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Simulation of the Fast Reactor Fuel Assembly Duct-Bowing Reactivity Effect using Monte Carlo Neutron Transport and Finite Element Analysis

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Simulation of the Fast Reactor Fuel Assembly Duct-Bowing Reactivity Effect using Monte Carlo Neutron Transport and Finite Element Analysis

This paper discusses a new method of simulating the fuel assembly duct-bowing reactivity coefficient for EBR-II run 138B. Quantification of the fuel assembly duct-bowing reactivity effect in liquid metal cooled fast reactors has been a persistent problem since they were first designed and operated. Simulation of the duct-bowing reactivity effect is difficult because the level-of-detail required to simulate the effect has exceeded most modeling capabilities. The new method outlined in this paper utilizes the finite element analysis code ANSYS to analyze the thermal and structural components. The displacement of the fuel assembly duct due to thermal expansion and mechanical interaction was calculated by ANSYS using recorded EBR-II run 138B temperature and power boundary value data. The displacement values were incorporated into to a Monte Carlo model of EBR-II run 138B and k_{eff} was calculated. Multiple Monte Carlo calculations were performed with duct displacement values corresponding to different reactor temperatures. Using the calculated k_{eff} values associated with the different duct displacement results allowed calculation of the duct-bowing reactivity coefficient. The duct-bowing reactivity coefficient was calculated to be -14.5 x 10^{-4} \$ / ^{o}C ± 4.4%.

I. INTRODUCTION

Experimental Breeder Reactor II (EBR-II) pioneered many advances in nuclear engineering, including on-site reprocessing of the reactor fuel. These advances were researched and characterized, but several phenomena proved extremely difficult to quantify. For example, observation and measurement of EBR-II fuel and reflector assembly bowing as well as attempts to model the behavior and quantify the reactivity effect have been documented. [1], [2], [3], [4], [5] However, effectively modeling individual fuel assembly duct displacement due to the thermal and mechanical forces generated within the reactor during operation and using the displacement values to calculate the resulting reactivity effect has been elusive.

The complicated nature of EBR-II fuel assembly duct-bowing originates from the EBR-II high-power density and pool-type design which generated a large change in temperature (~350 ^{o}C) from the center of the core to the reactor boundary. Thermal expansion due to the change in temperature across the core led to differential radial expansion of the structures, otherwise known as duct-bowing. The mechanical interactions created due to the thermal expansion were the primary drivers behind the complexity in modeling the duct-bowing phenomena on an individual duct basis.

The duct-bowing phenomenon has existed since Experimental Breeder Reactor I. During that time, efforts were made to minimize the duct-bowing because it was a positive reactivity coefficient and difficult to quantify. Duct-bowing was made more favorable in EBR-II where the positive reactivity was decreased to a small part of the power band, however, direct quantification was not achieved. Multiple efforts were made to calculate the movement of the ducts, but these efforts led to highly uncertain answers. The duct-bowing reactivity coefficient was accounted for by quantifying the other reactor coefficients and then attributing the remaining reactivity to duct-bowing. While this method matched the experimental data, it also had high uncertainty due to the combined uncertainty of the other parameters.

Much of the past work attempting to model the duct-bowing reactivity effect in EBR-II was impeded by the lack of sufficient modeling capability and computing power. Advances in these areas now allow a reexamination of the problem. The finite element analysis code ANSYS allows for generation of a detailed model of the EBR-II fuel assembly ducts that can determine individual duct displacements resulting from thermal and mechanical forces. [6] Additionally, detailed Monte Carlo modeling of the EBR-II core can be performed using the Monte Carlo neutron transport code MCNP to calculate k_{eff} as each fuel assembly duct geometry is altered by the thermal and mechanical forces. [7] Ultimately, as described below, using both ANSYS and MCNP, an effective method of calculating the fuel assembly duct-bowing reactivity now exists.

II. EXPERIMENTAL BREEDER REACTOR II

EBR-II was initially constructed to demonstrate a liquid metal fast breeder reactor for power production coupled with on-site fuel reprocessing. Initial criticality occurred in 1965, and subsequently in 1969, a closed fuel cycle was demonstrated. From 1965 to 1978, the reactor

operated mainly as an irradiation facility. Proposals were then sought to increase utilization of the reactor. From these proposals, the Shutdown Heat Removal Tests (SHRT) were conceived and performed from 1984 to 1986. The reactor was permanently shut down in August of 1994.

