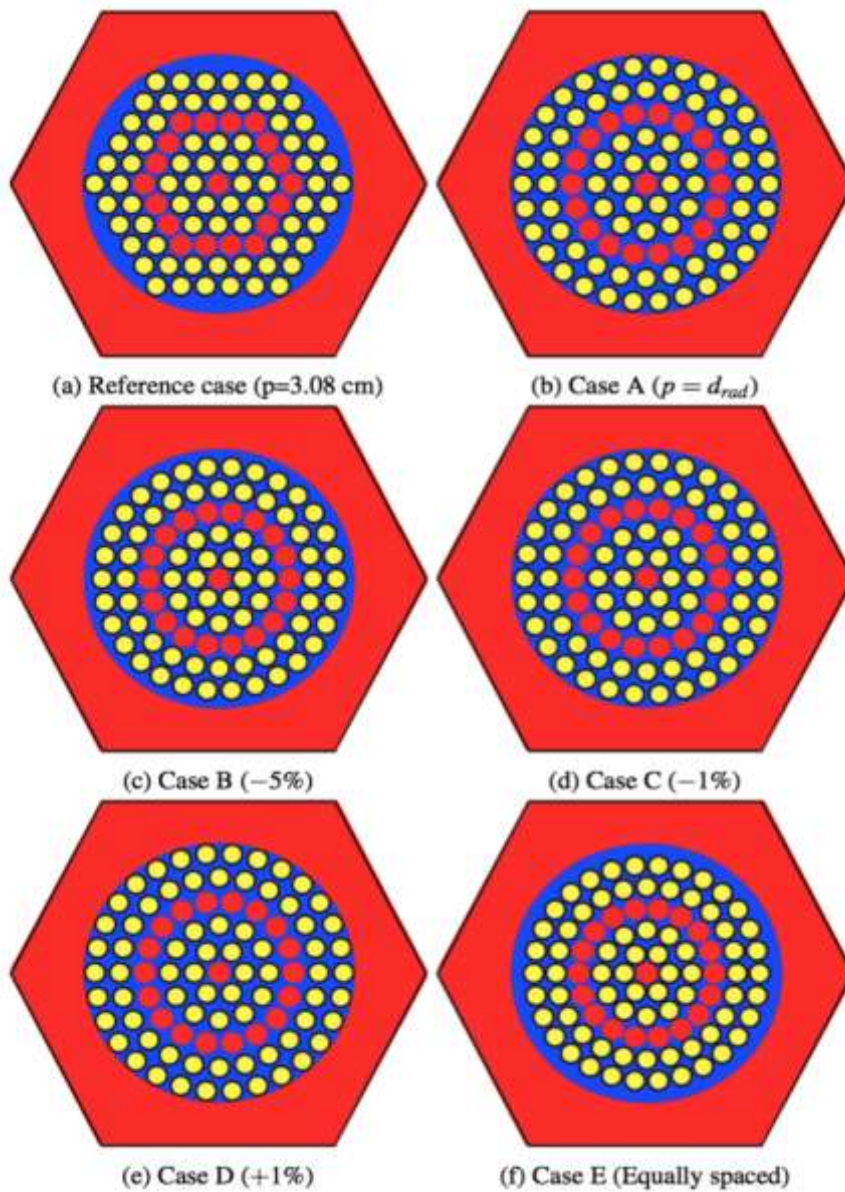


FIGURE 4. Fuel assembly designs for all test cases. Yellow, blue and red colors represent fuel, FLiBe coolant and graphite, respectively.

RESULTS

Figures 5 and 6 respectively show the infinite multiplication factor, k_{inf} and the difference in reactivity comparison between the triangular lattice design and all other test cases. It can be observed from the graphs that the triangular lattice arrangement has superior k_{inf} , about 2913 pcm reactivity difference, compared to that of the circular array design (case A), in which the pitch and radial distance are equal. Decreasing the radial distance by 1% (case C) and 5% (case B) from the original pitch yield slightly reactivity benefit, reducing the reactivity differences to 2547 pcm and 1079 pcm, respectively. Conversely, increasing the radial distance by 1% (case D) of the pitch causes even larger discrepancy, approximately 3240 pcm reduction in comparison to the reactivity of the triangular lattice design. Surprisingly, when the fuel pin rings are equally spaced radially inside the circular coolant channel (case E), the difference in reactivity throughout fuel depletion is found to be small, on average 187 pcm.

