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MCNP-6 Kinetics Simulation of Fast Periodic Pulsed Reactors

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Abstract -*In the design of fast periodic pulsed reactors, the time dependent simulation of the power pulse is based on a point kinetic model, which is known to have limitations. An accurate calculation method is desired for the design analyses of fast periodic pulsed reactors. Monte Carlo computer code MCNP6 is used for this task due to its three dimensional transport capability with a continuous energy library. Some new routines were added to simulate the rotation of the movable reflector parts in the time dependent calculation. IBR-2M fast pulsed reactor was utilized to validate the new routines. This reactor has prompt supercritical state for ~400 μs during the equilibrium state. This generates long neutron fission chains, which requires tremendously large amount of computation time during Monte Carlo simulations. Russian Roulette was applied for these very long neutron chains in MCNP6 calculation, combined with other approaches to improve the efficiency of the simulations. In the power pulse of the IBR-2M at equilibrium state, there is some discrepancy between the experimental measurements and the calculated results using the point kinetics model. MCNP6 results matches better the experimental measurements, which shows the merit of using MCNP6 calculation relative to the point kinetics model*.

I. INTRODUCTION

IBR-2M [1, 2] is a sodium cooled fast pulsed reactor, using plutonium dioxide fuel material. It is used for research purposes as a neutron source in the field of condensed matter physics, biology, and material science. A unique feature of this reactor is the periodic variation of its reactivity by the rotation of two movable reflector (MR) parts. At frequency of 5 Hz, the reactor is brought from a deep subcritical state when the MR parts are rotated off the core to a prompt super critical state when the two MR parts meet at the top of core. Such reactivity variation results in a large power pulse, as well as pulsed fast neutron flux up to 10^{17} n cm^{-2} s^{-1}. Therefore, the IBR-2M reactor produces one of the most intense pulsed neutron flux on the moderator surface of ~10^{16} n cm^{-2} s^{-1}. Due to the rotation scheme of MR parts, the total time period of IBR-2M is 0.2 seconds. When the two MR parts are rotated off the core, the reactor is in subcritical state and it is driven by delayed neutrons. Some fission products produced during the pulse decays after the pulse to generate these delayed neutrons. At certain reactivity level, an equilibrium state is reached so the intensity of the delayed neutron source is the same at the beginning and the end of the time period.

Accurate kinetics calculation for this type of reactors are essential to determine the equilibrium reactivity level as well as the pulse parameters. In the design analyses of these pulsed reactors including IBR-2M, point kinetics models combined with some modifications were used to predict the pulse parameters. To improve the accuracy of these analyses, a coupled MCNP6/Point Kinetic calculation procedure was developed. The reactivity profile was obtained by MCNP6 [3] steady state criticality calculation, with the MR parts rotated to different angular positions corresponding to the pulse period. In addition, the kinetics parameters were calculated using MCNP6. A simple point kinetics code was developed, using the reactivity profile and the obtained kinetics parameters to calculate the time dependent power and search for equilibrium state. Using this procedure, the reactivity and the power curve could be calculated without any assumptions or approximations. However, the limitation of point kinetic method still exists and an accurate method is desired for the design analyses of these type of reactors.

The Monte Carlo computer code MCNP6 was selected for accurate analyses, however MCNP6 can calculate the neutron flux and the power as a function of time only for stationary geometries. To simulate the rotation of the movable reflector (MR) parts in the fast pulsed reactor like IBR-2M, new routines were added. This MCNP6 modification was tested using the IBR-2M reactor model. In this test case, the maximum reactivity is kept below zero (i.e. subcritical state) to save the computation time by adjusting the control rod positions. The time dependent power calculated with MCNP6 agrees well with the results obtained from point kinetics calculation, which validates the MCNP6 modification. However for the IBR-2M at equilibrium state, the reactor is in prompt supercritical state with $\rho > \beta$ for ~400 μs at each time period, and this prompt supercritical state generates extremely long neutron fission chains. This requires huge computational resources, which is not possible to get. To resolve this issue, Russian Roulette was applied against the very long neutron histories combined with other approaches. With this methodology, it was possible to perform MCNP6 calculation for the IBR-2M equilibrium demonstration case. The power pulse was calculated with relatively small statistical errors. The power pulse calculated with MCNP6 agrees well with results from the point kinetics for most of the selected time period, except for a small time interval after the pulse. In this time interval, MCNP6 results are significantly higher than point kinetics. This difference is consistent with the difference between the experimental data and the point kinetics results [4, 5]. This confirms that the MCNP6 results are more accurate than the results obtained with the point kinetics model.