EBR-II was a sodium cooled fast neutron spectrum reactor. Key design features of the reactor included metallic fuel and a pool-type design where the reactor coolant pumps and intermediate heat exchanger were located within the primary tank along with the reactor core. The metal fuel, along with the pool-type reactor design, produced certain inherent safety properties owing to the large negative reactivity coefficients due to thermal expansion of the materials and natural convection cooling. Table I lists important EBR-II specifications.

SHRT number 45 (EBR-II run 138B) occurred in April 1986 where a station blackout without SCRAM scenario was performed. With no operator actions or safety system activation, the inherent safety mechanisms shut EBR-II down with no significant damage. [8]

Table I. EBR-II Specifications

Enrichment	67 %
Total ^{235}U mass	24,955 g
Coolant	Sodium
Assembly Pitch	Hexagonal 5.89 cm
Core Effective Height	34.29 cm
Core Effective Diameter	69.67 cm
Power (Electric)	62.5 MW (20 MW)
Bulk Coolant Temperature	617 K

In the April 1986 configuration, EBR-II had eight types of assemblies. Most of the fissile material was contained in the driver assemblies. Each of the 83 driver assemblies had an upper pole piece, upper extension, core region, lower extension, and lower adapter. The extensions contained stainless steel reflector blocks that had flow holes for the sodium coolant. Each driver

assembly contained 91 fuel pins attached to the top of the lower extension via a grid. The lower adapter had a fork used to interface the assembly with the reactor grid plate. Some driver assemblies were designed to be half-worth, where half of the fuel pins were replaced by stainless steel pins. The half-worth driver assemblies were used mainly near the center of the core to limit flux peaking.

The 10 reactor control assemblies were fueled rather than poisoned. Three types of control assemblies were used: safety, control, and high worth control. These differed from the driver assemblies by the ability to move for power control. Their geometry was similar to the driver assemblies, only smaller. Sixty-one fuel pins were loaded into a moveable inner hexagonal duct and then enclosed in an outer hexagonal duct, which remained stationary. The two safety assemblies and single control assembly were similar in design but with a different movement mechanism. The high worth control assemblies had 61 fuel pins also, but inside of the upper extension there were seven B_4C poison pins. For the reactor configuration associated with this work, both safety assemblies were fully inserted into the core (maximum positive reactivity), along with four high worth control assemblies, and the single control assembly. Two high worth control assemblies were fully withdrawn from the core. The remaining high worth control assembly was inserted into the core 7.65 cm to achieve criticality. Figure 1 shows the types of assemblies and their positions in the reactor.

[Figure 1 goes here]

Figure 1. EBR-II core layout run 138B.

The fuel pins in each assembly were 0.442-cm-diameter metallic uranium alloy slugs clad in 316 stainless steel. Stationary sodium filled the annular region between the uranium slug and the cladding to enhance heat transfer. Inert gas filled the plenum region above the uranium slug. The fuel pin cladding also had a wire wrap spacer, which ran toroidally down the length of the cladding to provide a sodium coolant flow path between the fuel pins.

EBR-II's primary mission was to perform research. To that end, experimental and fueled assemblies were constantly shuffled inside the reactor and replaced. The assembly movement resulted in unique burnup values for essentially all assemblies in the run 138B configuration. Figure 2 shows the average burnup values (in atom %) for the driver assemblies in the core. The

uranium alloy slugs were a singular piece of metal, however, from a Monte Carlo modeling perspective each fuel slug was divided into three equal axial pieces. Using three fuel slug pieces in the model was necessary to properly account for the axial burnup distribution. The resulting Monte Carlo model used 1,269 unique irradiated fuel compositions as well as 10 other material compositions for the structure and the coolant. The uranium alloy was approximately 95 wt. % metallic uranium and 5 wt. % fissium. Fissium was a material that simulated the dominant mid-cycle fission products of Mo, Ru, Rh, Pd, Zr, Nb, Ta, and Si. Table II contains information on the number, type, and material of the assemblies that were contained in EBR-II run 138B and the Monte Carlo model. A more detailed description of EBR-II run 138B is available as a reactor physics benchmark. [9]

Table II. EBR-II Assembly Types and Numbers

Assembly Type	Description	Number of Assemblies
Driver	91 U5-fissium fuel pins	70
Half-worth Driver	45 U5-fissium fuel pins & 46 SS dummy pins	13
High-worth Control Rod	61 U5-fissium fuel pins & 7 B_4C poison pins	7
Control Rod	61 U5-fissium fuel pins	1
Safety Rod	61 U5-fissium fuel pins	2
Dummy	7 solid Stainless steel pins	6
Blanket	19 Du pins used for breeding	429
Reflector	Hex Duct with SS304 & SS316 solid filler blocks	186

[Figure 2 goes here]

Figure 2. Burnup map for run 138B, numbers are at. % burnup.