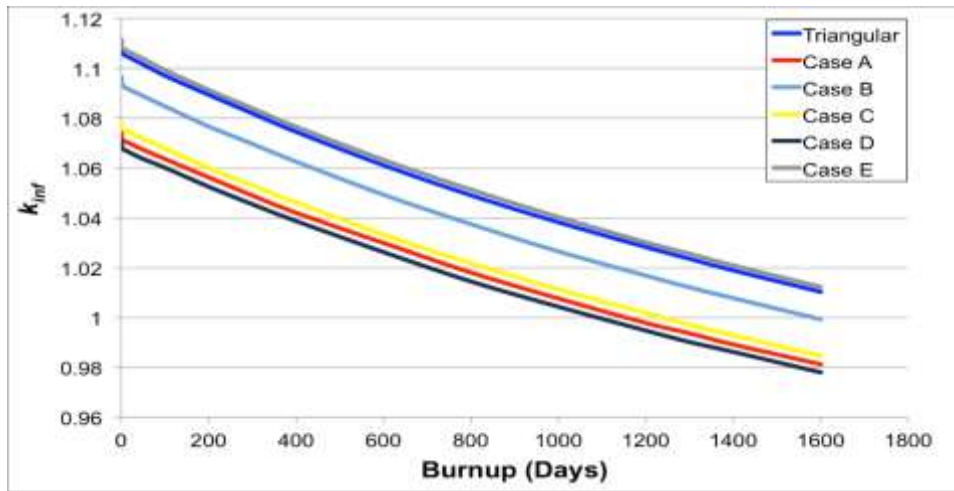


FIGURE 5. k_{inf} comparison between test cases.

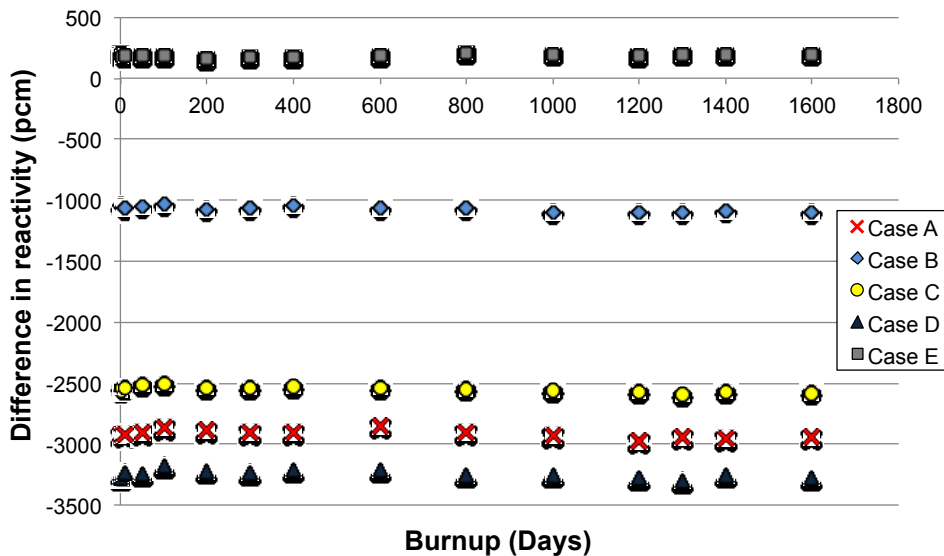


FIGURE 6. Difference in reactivity for all cases in relative to the triangular lattice assembly design.

The k_{inf} is related to the flux spectrum as the higher k_{inf} typically signifies better thermal spectrum. The flux spectrum in the fuel (Figure 7) does show differences between test cases but not so obvious because all of them use the same fuel and cladding. Nevertheless, the flux spectrum in the fuel assembly that consists of graphite, coolant, fuel and cladding shows significant differences as plotted in Figure 8. The triangular lattice design has better thermal neutron spectrum compared to that of case A, B, C and D, implying that in the triangular lattice configuration, neutrons are properly moderated. The pin arrangement in the triangular lattice provides consistent neutron moderation and fission reaction for a fuel pin in every direction in the middle of the assembly because the pitch, p is constant. In a circular array design, the radial distance between pins and the circumferential distance between adjacent pins in a ring are not the same. Thus, this might also cause non-uniform and weak neutron moderation and fission reaction.