II. MCNP6 TIME DEPENDENT CALCULATION WITH MOVABLE GEOMETRY

To simulate the rotation of the MR parts in the fast pulsed reactor IBR-2M, new routines were added to MCNP6. To test and validate this modification, the IBR-2M reactor model with MR rotation was used and the radial configuration of this geometrical model is shown in Fig. 1. The movable reflector (MR) of IBR-2M has two parts, main movable reflector (MMR) and auxiliary movable reflector (AMR), which rotate in opposite direction at constant speeds. The MMR has an angular rotation speed of 3600°/sec (10Hz) and the AMR has an angular rotation speed of 1800°/sec (5Hz). For every 0.2 seconds the MMR and AMR meet at the reactor centerline, which cause the maximum reactivity. Therefore, the total time period of the pulse is 0.2 second [1]. To save the computation time, only part of the whole time period is selected for the MCNP6 time dependent calculation and the control rods positions are adjusted to keep the reactor in subcritical state all the time. A constant delayed neutron source was used during this calculation.

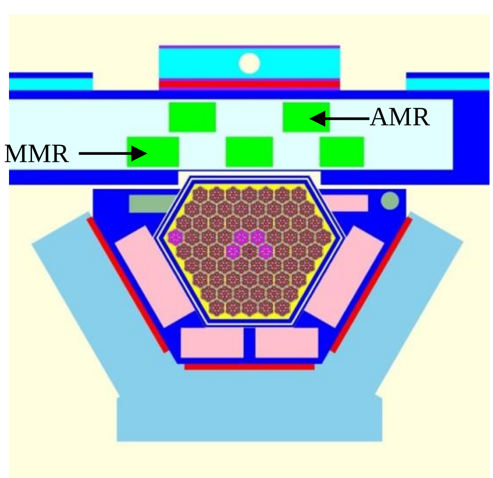

Fig. 1. Radial Configuration of the IBR-2M reactor model, with both pieces of MR rotated to the core center position for maximum reactivity

The total length of the time period in the calculation is 4200 μs, and the corresponding reactivity curve were obtained by a series of MCNP6 steady state criticality calculations, with MR parts positioned at specific angular positions corresponding to the time points of Fig. 2. To get an accurate reactivity curve, the statistic error of the calculated k-eff is very small, less than 2 pcm. Previous studies show the shape of reactivity curve has very little dependence on the control rods positions. Therefore, the reactivity curve shown in Fig. 2, for this subcritical test problem, has the same shape as the reactor reactivity curve during the equilibrium state. The maximum reactivity occurs at t = 2100 μs, when two parts of MR meet at the core centerline.

The reactivity curve shown in Fig.2 was used in point kinetics calculation to obtain the time dependent power distribution. MCNP6 time dependent calculation was also performed to obtain the power distribution. The time dependent power curves calculated by MCNP6 and point kinetics are compared in Fig.3. In both calculations, 10 μs constant time step is utilized and the power is normalized to unity at t = 100 μs.