III. EBR-II REACTIVITY EFFECTS

Table III lists the largest reactivity coefficients calculated by Argonne National Laboratory for run 138B. [8] The reactivity effects are concentrated in the first six rows of the EBR-II core. The first 6 rows contained the enriched uranium and subsequently a majority of the power was generated in this space. For reference, a row is defined as each set of assemblies that creates a hexagonal ring moving radially outward. For example, row 1 had one assembly, row 2 had six assemblies, row 3 had 13 assemblies, etc.

Table III. Calculated Reactivity Components and Uncertainties for Run 138B

Components	Nominal Reactivity Coefficient		Power Reactivity Decrement (PRD) ($)	Estimated Uncertainty (%)
	Contributing Region (rows)	Values used in the analysis (10^{-4} \$/ºC)		
Sodium Expansion	1-6	-11.9	-0.0812	7
Control-rod Bank Extension	5	-7.16	-0.0672	5
Grid Plate Expansion	1-6	-14.5	0	20
Thermal Bowing	2-10	+9.8	+0.025	25

Table III shows that the most significant reactivity effects were due to thermal expansion of stainless-steel structures and sodium. Grid plate expansion was the most significant reactivity coefficient, by ~18%, compared to the second largest coefficient. The grid plate was the stainless-steel plate where the assemblies were attached. The significant impact on reactivity was due to the grid plate determining the assembly pitch. Temperature changes in the grid plate led to changes in the overall pitch of the assemblies. The grid plate was the only mechanical restraint on the assemblies; the other parts of the assemblies were in contact with each other but without any mechanical restraint. The assemblies rested against the side of the reactor liner and were free at the upper pole piece.

The duct-bowing phenomena existed since the original construction of EBR-I. Experience from EBR-I "demonstrated that mechanical bowing of fuel elements toward the center of the reactor caused by the power gradient across the reactor produced a positive power coefficient." [10] The reason for the inward bowing in EBR-I was due to the upper assembly restraint. The magnitude of the bowing positive reactivity coefficient was not large enough to overcome the other negative reactivity coefficients, but it was a concern for the research and design of EBR-II given that the effect scales with power. The bowing reactivity coefficient was proportional to the power generated leading to concerns that the positive reactivity trend might overwhelm the other negative reactivities. These concerns were primarily due to how the assemblies would be restrained. EBR-I restrained the assemblies in the grid plate and restricted their movement using the outer wall. Analysis of duct-bowing led to the conclusion that the assembly duct walls being in direct contact

with each other and the outer wall caused the assemblies to bow in a manner where the fuel elements were being moved towards the center of the core, yielding a positive reactivity insertion.

In EBR-II, no mechanical restraint was used above the core mid-plane, which led to the top of the core expanding axially and radially more than the bottom. The difference in expansion was called core flowering which was the integrated core effect of duct-bowing. Core flowering led to a core configuration that would pinch the fueled assemblies using the liner wall as a cantilever. Duct-bowing was further complicated by the grid plate which had a different thermal expansion regime. Table III shows the power independence of grid plate expansion because the calculated power reactivity decrement was zero.

Small raised buttons were placed on the outer duct walls to produce a radial restraint right above the core mid-plane. This meant the assemblies were restrained at the grid plate and the core mid-plane. The bow cantilever would only allow the top of the core to expand outward, leading to a mostly negative reactivity effect. The buttons did not completely mitigate the positive reactivity effect due to bowing, but it reduced the power band where bowing caused positive reactivity. Use of the buttons led to an overall negative reactivity effect. The reason the reported value for thermal bowing in Table III was $+9.8 \times 10^{-4}$ \$/ºC was an acknowledgement of the uncertainty of the reactivity change. It was unknown at what power the coefficient was positive; hence, the most conservative value was used to establish the safety basis.