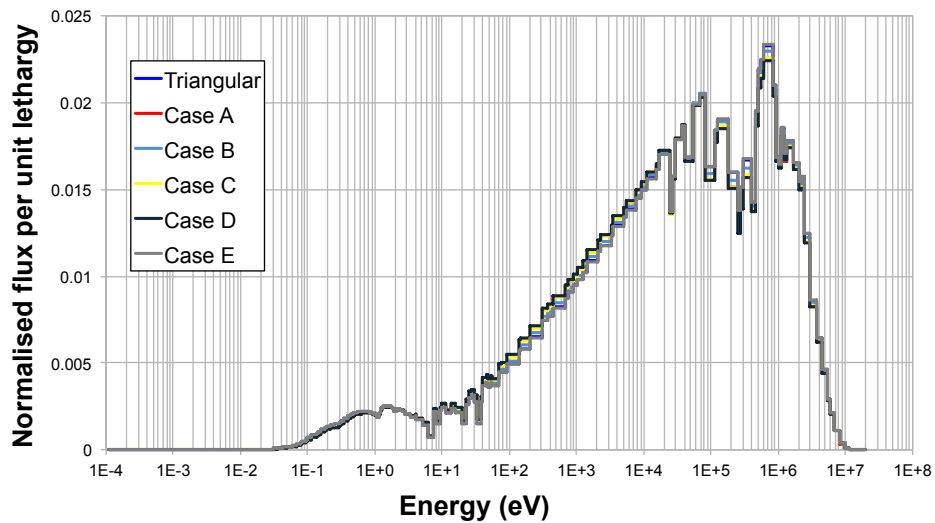


Figure 7. Comparison of flux spectra in the fuel for all test cases (172 energy bins).

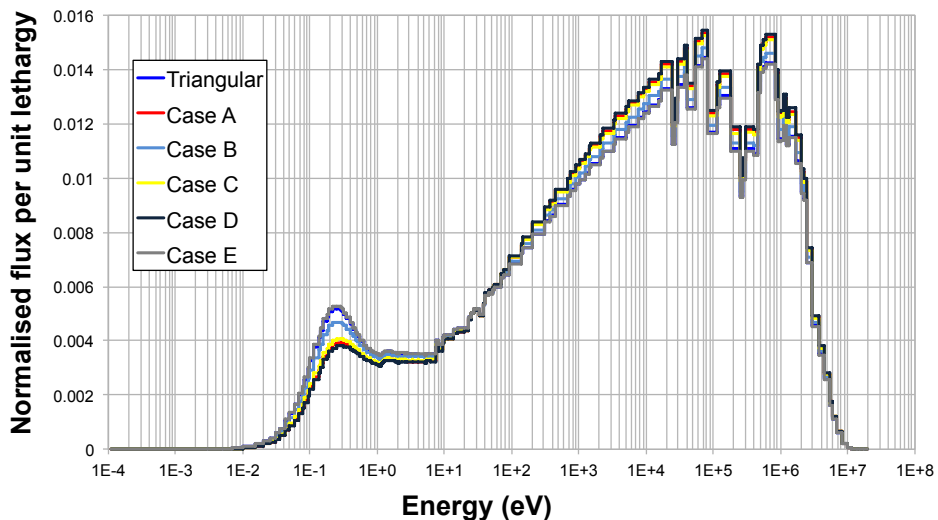


Figure 8. Comparison of flux spectra in the fuel assembly for all test cases (172 energy bins).

In case B and C, a slight improvement in thermal spectrum occurs because the radial distance is decreased and hence fuel pins are arranged closer to the graphite pins, which are located in the third ring of the arrangement (Figure 4). This then provides improved neutron moderation and softens the flux spectrum in the middle of the

fuel assembly, where it is known to have hard neutron spectrum. On the other hand, in case D, although the fuel pins in the outermost ring are located very close to the graphite reflector, the fuel pins in the middle of the fuel assembly are weakly moderated because of the increment in radial distance by 1%. For case E, the flux spectrum of the circular array design has a very similar plot to that of the triangular lattice configuration. The improved neutronic performance of the circular array is mainly because the radial distance has been reduced to even shorter amount by 8.34% from the original pitch. As a result, this provides improved and similar flux spectrum to that of the triangular lattice design. From cases A, B and C, one can find the radial distance in which the difference in reactivity is zero from interpolating the linear relationship of the reactivity difference and the radial distance as shown in Figure 9. Based on the plot and the linear correlation shown on the figure, the interpolated radial distance is found to be 2.83 cm, which is less than 8.12% from the original pitch. Then, using the same correlation displayed on the plot, and inserting back the reactivity difference found for case E, which is 187 pcm, the interpolated radial distance is found to be 2.82 cm. This interpolated radial distance is indeed the same radial distance used for case E.