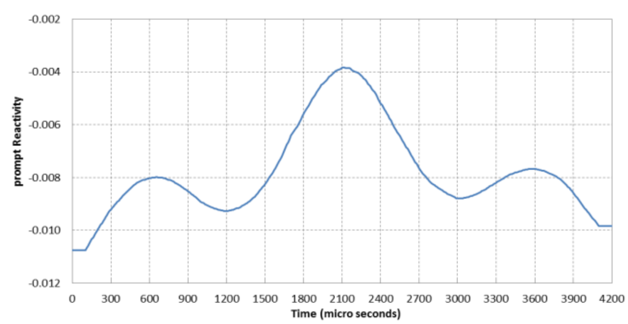

Fig. 2. Reactivity curve of IBR-2M subcritical test case

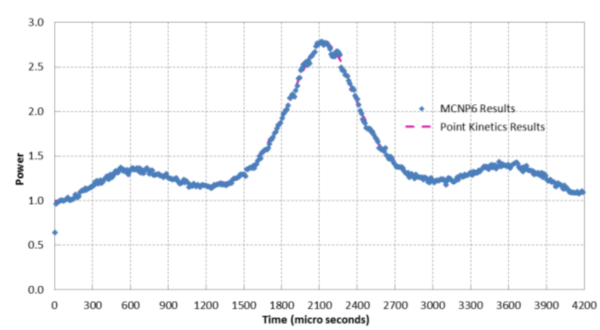

Fig. 3. Comparison of time dependent power calculated by MCNP6 and the point kinetics for the IBR-2M subcritical test case

For this subcritical test case, the neutron fission chain in MCNP6 calculation is not very long. The total fission power of the core was tallied in MCNP6 calculation at each time step, with the statistic error ~ 1.5 %. From Fig. 3, it can be seen that the time dependent power curve calculated by MCNP6 agrees well with that from point kinetics model. This agreement validates the MCNP6 modification to simulate the dynamic behavior of the IBR-2M reactor.

III. RUSSIAN ROULETTE FOR LONG NEUTRON FISSION CHAINS IN MCNP6

For the fast pulsed reactor like IBR-2M, one important parameter is the pulse multiplication factor *M*. It is defined as the total number of fission neutrons generated in the pulse normalized per delayed neutron per second before the pulse [1]. For IBR-2M reactor at equilibrium state, the pulse multiplication factor *M* is ~ 85 based on the benchmark calculation. This number can be explained in another way. For the IBR-2M at equilibrium state, the power pulse lasts for ~750 µs, which starts when ρ_{prompt} (ρ - β) is first above 0. At the end of the pulse, the power returns to the same level at the start of the pulse. In this time period, the number of source neutron released is ~7.5 × 10^{-4} and 85 fission neutrons are generated, ignoring the change of delayed neutron source intensity. This indicates that on the average ~1.1 × 10^5 fission neutrons are generated during the power pulse per source neutron.

In MCNP6 calculation, the computational time is proportional to the number of fission neutrons generated per source neutron. Therefore, large amount of computation is needed for IBR-2M at the equilibrium state. Considering the large value of the source multiplication factor in the IBR-2M power pulse, as well as the stochastic nature of MCNP calculation, the neutron fission chains for some source particles could be extremely long. These very long chains cause difficulties in the parallel computation of MCNP6, because the computer processors with the very long chains will run for extremely long time while the other processors are finished and waiting for the completion of the long neutron chains.

MCNP6 has several techniques to improve the parallel efficiency. For example, load balancing option, larger size patches for rendezvous, and analog instead of implicit (default of MCNP6) simulation scheme. These options are helpful; however, they are not sufficient for the long neutron chains during the power pulse. A new procedure was introduced to reduce the computational time of the long neutron chains. Russian Roulette is applied for these long fission chains. Some long fission neutrons are killed and the weight of the survived neutrons increased to preserve the neutron population. Some MCNP6 routines were modified to add this feature. It is also realized that using Russian Roulette for the long fission chains impact the statistical error of the calculated results because of the generated neutrons with large weights. Therefore, the Russian Roulette is not played for neutrons with weight above a certain limit. If the neutron weight is above this limit, it is tracked normally.

A supercritical test case of IBR-2M was analyzed. The control rods positions of IBR-2M were adjusted to limit the maximum prompt reactivity ($\rho_{prompt} = \rho - \beta$) to ~0.00034. With this reactivity level, the pulse multiplication factor *M* is ~ 5.4. This small pulse multiplication factor allows the use of MCNP6 time dependent calculation without the proposed Russian Roulette procedure for the long fission chains. The obtained results are used to study the impact of the Russian Roulette procedure for long fission chains on the calculated results. In addition, results from point kinetics was also obtained for comparison purpose. The reactivity curve is shown in Fig. 4 and the reactivity change occurs in the time interval from 200 µs to 820 µs is caused by the rotation of MR parts, and the maximum reactivity appears at *t* = 510 µs.

