A Comparison of Results from LANCER02 and MCNP on a Series of Two-Dimensional Multiple BWR Bundle Configurations

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Abstract

This paper discusses recent extensions to the LANCER02 lattice physics code that allow for the analysis of multiple bundles lying along a two-dimensional plane of a reactor core. The paper presents results from LANCER02 on a study consisting of analyses on single assemblies, 2x2 arrays of bundles, and 4x4 arrays of bundles at different operating conditions. LANCER02 eigenvalues and rod-by-rod fission rates are compared against results from corresponding MCNP analyses. Results indicate that the LANCER02 multi-bundle modelling option is equivalent in accuracy to its single-assembly capability.

KEYWORDS: Lattice Physics, Multi-Bundle Analysis, Monte Carlo, BWR Analysis

1 Introduction

LANCER02 is a lattice physics code, based on the Method of Characteristics, that is designed to supply data to the AETNA02 nodal code currently under development for analyzing Boiling Water Reactors (BWR). [1,2] The emphasis of this paper is to introduce the multi-bundle modelling capability of LANCER02 and present results from a small series of comparisons against MCNP reference solutions that illustrate the overall accuracy of LANCER02. [3]

2 Single-Assembly Methodology

The LANCER02 calculation begins by retrieving microscopic cross section data from an accompanying cross section library. The library is based on a 118-group energy structure that replaces the 190-group energy structure used by LANCER01. There have been two separate 118-group libraries generated to-date: (1) a library based on ENDF/B-6 release 8 data, generated using NJOY94.105; and (2) a library based on ENDF/B-7 β-release 0 data (circa June 2005), generated using NJOY99.112. [4] The energy group-dependent cross sections span the energy range from 10^{-5} eV to 20 MeV and include data for 31 individual actinides and 99 individual

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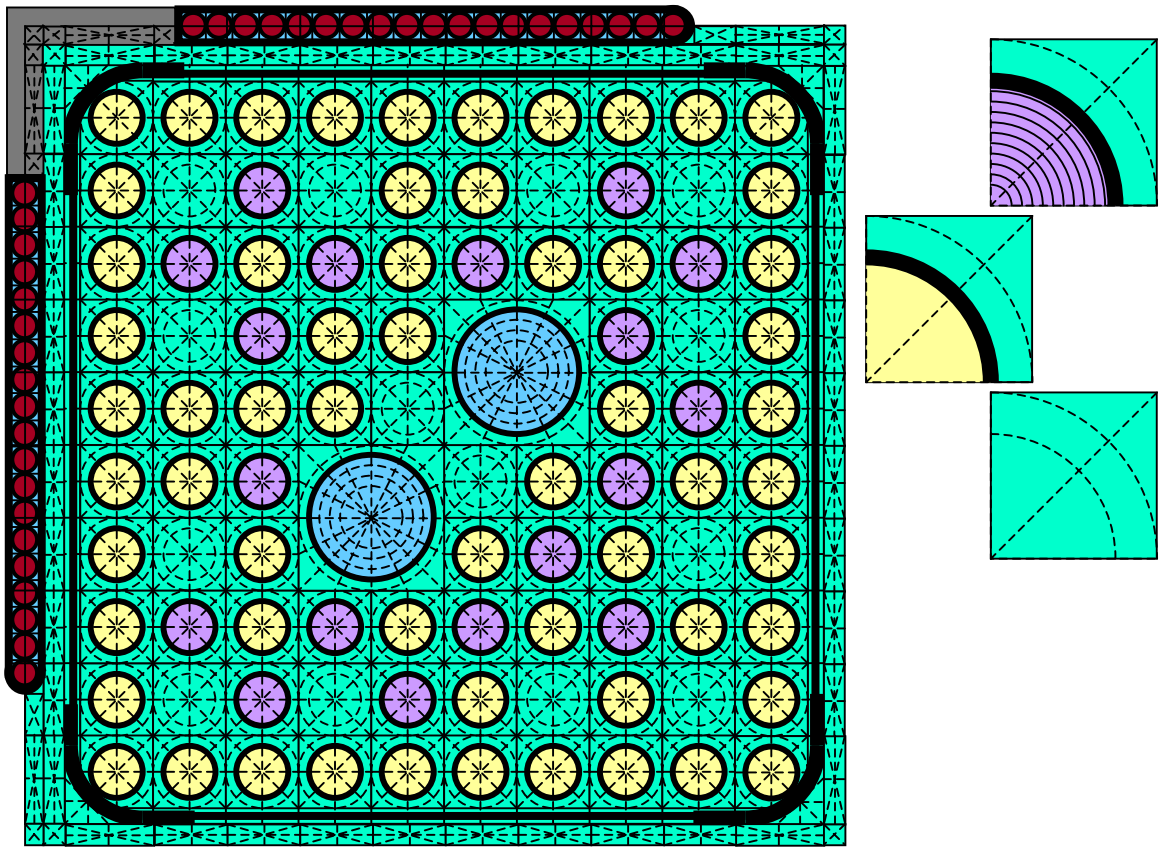
fission products, along with data for an assortment of other elements such as hydrogen, oxygen, boron, carbon, hafnium, zirconium, plus various elements that comprise stainless steel, etc.