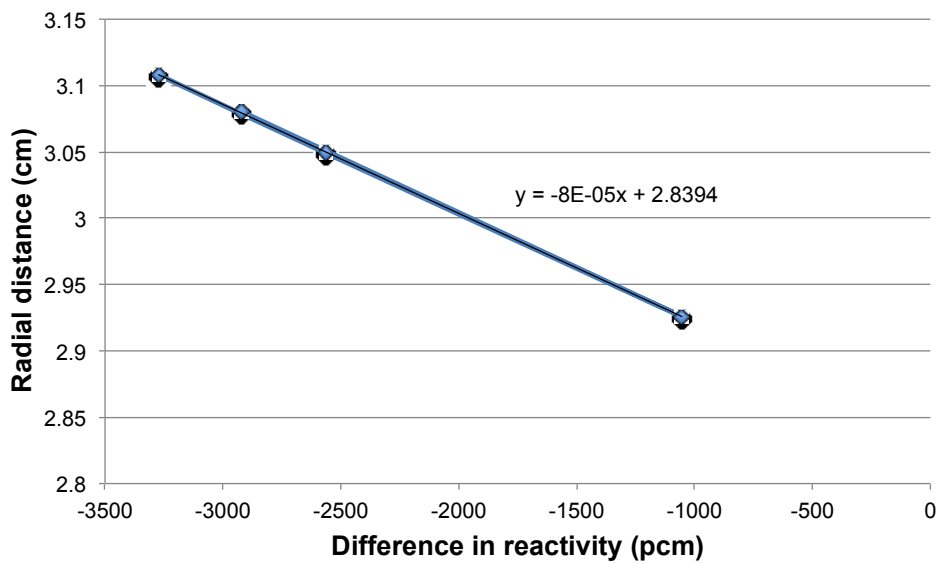


Figure 9. Linear relationship between radial distance and reactivity difference.

CONCLUSIONS

This finding clearly implies than one cannot simply use a triangular lattice to represent a circular array arrangement to simplify modeling (e.g. in WIMS) prior to finding the properly adjusted radial distance. In order to obtain similar neutronic performance, the circular array radial distance has to be decreased by a certain percentage from the pitch of a triangular lattice design, in this case roughly 8%. The risk of not doing so is that it may cause a significant difference in k_{mf} estimation as obtained earlier for case A. The percentage decrement of the radial distance required will of course differ according to presence of graphite pins in the fuel assembly and the fuel assembly size. The neutronic performance of the triangular lattice arrangement is better than that of a circular array arrangement when the radial distance and pitch are equal. The neutronic performance of the circular array design can be incrementally improved by decreasing the radial distance to make the performance similar to that of the triangular lattice. The circular array design has to concede smaller radial distance and tighter spacing between pins to achieve similar neutronic performance of the triangular lattice arrangement. Nonetheless, this tighter radial spacing can introduce a higher pressure drop in a subchannel and essentially across the fuel assembly. Hence, the triangular lattice design seems to be the more preferable choice in order to avoid such mechanical issues in addition to its superior neutronic performance.

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REFERENCES

- [1] S. R. GREENE, “Pre-Conceptual Design of a Fluoride-Salt-Cooled Small Modular Advanced High-Temperature Reactor (SmAHTR),” Technical Report ORNL/TM-2010/199, Oak Ridge National Laboratory, Oak Ridge, Tennessee (2010).
- [2] F. J. SZAKALY, T. K. KIM, and T. A. TAIWO, “Neutronics Assessment of Stringer Fuel Assembly Designs For the Liquid-Salt-Cooled Very High Temperature Reactor (LS-VHTR),” In Proceedings of Joint International Topical Meeting on Mathematics & Computation and Supercomputing in Nuclear Applications (2007).
- [3] N. E. TODREAS and M. KAZIMI, “Nuclear Systems Volume I: Thermal Hydraulic Fundamentals,” ISBN 978-1560320517, Taylor & Francis, 2nd edition (1989).
- [4] J. LEPPÄNEN, M. PUSA, T. VIITANEN, V. VALTAVIRTA, and T. KALTIAISENAHO, “The Serpent Monte Carlo Code: Status, Development and Applications in 2013,” *Annals of Nuclear Energy*, 82:142–150 (2015).
- [5] ANSWERS, WIMS User Guide for Version 11, Amec Foster Wheeler, 11th edition (2015).