For this IBR-2M supercritical test case, the average source multiplication factor in the pulse f_m, is ~1.1 ×10^4. A parameter L_f, which is 100 times of f_m was used for the Russian Roulette, in this case L_f is equal 1.1 ×10^6. When Russian Roulette was played, the fission neutrons has a survival probability of 0.8 and the weight of survived neutron is adjusted by a factor of 1.25. Five steps are used based on N_{fis} value, which is the total number of fission neutrons generated in the neutron history:

1) $N_{fis} < L_f$: The history is not 'long', and Russian Roulette is not used. The neutrons are tracked normally.
2) $L_f < N_{fis} < 3L_f$: Russian Roulette is used if the neutron weight is less than 2.5
3) $3L_f < N_{fis} < 9L_f$: Russian Roulette is used if the neutron weight is less than 2.5^2
4) $9L_f < N_{fis} < 27L_f$: Russian Roulette is used if the neutron weight is less than 2.5^3
5) $N_{fis} > 27L_f$: Russian Roulette is used if the neutron weight is less than 2.5^4

Analog MCNP6 calculation was utilized in the simulations. Russian Roulette was played in step 2 to 5. At each stage, the upper neutron weight limit is increased by a factor of 2.5 from previous step. In any step, if the neutron weight is above the weight limit of current step, Russian Roulette is not used and the neutron is tracked normally. Several iterations were performed to obtain the selected stage parameters.

The time dependent power calculated by MCNP6, with and without the use of Russian Roulette for long fission chains and the point kinetics results are compared in Fig.5, with the power normalized to unity at t = 200 μs. In all these results, a fixed time step size of 10 μs was utilized.

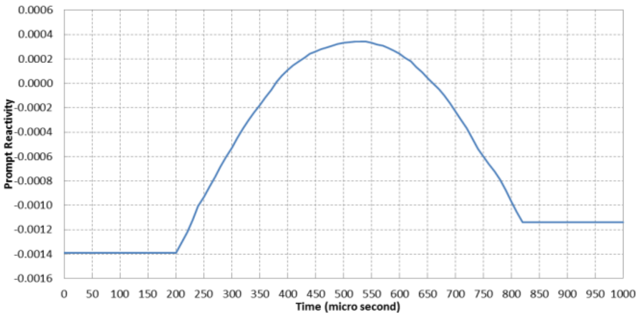

Fig.4. Reactivity curve of IBR-2M supercritical test case

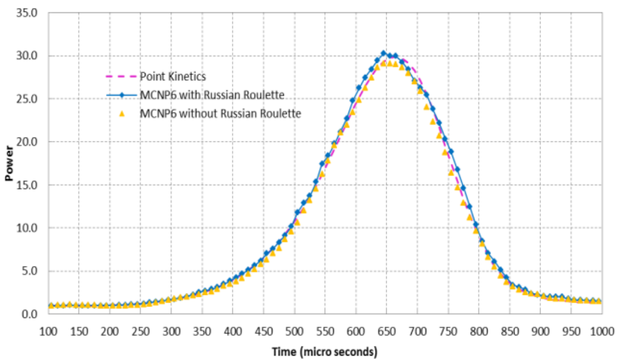

Fig.5. Comparison of time dependent pulse power calculated with MCNP6 and the point kinetics model for the IBR-2M supercritical test case

Based on the results shown in Fig.5, both MCNP6 results agree well with that from point kinetics calculation. For the MCNP6 results with the Russian Roulette procedure for long fission chains, the statistical error in the time range of power pulse is relatively large as shown in Fig. 6. However, the difference between the results is relatively small and it is within the statistical error.