IV. SIMULATION METHOD

The duct-bowing phenomena complexity arises from mechanical interactions after thermal expansion. A single duct can be modeled using fundamental equations since a hexagonal duct can be represented as a hollow bar. The difficulties appear when modeling a bowed duct where contact occurs with another bowed duct. Stress builds in each duct as the overall pressures come into equilibrium, leading to a net displacement for each duct. If the non-bowed duct starts to bow from either a thermal differential or pressure exerted from another duct, then the system pressures and displacements become even more complex. Each hexagonal duct has six interaction surfaces from which to receive pressure and displacement, and six points from which the duct can exert pressure and displacement to its neighboring ducts. The mechanical interactions occur for each duct in EBR-II leading to thousands of mechanical interactions. When integrated over the whole core, the

net pressure and displacement becomes a problem with millions of degrees of freedom. The following quotation was from an EBR-II scientist who had done extensive work on duct-bowing: "It seems now acceptable to state that the accuracy of subassembly bowing feedback coefficients is not limited by the scheme which is used to compute them, but rather by the quality of the information provided to that scheme." [11] The information provided to the scheme was the mechanical displacement information which ultimately produced such high uncertainty.

Duct-bowing simulation in EBR-II necessitated using finite element analysis (FEA) to capture the millions of degrees-of-freedom. The FEA simulation provided the thermal input to a structural displacement model. The net pressure and displacement for the core was calculated. The core was then divided into axial slices, and a net displacement was calculated for each slice and each duct. These displacements were applied to similar axial slices in a Monte Carlo neutron transport model. Neutron transport simulations were then performed, and k_{eff} was calculated. The process was repeated for several different configurations corresponding to different steps in the assent to power. The change in k_{eff} from one configuration to the next was used to determine the reactivity temperature coefficient associated with duct-bowing.

The calculations were executed on a Dell T7610 Precision Workstation with 48 threads, 256 GB memory, 4 TB storage, and 2 NVIDIA K-40 Tesla GPUs. A similar process for coupling FEA calculations and Monte Carlo neutron transport calculations was performed on the GODIVA-IV apparatus. [12] That work successfully calculated the negative temperature coefficient of GODIVA-IV in comparison to the measured results with a high degree of accuracy.

ANSYS was chosen as the FEA code for the heat transfer model as well as the structural displacement model. [6] ANSYS is a commercial code used for a wide variety of engineering applications with the capability to handle millions of degrees of freedom models on parallel CPUs. MCNP6.1.1b was chosen for the Monte Carlo transport calculations because of the high-fidelity modeling that was achievable. [7]

IV.A. EBR-II Duct-Bowing FEA model

The duct-bowing FEA geometry model approximated the true duct geometry for EBR-II. Simplifying the geometry was necessary to keep the model size manageable. The core-flowering effect cannot be modeled correctly by simulating a single bowed duct and then extrapolating to

the entire core, modeling each duct explicitly in an overall core model was necessary such that all the exerted pressures and displacements were captured. The FEA simulation consisted of two models, the first was a transient heat transfer model, which used boundary conditions that approximated the heat flux during operation, and the second was a thermal stress model which calculated the displacement of the assembly duct due to thermal expansion of the ducts. The geometry for each model was the same.

Previous work demonstrated that modeling the inner components of the assembly was unnecessary. [11] The internal components of the assembly allowed limited duct curvature without exerting any mechanical feedback. The attachment points for the fuel pins also allowed lateral movement. Additionally, the gap tolerances inside the assembly allowed for duct curvature.

The heat transfer model simulated three blocks of sodium inside the duct. These blocks represented the bulk sodium inlet, the power producing region, and the hot sodium outlet. Figure 3 shows the duct and sodium blocks.

[Figure 3 goes here]

Figure 3. Driver assembly CAD model part breakdown.

The heat transfer model applied heat in the core region sodium coupled with boundary conditions of the core and the upper extension sodium to approximate the outlet temperature as measured in EBR-II. Approximate convection coefficients were calculated using thermal values that were reported in other EBR-II analyses. [13] Thousands of boundary conditions were required to model the heat transfer, they are listed in the referenced works. [14] [15] Figure 4 shows a simulation time steps of when the boundary conditions were applied. The steps refer to calculation steps in the FEA simulation where the matrix converged to an answer within the convergence criteria. The structural model then used the temperature output from the heat transfer model to simulate the thermal expansion.

[Figure 4 goes here]

Figure 4. FEA duct-bowing heat transfer model simulation steps.