Prior to solving the transport equation, macroscopic cross sections are condensed from the 118-group energy structure to a smaller energy group structure to help reduce execution time and memory requirements. The weighting function used to condense the cross sections is generated by a two-step condensation scheme consisting of a series of 1-D pin cell calculations followed by a 2-D response matrix calculation using a simplified transmission probability approach. [5]

The combined fluxes from the series of 1-D pin cell calculations and the 2-D response matrix calculation are used to condense all macroscopic cross sections from the 118-group energy structure to a coarser group structure – currently set at 22 energy groups – for use in the fine-mesh lattice calculation. The fine-mesh lattice calculation models the true geometry of the bundle and solves for the flux using the Method of Characteristics (MoC). [1,5] An example of the default fine-mesh used for the MoC calculation is contained in Figure 1.

Figure 1: Example of MoC Default Meshing for the Vanish Portion of a GE14 Fuel Design.



Following the flux calculation, the code proceeds to the burnup module, where the burnup equations are solved in matrix form. Boron and hafnium are modelled as exposure-dependent isotopes in the control blades, if desired, and each pin or plate in a control blade can be its own separate burnup zone. There is also a shutdown cooling capability to calculate the change in fuel isotopics following long periods of inactivity.

The single-assembly capability of LANCER02 has been benchmarked extensively against MCNP reference solutions for a wide variety of lattice designs over a wide range of operating conditions. The interested reader can find a sampling of results from the comparisons in [1].

3 Multiple Bundle Modelling Capability

Multi-bundle analysis at the lattice physics level is concerned with modelling large arrays of fuel bundles along a plane of a reactor core. This type of extension to LANCER02 has been included in order to supply reference solutions for validating the physics methods used in AETNA02.

3.1 Ray Tracing Scheme

To solve the Characteristics form of the transport equation, streaming tracks – or rays – are traced over the geometry of the problem at a number of different angles. The more angles that are modelled, the more accurate the solution to the transport equation becomes. In LANCER02, ray tracing on a single-assembly level is performed across the entire lattice and rays are perfectly aligned with their reflective counterparts along the boundaries of the lattice. This allows for an exact solution to the Characteristics equation.

For multi-bundle applications in LANCER02, ray tracing takes place within each bundle, individually, and the bundles are connected to each other via their surface angular fluxes. The ray tracing is performed such that each out-going ray from any bundle will align perfectly with an in-coming ray to a neighbouring bundle, allowing for an exact solution to the Characteristics equation. This method was first proposed as the Direct Neutron Path Linking technique (DNPL). [6] What lies inside a bundle is inconsequential to the rays that align along the boundaries of the bundle. All material regions can be modelled at unique temperatures, if desired, and the core can be comprised of any number of different bundle designs.

From a coding standpoint, this is very attractive because it allows the ray tracing routine from the single-assembly model to be used on a multi-bundle basis without modifications. The only detail that changes is the array that couples inward-directed boundary angular fluxes with their outward-directed counterparts. On a multi-bundle level, rays are coupled to their periodic counterparts from a neighbouring bundle, rather than being coupled to their reflective counterparts from within the bundle.