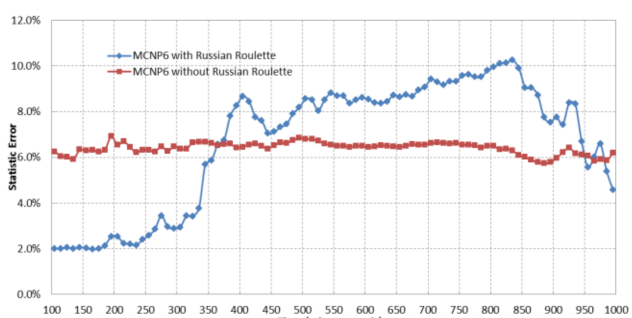

Fig.6. Statistical errors of MCNP6 results, for the IBR-2M supercritical test case

For the MCNP6 calculation, the average source multiplication factor in the whole time period of 1000 μs for this IBR-2M supercritical test case, referred to as $f_{m,tot}$, is tallied in the summary table. It is also utilized to validate the accuracy of the calculated results. Because the statistical error of the MCNP6 power at each time step varies, the statistical error of $f_{m,tot}$ is utilized to evaluate the Figure of Merit (FOM) of the calculation. The comparison of $f_{m,tot}$ values and the MCNP6 parallel efficiency values are shown in Table 1.

Table 1. Comparison of $f_{m,tot}$ and the parallel efficiency of MCNP6 calculations without and with the Russian Roulette for long fission chains for IBR-2M supercritical test case

MCNP6 calculation	$f_{m,tot}$	nps (million)	computation time (hours)	Parallel efficiency	FOM
Without Russian. Roulette	5.70e+03 ±5.59%	4	203.0	42.7%	2.053e-04
With Russian. Roulette	6.02e+03 ±6.03%	40	185.3	81.4%	1.933e-04

The average source multiplication factor in this 1000 μs, calculated by point kinetics code, is ~5.94 $\times 10^3$. Both MCNP6 calculations were executed on 128 computer processors, using the balancing load parallel option. The rendezvous size is also maximized in both MCNP6 calculations, which is equal to the total nps, to get the best parallel efficiency. It can be seen that both MCNP6 calculations can tally the average source multiplication factor accurately. The calculation with the Russian Roulette improves significantly the efficiency of parallel calculation, although the Figure of Merit is not improved for this IBR-2M supercritical test case.

IV. MCNP6 CALCULATION FOR IBR-2M EQUILIBRIUM DEMONSTRATION CASE

At equilibrium state, the IBR-2M reactor has a pulse multiplication factor M of ~85, a maximum prompt reactivity of ~0.00110, and an average prompt neutron generation time Λ of ~65 ns [2]. However, the calculated average prompt neutron generation time using MCNP6 is only ~48 ns. The difference could be due to the missing geometrical details for the reactor surroundings. Due to the difference in Λ values between MCNP6 calculation and reference IBR-2M data, the MCNP6 results cannot be accurately compared with the experimental data of IBR-2M.

The MCNP6 computational time for the fast-pulsed reactor is majorly determined by the pulse multiplication factor M. Therefore, an IBR-2M demonstration model with about the same M factor as of the equilibrium state was used for MCNP6 calculation. In this case, the control rods positions were adjusted to make the pulse multiplication factor M is ~ 85 and the maximum prompt reactivity ρ_{prompt} is ~ 0.00078. For this IBR-2M equilibrium demonstration model, the coupled MCNP6/point kinetics calculation was first performed, and the average source multiplication factor f_m in the pulse is ~1.30 × 10^5. The Russian Roulette methodology was utilized in the MCNP6 time dependent calculation combined with the load balancing option. The Russian Roulette parameters were shown in previous section except that the L_f value is 1.30×10^7. In addition, at the end of the run for the last few histories (three or less), the upper limit of the neutron weight for the Russian Roulette used in step 5 is ignored.

The reactivity curve is shown in Fig.6, with the MR parts rotating in the time interval of 260 µs to 2600 µs, and the maximum reactivity occurs at t = 600 µs. The total time period in the calculation is set to 2700 µs, which is sufficient to show the power pulse during and after the reactivity pulse. The MCNP6 time dependent power profile is compared with the results from point kinetics model in Fig.7, with the power normalized to unity at t = 260 µs. A fixed time step of 10 µs was used. Russian Roulette for the long fission chains was utilized in the MCNP6 calculation. In this case, it is not possible to perform MCNP6 calculation without the use of the Russian Roulette for the long fission chains even with the use of a very large amount of computational time.