The structural displacement simulations had fewer boundary conditions compared to the heat transfer simulation and used the temperature data as the primary input to calculate the displacement. The structural boundary conditions were primarily restraints to fix the model in space and to aid in convergence. The convergence aids were only present during the first solution step. In the simulation, the ducts were attached to a stainless-steel plate to capture the thermal expansion of the reactor grid plate, which moved the origins of the ducts before reactor power-up. EBR-II in shutdown mode was still at 350^{o}C, above the freezing point of sodium (~100^{o}C). The result was that EBR-II ducts were in a pre-stressed state before any power was applied. Simulating the pre-stressed state was a necessary requirement to modeling duct-bowing. Without simulating the pre-stressed state, regardless of the accuracy of the bowing calculation, the zero-power positions would have been incorrect. Figure 5 shows an exaggerated example of the core-flower effect in the FEA model using 27 ducts.

[Figure 5 goes here]

Figure 5. Core-flowering example FEA figure.

Due to the model complexity and the numerous selection of nodes that were required, the ANSYS input file was 50 gigabytes containing ~1.1 billion lines of text. Table IV shows the FEA model size and approximate computation time. A special reader called MICKA was written such that it would search the input file and extract needed information. [15] The program generated a database of assembly position and corresponding node numbers. The reader program would also read the displacement data and match the node numbers and assembly position with the node position and the directional displacement information. New points were generated such that the program had a record of assembly positions, node numbers per assembly, position before displacement, and position after displacement. After this information was gathered, the MCNP input file was automatically constructed by the program.

Table IV. EBR-II ANSYS Duct-Bowing Model Parameters

Property	Value
Number of Nodes	5,806,191
Number of Elements	1,661,623
~Computation time	3 weeks

Table V shows average displacement in the x and y directions.

Table V. Duct-Bowing Average Duct Node Displacements [14]

Property	Value
Max average x displacement	0.4197 cm ± 0.0026
Max average y displacement	0.3483 cm ± 0.0026

IV.B. EBR-II Duct-Bowing MCNP 6.1.1b model

MCNP 6.1.1b cannot model a bowed duct directly. An approximation of a bowed-duct was created using displaced axial slices of a hexagonal duct. The core geometry model was axially sliced at the boundaries between the fuel slug sections and the gas plenum boundary leading to four distinct core parts. The ANSYS displacement results were then modified to divide the displacement data per assembly into the four axial parts. Node numbers and positions were sorted by the Z axis to determine where they were in relation to the slices. For each set of node numbers, an average displacement was calculated. The displacement values were used to simulate duct-bowing by displacing each assembly axial part by the average displacement calculated by ANSYS. The displaced axial parts were then added to a lattice arrangement in the MCNP input file according to their axial height. Table VI shows the MCNP model parameters. Due to the sheer number and complexity of the materials, they are not included in this paper and can be found in the benchmark evaluation EBR2-LMFR-RESR-001. [9] Figure 6 shows axial slices with displacements plotted in MCNP 6.1.1b.

Table VI. EBR-II MCNP Duct-Bowing Model Parameters

Property	Value
Number of particles per generation	150,000
Number of generations	1,030
Number of generations skipped	30
Cells	5,485
Surfaces	4,034
Materials	298
Data Library	ENDFB-VII.1
Lines of input	43,787
Computation time	8 hours

[Figure 6 goes here]

Figure 6. EBR-II Duct-Bowing MCNP 6.1.1b model.

V. RESULTS

The duct-bowing reactivity coefficient was calculated by using the reactivity change from a reference k_{eff} and then performing a linear least-squares-fit of temperature versus reactivity. The beta effective used was $\beta = 0.0068$.

The equation used to calculate change in reactivity was:

$$\Delta\rho = \frac{k_1 - k_{ref}}{k_1 * k_{ref}} \quad (1)$$

The uncertainty of these results has three primary components: temperature, Monte Carlo uncertainty, and linear fit assumption. The temperature input uncertainty is unknown. The stochastic uncertainty from MCNP was $\pm 5 \times 10^{-5}$ on k_{eff}. The last component was the linear fit assumption. The linear fit assumption has the highest uncertainty due to the spread of the MCNP results.

V.A. Reactor Grid Plate Reactivity Coefficient

The reactor grid plate expansion simulation consisted of MCNP input files created for approximately every 32 °C change in temperature. Only the geometry displacements were changed between each run in order to isolate the thermal expansion and not to calculate the integrated effect due to multiple other expansions. The reference value used was the room temperature model at 22°C. Figure 7 shows temperature versus reactivity with the error bars representing the stochastic uncertainties from MCNP 6.1.1b on k_{eff}.