3.2 Iteration Scheme

The iteration scheme for multi-bundle analysis is, to some extent, dictated by the choice of the ray tracing scheme. The LANCER02 approach is to ray trace and iterate on a bundle-by-bundle basis and continue to loop over all bundles in the problem until the flux converges globally. The outward-directed angular fluxes along the surfaces of any bundle are used to determine the inward-directed angular flux along the surface to each of the neighbouring bundles. As the calculation loops over each bundle, the inward-directed surface angular fluxes are updated using the most recent values available for the outward-directed surface angular fluxes from the neighbouring bundles, defining a Gauss-Seidel type of iteration scheme.

The advantage of the above technique is the small amount of memory needed to perform the multi-bundle analysis. In LANCER02, the memory required to analyze an entire plane of a reactor core is only marginally greater than the amount of memory needed to analyze a single-assembly. The poor computational efficiency of the method can be improved significantly by

distributing the calculation over a cluster of processors. [6] In this approach, all individual bundle calculations are performed simultaneously and the modified iteration scheme describes a straightforward Jacobean method, where the new outward-directed angular flux along the surface of each bundle is unavailable until the end of a complete sweep. This is computationally inefficient, but is unavoidable in order to distribute the calculation across the computer platform. The cross section generation and ray tracing for each bundle in the problem can also be distributed across the platform, as can the memory required to store all optical path lengths for each bundle.

3.3 Geometry Representation

One of the many features that makes the MoC such an attractive solution technique for BWR modelling applications is its ability to avoid all geometry approximations that plagued earlier methods. This capability has been preserved for the multi-bundle modelling application as well. In essence, all bundles are modelled without any geometry approximations – including the presence of control blades and instrument tubes. Multiple control blade types (e.g., GE Marathon, Hitachi Hf flat plate, ABB with horizontal tubes, etc.) are allowed to be scattered throughout the problem.

Each bundle can be modelled at a different stage of its life. Bundles can be depleted individually and then isotopics for each material zone of the bundle can be obtained from a restart file for use in the multi-bundle problem. The multi-bundle system, itself, can be depleted as an average or can be depleted relative to the burnup rate of a reference bundle. This includes the depletion of each individual absorber material in each control blade. Isotopics from each bundle can be stored in a separate restart file and can be applied to a shuffled core location in a subsequent analysis.

Cross sections for the multi-bundle problem are generated by processing each bundle as a typical single-assembly, where microscopic cross sections are obtained from the cross section library and the two-step condensation process is applied using perfect reflexion along all boundaries of the lattice. This procedure produces cross sections for use in the multi-bundle problem that are identical to those generated for the single-assembly analysis. Any energy group structure can be chosen for use in the multi-bundle problem, although the current default 22-group energy structure for the MoC calculation has proven to be adequate for all problems.