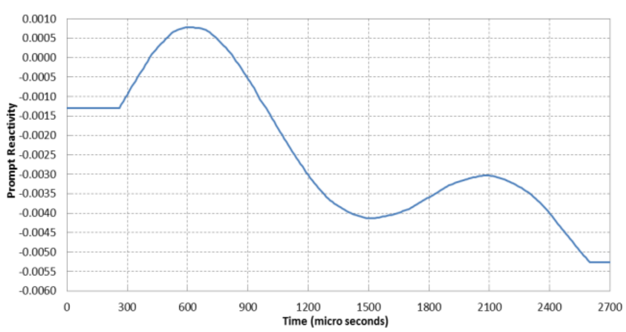

Fig.6. Reactivity curve of IBR-2M equilibrium demonstration problem

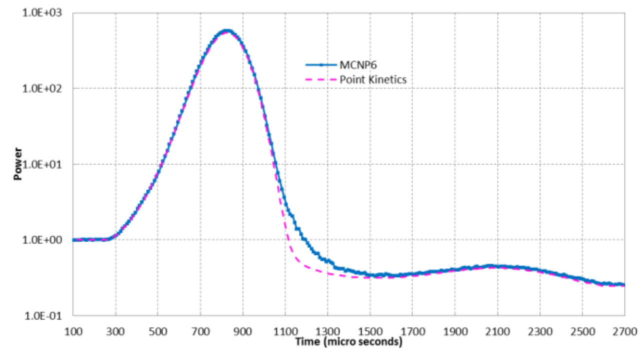

Fig.7. Comparison of the time dependent power calculated by MCNP6 and the point kinetics model for the IBR-2M equilibrium demonstration case

For this IBR-2M equilibrium demonstration case, the MCNP6 calculation used 160 computer processors. Four rendezvous were performed, each has 50 million source neutrons. The computation time and the parallel efficiency are shown in Table 2. The total computation time of these four rendezvous exchanges is ~1800 hours and parallel efficiency is ~ 80%. The average source multiplication factor $f_{m,tot}$ in the 2700 µs time interval, calculated by point kinetics code, is ~3.31 $\times10^4$, while the value calculated by MCNP6 is ~ 3.38 $\times10^4$ (± 4.79%).

Table 2 results show the statistical error of $f_{m,tot}$ decreases consistently with the number of rendezvous exchanges and the difference between the tallied $f_{m,tot}$ is always within the statistic error. No oscillations were observed for the $f_{m,tot}$ and the statistical error.

Table 2. Comparison of $f_{m,tot}$ and parallel efficiency of the MCNP6 calculations, at the end of rendezvous exchanges for IBR-2M equilibrium demonstration problem

Rendezvous exchange	nps (million)	$f_{m,tot}$	Computation time (hour)	Parallel efficiency
1	50	3.585e+04 (±9.66%)	~499	~76 %
2	100	3.431e+04 (±6.86%)	~421	~81 %
3	150	3.383e+04 (±5.60%)	~439	~78 %
4	200	3.377e+04 (±4.79%)	~439	~80 %

The difference between MCNP6 and the point kinetics results at each time step is shown in Fig.8. The power pulse results calculated by MCNP6 and the point kinetics model agree for the time period before and during the pulse for t < 1000 µs and the differences are within the statistical error. However, for the time period after the pulse (1000 µs < t < 1300 µs), large differences between MCNP6 and the point kinetics results are observed, with the maximum difference is ~190 %, while the statistical error of MCNP6 is only ~5%. This large difference cannot be explained by the statistical error. The same discrepancy was also observed between the experimental measurements and the results from the point kinetics model [4, 5]. This discrepancy might be due to the limit of point kinetics model. Although an absorber layer is located outside the stationary reflector, a small fraction of thermal neutrons could still be scattered back to core from the surrounding components [4, 5], which can cause such differences. These thermal neutrons scattered back, called 'room neutrons' [4], has delayed time effect due to the transport time spent outside the core. The impact from 'room neutrons' cannot be considered in the point kinetics calculation but it is included in the MCNP6 calculation.