[Figure 7 goes here]

Figure 7. Grid plate expansion reactivity coefficient.

Using a linear least-squares-fit of the data in Figure 7, the grid plate reactivity coefficient was calculated and is presented in Table VII.

Table VII. Grid Plate Expansion Reactivity Coefficient Comparison

Method	Reactivity coefficient (10^{-4} \$/ ^oC)	Estimated uncertainty (%)
Values used for run 138B [8]	-14.5	20
ANSYS coupled MCNP	-14.1	2.6

Table VII shows that the ANSYS MCNP method of calculating the reactivity coefficient agrees well with the reported value.

V.B. Duct-Bowing Temperature Coefficient

The duct-bowing MCNP models were created for every 3°C to 4°C change in temperature. Like the grid plate expansion calculation, only the displacements were changed for each run. The reference k_{eff} value used to calculate the reactivities was for the displacements at 344°C. The displacements at 344 °C represent the zero-power hot thermal expansion of the core. Not including these initial displacements would over-estimate the core-flowering effect. The thermal expansion increases the assembly pitch leading to an increase in the gap between assemblies. Increasing this gap changes the duct-bowing reactivity coefficient by allowing more bowing to take place before initial contact occurs between the ducts. More bowing before contact would mean an increase in

the positive reactivity effect leading to an overall decrease in the reactivity effect. Not including the extra gap would decrease positive reactivity and would allow for more flowering to take place. Figure 8 shows the calculated reactivities versus temperature. The error bars are the stochastic uncertainties from MCNP on k_{eff}.

[Figure 8goes here]

Figure 8. Duct-bowing reactivity results.

Using a linear least-squares-fit of the data in Figure 8, the duct-bowing reactivity coefficient was calculated and is shown in Table VIII.

Table VIII. Duct-Bowing Reactivity Coefficient

Method	Reactivity coefficient $(10^{-4}\ \$/\ ^{o}C)$	Estimated uncertainty (%)
ANSYS coupled MCNP	-14.5	4.4

The EBR-II duct-bowing reactivity coefficient was never directly measured. Estimations were made by quantifying the other known coefficients and then attributing the remaining reactivity to duct-bowing. Early observations at EBR-II made after initial wet critical demonstrated that at low-power, EBR-II had a positive duct-bowing coefficient. The results in Figure 8 show that at 344^{O}C and 351^{O}C there was little change in k_{eff} while surrounding temperatures show large changes. Beyond these temperatures, a linear trend exists demonstrating an overall non-linear trend in the duct-bowing reactivity coefficient. The non-linearity could be attributed to the stochastic uncertainty of MCNP; however, the non-linear trend matches the original observations made regarding positive duct-bowing reactivity at low-powers.

VI. CONCLUSION

Knowing the value of the assembly duct-bowing reactivity coefficient in sodium cooled fast reactors is important because it contributes to the overall reactor temperature coefficient. This is especially true since if the assembly duct-bowing reactivity coefficient is positive which can have significant safety implications. Both calculating and measuring the assembly duct-bowing reactivity coefficient in a sodium cooled fast reactor setting has proven to be difficult. Past

practices relied upon crude calculation techniques or measuring other contributors to the overall reactivity temperature coefficient and then attributing the remainder to the duct-bowing reactivity coefficient. These approaches necessarily produce large uncertainty values and thus relegated the duct-bowing reactivity coefficient value to a coarse bounding value.

This paper details the coupled use of a finite element analysis of assembly duct-bowing resulting from thermal expansion and mechanical interaction coupled with a Monte Carlo neutron transport calculation of k_{eff}. By repeatedly performing the calculations using recorded reactor power outlet temperatures as boundary conditions, it is possible to calculate the assembly duct-bowing reactivity coefficient resulting from changes in the duct displacements from one reactor temperature to another.

Using the coupled finite element analysis and Monte Carlo neutron transport methodology, the EBR-II grid plate reactivity coefficient was calculated to be -14.1 x 10^{-4} $\$/{}^{o}C$ which compares well with the previously reported value of -14.5 x 10^{-4} $\$/{}^{o}C$. Additionally, the calculated value uncertainty estimate, 2.6%, is an order of magnitude less than the previously report value, 20%.