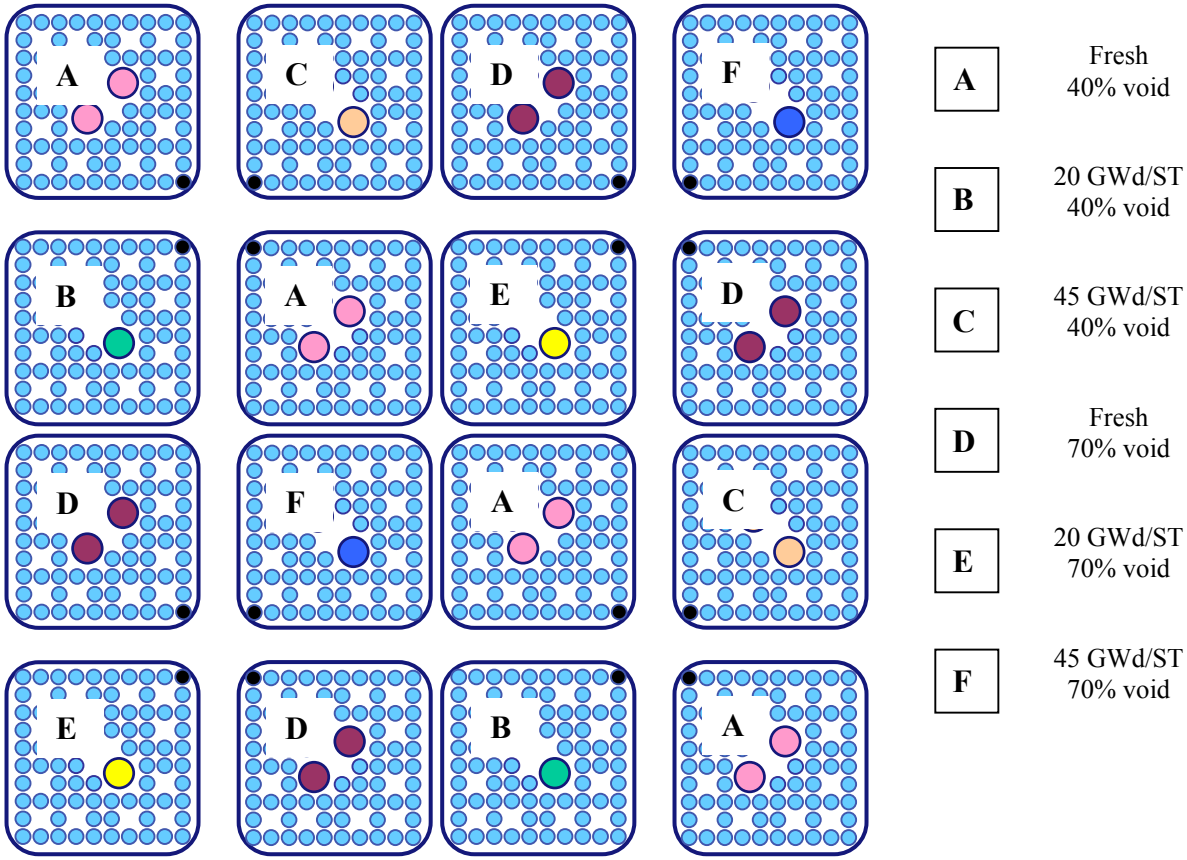
Recent work has focused on an alternative approach for generating cross sections that consists of following the above process, but also performing the single-assembly MoC calculation and using the resulting 22-group MoC flux distribution to collapse cross sections to a 7-group energy structure. The 7-group cross sections are then used for the multi-bundle problem. Using this approach, the 7-group energy structure produces results that are equivalent to results generated by the 22-group energy structure while reducing execution time and memory requirements.

4 Benchmarking the Multi-Bundle Modelling Capability

The accuracy of the LANCER02 multi-bundle capability can be quantified by conducting a study based on the multi-bundle configuration shown in Figure 2 and using MCNP to generate reference solutions. The configuration in Figure 2 is a repeating periodic array of 16 bundles, where each lattice (the terms “lattice”, “assembly”, and “bundle” are interchangeable in the context of this paper) is of the same product line, but is at a different burnup and/or at a different void condition. These conditions are similar to conditions found in the top-half of a core at the

beginning of a cycle, where fresh fuel is arranged in a checkerboard pattern with once-burnt fuel (represented at a lattice average exposure of 20 GWd/ST) and twice-burnt fuel (45 GWd/ST). All fresh fuel bundles contain 9 pins of 7 wt% Gd_2O_3, 8 pins of 6 wt% Gd_2O_3, and are of an average lattice enrichment of 4.51 wt% U^{235}. The once-burnt bundles have surpassed the Gd burn-out point and contain an average lattice enrichment of approximately 2.50 wt% U^{235} and 0.5 wt% Pu^{239}. The twice-burnt bundles contain an average enrichment of less than 1 wt% U^{235} and approximately 0.5 wt% Pu^{239}. The arrangement in Figure 2 represents a D-lattice plant, where the wide water gaps are roughly twice the width of the narrow water gaps. Isotopics for the depleted bundles were obtained from LANCER02 single-assembly depletions. The problem exhibits symmetry along the SW to NE diagonal.

Figure 2: MCNP 16 Bundle Reference Problem.



4.1 Single-Assembly Analysis of Each Unique Lattice

The first step in the study was to analyze each of the six unique lattices (lattices A through F in Figure 2) as single-assemblies and compare the LANCER02 eigenvalues and rod-by-rod fission rates against the corresponding MCNP reference solutions. Each MCNP single-assembly analysis was run using 4.5 million histories, with the first 500,000 histories being excluded from the statistics. All isotopes from LANCER02 were modelled by MCNP. Both codes used cross section data from the ENDF/B-VI release 8 evaluation. All fuel isotopes were modelled at 748 Kelvin, while all non-fuel isotopes were modelled at 559 Kelvin.