The statistical error of MCNP6 power at each time step, with different nps number, is shown in Fig.9 for different NPS numbers. The statistical errors decreases as the NPS number increases as expected. With 200 million source neutrons, the maximum statistical error is 6 % during the power pulse, relative to the less than 2 % after the pulse. The use of the Russian Roulette during the pulse leads to such increase in the statistical error. The maximum statistical error of the calculated power occurs ~ 300 µs after the peak power.

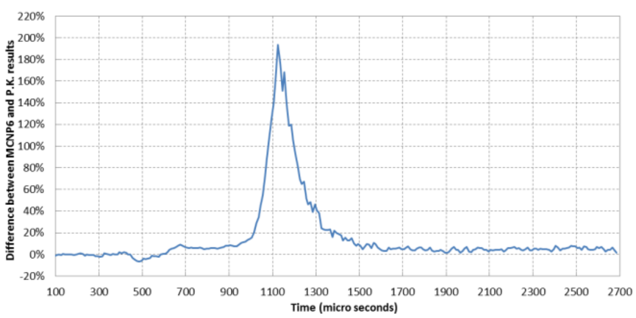

Fig.8. Difference between the pulse power profile calculated with MCNP6 and the point kinetics results for the IBR-2M equilibrium demonstration case

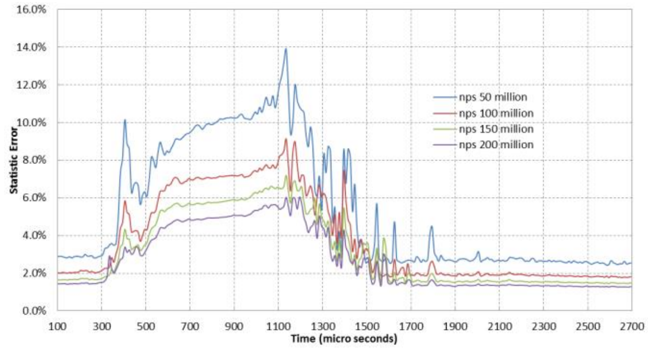

Fig.9. Statistical error of MCNP6 power profile results for different number of source neutrons of the IBR-2M equilibrium demonstration problem

V. SUMMARY AND CONCLUSION

Fast periodic pulsed reactors require kinetics analyses, which were historically done with point kinetic models. These models were modified by introducing some empirical formulation to match the experimental results from these reactors as much as possible. An accurate calculation methodology is needed for the design analyses of these fast periodic pulsed reactors. Monte Carlo computer code MCNP6 is used for this task due to its three dimensional transport capability with a continuous energy library. New routines were added to MCNP6 to simulate the rotation of the movable reflector parts in the time dependent calculation.

IBR-2M fast pulsed reactor was utilized to validate the new routine changes. A subcritical IBR-2M test problem was introduced, for which the MR parts were rotated within a time period to change the reactor reactivity but the maximum prompt reactivity was less than zero . The time dependent power curves calculated by MCNP6 and the point kinetics model were compared, and they did match.

The IBR-2M stays in prompt supercritical state for ~ 400 µs during the equilibrium state. This generates long neutron fission chains, which requires tremendously large amount of computation time during Monte Carlo simulations. To solve this problem, Russian Roulette was applied for the very long neutron chains in MCNP6 calculation, combined with other approaches to improve the efficiency of the simulations. A supercritical IBR-2M test problem was introduced to test the Russian Roulette methodology for long fission chains. The MCNP6 results with and without the use of the Russian roulette methodology did match but the parallel efficiency was improved significantly with the use of the Russian Roulette methodology.

Due to the inconsistency of average prompt neutron generation time Λ between MCNP6 and IBR-2M reference data, an IBR-2M equilibrium demonstration problem was introduced, which has the same pulse multiplication factor *M* as IBR-2M equilibrium state. For this IBR-2M equilibrium demonstration problem, the time dependent power calculated by MCNP6 agree well with the point kinetics results, except for a small time period after the pulse. It was observed in the power pulse of the IBR-2M at equilibrium state that there is also some discrepancy between the experimental measurements and the calculated results using the point kinetics model. The MCNP6 results matches better the experimental measurements, especially after the pulse, which shows the merit of using MCNP6 calculation relative to the point kinetics model for such analyses.

ACKNOWLEDGMENTS

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