When applied to the significantly more complicated assembly duct-bowing reactivity coefficient problem, the coupled finite element analysis and Monte Carlo neutron transport methodology produced a calculated EBR-II assembly duct-bowing reactivity coefficient of -14.5 x 10^{-4} $\$/{}^{o}C$ with an estimated uncertainty of 4.4%. The calculated reactivity coefficient is based on a linear fit assumption which has some drawbacks since there appears to be some nonlinearity in the calculated results associated with the initial part of the assent to power. Nonetheless, the methodology detailed in this paper provides a significant improvement over past approached to estimate the assembly duct-bowing reactivity coefficient.

VII. REFERENCES

[1] P. G. Reinhall, K. Park and R. W. Albrecht, "Analysis of Mechanical Bowing Phenomena of Fuel Assemblies in Passively Safe Advanced Liquid-Metal Reactors," *Nuclear Technology,* vol. 83, no. 2, pp. 197-204, 1988.

[2] L. C. Walters and C. M. Walter, "Observations of Dilation and Bowing in Experimental Breeder Reactor II Ducts and Cladding," *Nuclear Technology,* vol. 46, no. 1, pp. 134-148, 1979.

[3] J. A. Shields, "Bow in Experimental Breeder Reactor II Reflector Subassemblies," *Nuclear Technology,* vol. 52, no. 2, pp. 214-227, 1981.

[4] R. W. Schaefer, "Critical Experiment Tests of Bowing and Expansion Reactivity Calculations for Liquid-Metal-Cooled Fast Reactors," *Nuclear Science and Engineering,* vol. 103, no. 2, pp. 196-209, 1989.

[5] H. Ohta, T. Yokoo, M. Nakagawa and S. Matsuyama, "Development and Validation of ARKAS_cellule: An Advanced Core-Bowing Analysis Code for Fast Reactors," *Nuclear Technology,* vol. 146, no. 2, pp. 131-142, 2004.

[6] ANSYS Inc, *ANSYS Mechanical Products Release 17.0,* Canonsburg PA, 2015.

[7] L. Alamos, "Monte Carlo Code Group," Los Alamos, [Online]. Available: https://laws.lanl.gov/vhosts/mcnp.lanl.gov/index.shtml. [Accessed 31 05 2016].

[8] D. Mohr, L. Chang, E. Feldman, P. Betten and H. Planchon, "Loss-of-primary-flow-without-scram tests: Pretest predicitions and preliminary results," *Nuclear Engineering and Design,* vol. 101, no. 1, pp. 45-56, 1987.

[9] S. E. Lum, C. L. Pope, R. Stewart, B. Byambadorj and Q. Beaulieu, "Evaluation of Run 138B at Experimental Breeder Reactor II, a Prototypic Liquid Metal Fast Breeder Reactor (EBR2-LMFR-RESR-001-CRIT)," Nuclear Energy Agency International Reactor Physics Experiment Evaluation Project, Paris, France, 2018.

[10] L. J. Koch, Experimental Breeder Reactor-II (EBR-II) An Integrated Experimental Fast Reactor Nuclear Power Station, Argonne: Argonne National Laboratory, 1987.

[11] J. P. Finck, "A Technique for Computing the Reactivity Feedback Due to Core Assembly Bowing in LMFBR's," Argonne National Laboratory, Argonne, 1987.

[12] E. Lum and C. Pope, "GODIVA-IV reactivity temperature coefficient calculation using finite element and Monte Carlo techniques," *Nuclear Engineering and Design*, vol. 331, pp. 116-124, 2018.

[13] Laboratory, Argonne National, "EBR-II Specification E0288-002-SF-06," Argonne National Laboratory, Argonne, Il.

[14] E. S. Lum, Simulating the Katana Effect Monte Carlo Neutron Transport Combined with Finite Element Analysis to Calculate Negative Reactivity Due to Duct-Bowing, Pocatello: Idaho State University, 2017.

[15] R. Stewart, E. Lum and C. Pope, "Design of an experimental breeder reactor run 138B reactor physics benchmark evaluation management application," *Journal of Nuclear Science and Technology,* vol. 57, no. 3, 2020.

[16] D. Meneghetti and D. A. Kucerfa, "Comparisons of PRD Componenets for Various EBR-II Configurations," in *ANS Topical Meeting on Advances in Reactor Physics*, Saratoga Springs, New York, 1986.