Results from the six single-assembly analyses are summarized in Table 1. Contents of the table include: differences in eigenvalues between the two codes ($\Delta k = (k_{LANCER02} - k_{MCNP})/k_{MCNP}$), expressed in pcm (1 pcm = 0.00001 Δk); standard deviation in the eigenvalue from each MCNP analysis, expressed in pcm; rod-by-rod fission rate rms between the two codes, expressed in %; and the rod-by-rod fission rate rms from each MCNP analysis, representing the difference in fission rates between symmetric rod locations, expressed in %. This last row in the table is a good measure of the uncertainty in the MCNP fission distribution.

Table 1: Summary of Results from Single-Assembly Analyses.

	A	B	C	D	E	F
	40% void	40% void	40% void	70% void	70% void	70% void
	0 GWd/ST	20 GWd/ST	45 GWd/ST	0 GWd/ST	20 GWd/ST	45 GWd/ST
Δk (pcm)	37	-42	-68	8	-12	-59
MCNP 1σ (pcm)	±30	±28	±31	±34	±27	±29
fission rate rms (%)	0.40	0.56	0.38	0.47	0.63	0.52
MCNP rms (%)	0.46	0.49	0.36	0.31	0.43	0.35

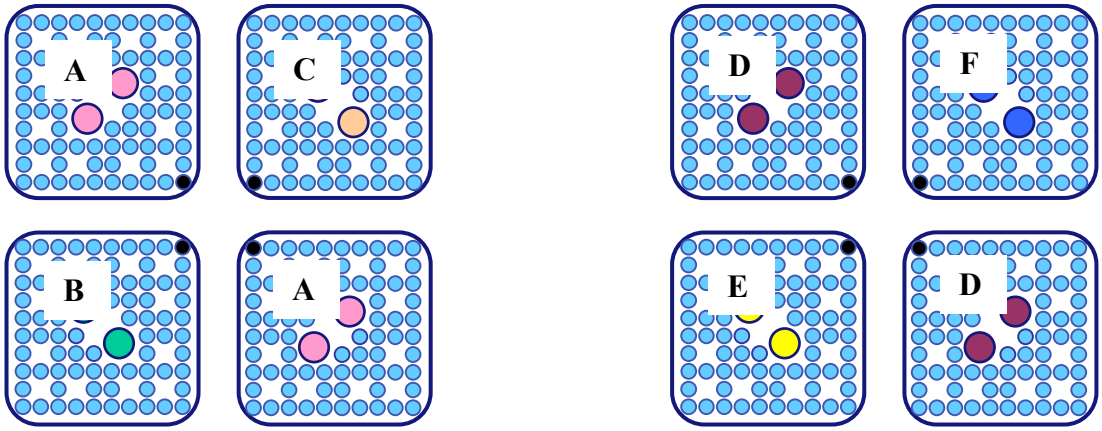
Results contained in Table 1 indicate very good agreement between LANCER02 and MCNP for all six single-assemblies analyzed.

4.2 2x2 Analysis of Each Control Cell

The next step in the study was to analyze each of the two unique control cells in the problem – the 40% voided control cell and the 70% voided control cell. The two unique cells are illustrated in Figure 3.

Each 2x2 cell was modelled using periodic boundary conditions. Each of the two MCNP analyses modelled 22 million histories, with the first 2 million histories being excluded from the statistics. Tallies were recorded for every fuel region in each lattice and were used to calculate a rod-by-rod fission distribution, along with a "power" split between the lattices, which is more precisely a bundle-by-bundle fission distribution.

Figure 3: Unique Control Cells in MCNP 2x2 Problems.



40% Voided Control Cell 70% Voided Control Cell

Results from the two 2x2 analyses are contained in Table 2. The contents of the table have been separated by bundle type within each control cell type and include: differences in eigenvalues between LANCER02 and MCNP (Δk); standard deviation in the eigenvalue from each of the two MCNP analyses; rod-by-rod fission rate rms between the LANCER02 distribution and the corresponding MCNP distribution; and the difference in bundle power splits between LANCER02 and MCNP, expressed in %.

Table 2: Summary of Results from 2x2 Analyses.

	40% Voided Control Cell			70% Voided Control Cell		
	A	B	C	D	E	F
	0 GWd/ST	20 GWd/ST	45 GWd/ST	0 GWd/ST	20 GWd/ST	45 GWd/ST
Δk (pcm)	52			55		
MCNP 1σ (pcm)	±12			±14		
fission rate rms (%)	0.47	0.61	0.45	0.63	0.55	0.53
Δ lattice power (%)	0.64	-0.06	-1.22	0.90	-0.30	-1.50

Differences in results between LANCER02 and MCNP for the two 2x2 analyses are of the same magnitude as the differences from the single-assembly analyses. These are encouraging results, since they indicate that there is no additional bias in LANCER02 accuracy when moving from single-assembly applications to 2x2 multi-bundle applications.

4.3 Results from the 4x4 Analysis

The last step in the study was to analyze the 4x4 configuration in Figure 2. The MCNP problem modelled 22 million histories, with the first 2 million histories being excluded from the statistics. This is the largest BWR multi-bundle problem that the GNF version of MCNP is currently capable of modelling. For this problem, tallies could not be recorded for every fuel region in every bundle because of limitations in MCNP. Instead, tallies for each of the six unique

bundles in the problem were averaged together. This is not an issue for bundles B through F in Figure 2 because those specific bundle locations exhibit diagonal symmetry with their sister bundles. The four bundles comprising bundle type A, however, do not all lie in locations that are perfectly symmetric with all sister locations and the averaging technique destroys the uniqueness of the fission distributions in the four bundles. Nevertheless, the averaging was necessary and LANCER02 fission distributions were averaged in a similar way to supply a direct comparison of results.

A summary of results from the analysis are contained in Table 3. The type of information contained in Table 3 is the same as that contained in Table 2. The MCNP eigenvalue for this problem was 1.00310 ±0.00013. The LANCER02 eigenvalue was 1.00371.

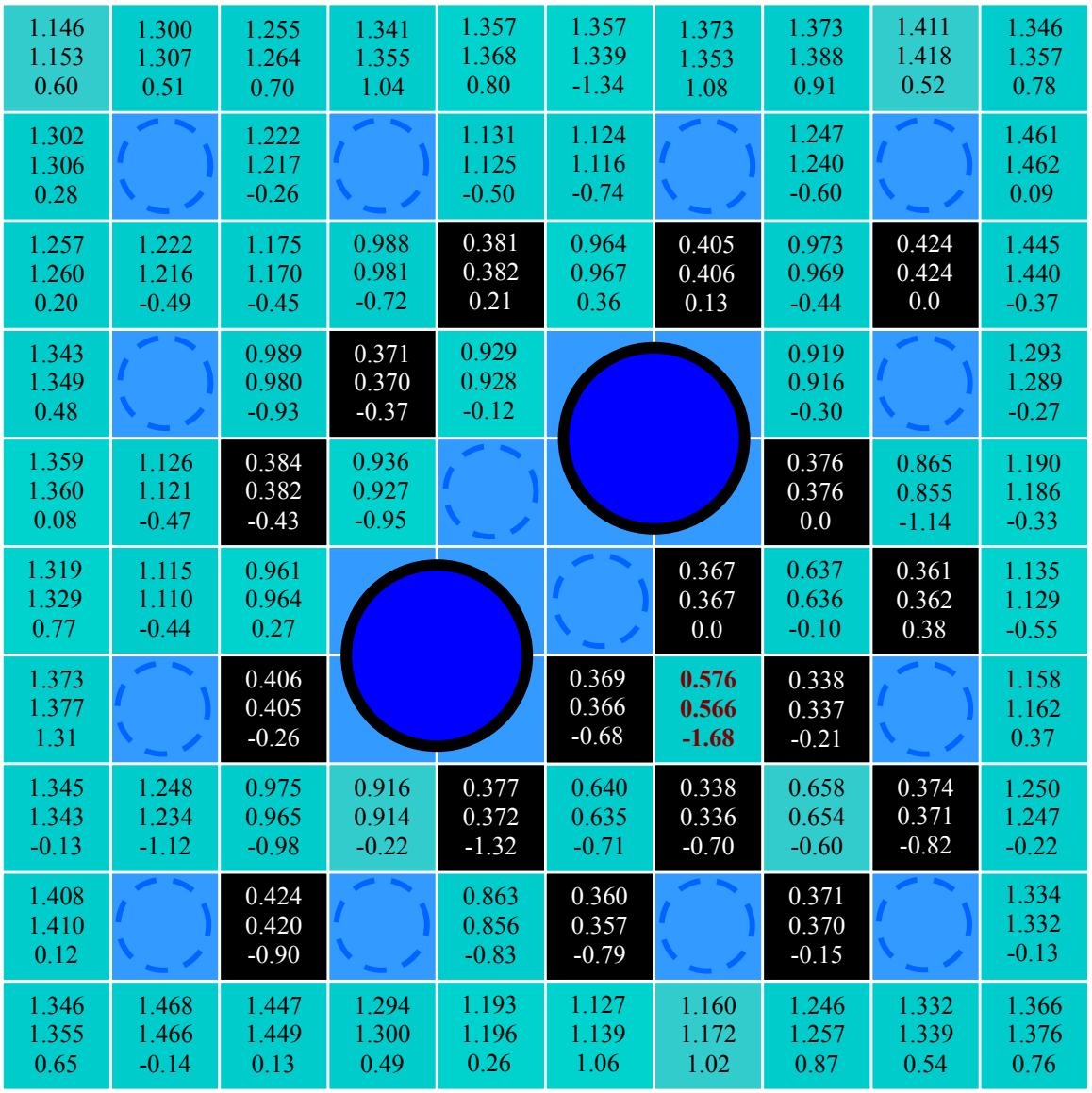
Table 3: Summary of Results from 4x4 Analysis.

	A	B	C	D	E	F
	40% void	40% void	40% void	70% void	70% void	70% void
	0 GWd/ST	20 GWd/ST	45 GWd/ST	0 GWd/ST	20 GWd/ST	45 GWd/ST
Δk (pcm)	61					
MCNP 1σ (pcm)	±13					
fission rate rms (%)	0.61	0.74	0.67	0.64	0.52	0.55
Δ lattice power (%)	0.7	0.0	-1.5	0.9	-0.3	-1.4

Agreement between LANCER02 and MCNP is very good. Differences in results between LANCER02 and MCNP for the 4x4 analysis are consistent with the differences seen from the six single-assembly analyses and the two 2x2 analyses. The fresh bundles in the LANCER02 calculation are slightly more energetic than they are in the MCNP analysis and the twice-burnt bundles are slightly less energetic in LANCER02 than in MCNP. This trend can also be seen in the single-assembly eigenvalues and in the power splits from both 2x2 analyses. The differences are felt to be too small to be of concern.

LANCER02 and MCNP rod-by-rod fission rate distributions for bundle type D are contained in Figure 4. Both sets of fission rates have been normalized within the bundle to a rod-average fission rate of 1.0. Empty rod locations containing a broken circle represent a vanish cell filled with voided coolant. The location of fuel rods containing gadolinium are represented by the black boxes. The wide water gaps in the figure are located along the west and north surfaces of the bundle. The %Δ values have been calculated as $\%\Delta = (F_{LANCER02} - F_{MCNP})/F_{MCNP} \times 100\%$, where F is the relative fission rate in any particular rod. The comparison contained in Figure 4 is indicative of all fission rate comparisons from every problem analyzed for this study. The largest discrepancy in Figure 4 is 1.68% and occurs in one of the UO_2 rods surrounded by four Gd_2O_3 rods. All values in Figure 4 have been rounded to the nearest digit shown in order to fit the figure neatly onto the page. The %Δ values have been calculated from the original raw data, not the data in the figure.

Figure 4. Fission Rate Comparison for Bundle Type D from 4x4 Problem.



5 Conclusions

This paper has presented a comparison of results between the lattice physics code LANCER02 and the continuous energy Monte Carlo code MCNP for a narrow range of single-assembly and multi-bundle problems. Results from the small collection of problems presented indicate that LANCER02 accuracy for multi-bundle problems is equivalent to the accuracy of the code on single-assembly analysis, which is to say that results from LANCER02 are in very good agreement with results from MCNP. These results help to support the premise that, for all practical BWR analysis, LANCER02 can be used to generate two-dimensional reference solutions on multi-bundle problems in place of an MCNP analysis.

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