Analysis of the EBR-II SHRT-45R Neutronics Benchmark with ERANOS-2.0

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Abstract. This paper discusses our calculations of the neutronics benchmark of the EBR-II Shutdown Heat Removal Test 45R (SHRT-45R). The SHRT-45R experiment was performed about 30 years ago in the EBR-II and involved an Unprotected Loss of Flow (ULOF). The experiment is now evaluated as a benchmark in a Coordinated Research Program of the IAEA. The SHRT-45R neutronics benchmark was analyzed with the ERANOS v2.0 code using cross sections based on JENDL-4.0. Calculated results include the multiplication factor, several feedback coefficients, as well as kinetics parameters and the power distribution throughout the core. Where possible, the uncertainty of the calculated parameters is also calculated. Results obtained with ERANOS v2.0 are generally in line with results from other benchmark participants. The energy deposition due to gamma rays in the core is not well calculated. Results with ERANOS v2.0 are generally satisfactory. Recommendations are included.

Key Words: EBR-II Shutdown Heat Removal Test 45R (SHRT-45R), IAEA CRP, Fast reactor core physics, inherent feedback and inherent safety.

1. Introduction

In the EBR-II reactor a series of experiments concerning accidental situations were performed in the 1980s: the Shutdown Heat Removal Tests (SHRT). Two of these tests, SHRT-17 and SHRT-45R, are the subject of a benchmark exercise, implemented as a Coordinated Research Program (CRP) by the IAEA [1]. Of these two benchmark calculations, SHRT-17 concerns a Protected Loss of Flow (PLOF), and SHRT-45R concerns an Unprotected Loss of Flow (ULOF). Since there is no SCRAM of the reactor in SHRT-45R, a detailed evaluation of the inherent neutronic feedback effects is necessary. In this paper, the calculation of the SHRT-45R neutronics benchmark with the ERANOS v2.0 code is discussed. It was decided to participate in this benchmark for two reasons: (1) to validate our own custom cross section libraries for ERANOS, and (2) to determine feedback coefficients and point kinetics parameters for subsequent use in thermal-hydraulic calculations. The benchmark specification calls for the calculation of several reactor physics parameters of the core, i.e. the multiplication factor, Doppler effect, coolant void effect, effects of radial and axial expansion, as well as the effect due to expansion of the control rods. This paper is organized as follows: in Section 2 there is a discussion of the ERANOS v2.0 code and its cross sections, in Section 3 there is a description of the modelling effort for SHRT-45R, and in Section 4 the reader will find the results. Finally, in Section 5 concerns a discussion and presents the lessons learnt from the work.

2. Features of the ERANOS Code System

The ERANOS code system is a complete set of simulation tools for reactor physics analysis, focusing on fast reactors [2]. Originally a European project (**E**uropean **R**eactor **A**nalysis

Optimized **S**ystem), the code has been under continuous development at the CEA for approximately 25 years. At present, ERANOS v2.0 is publicly available through the NEA Data Bank while v2.3 should become available in the near future. The ERANOS analysis is based on the classic two-step approach of cell calculations – homogenization – core calculation – post processing. Cell calculations are done with the ECCO cell code, core calculations can be done with diffusion theory (3D XYZ, Hex-Z), 2D SN transport theory (BISTRO), or variational nodal transport (TGV-VARIANT). Depletion calculations are possible, as are sensitivity and uncertainty (S/U) analysis, with a choice of first-order perturbation theory for S/U analysis of the eigenvalue, exact perturbation theory to determine the spatial distribution of reactivity effects, generalized perturbation theory for the S/U analysis of reaction rate ratios, and extended generalized perturbation theory for the S/U analysis of reactivity effects. Parameters for point-kinetics calculations can also termined.

2.1.Cross Sections for ERANOS

For the SHRT-45R analysis, cross sections for ERANOS (ECCO) were prepared based on JENDL-4.0 [3]. The process of generating an ECCO library is given in FIG.1. A unique feature of the ECCO cell code is the option to use cross section libraries with various group structures. In the present work, the ECCO 1968-group structure was used for the major isotopes (the actinides and several scattering isotopes) while the ECCO 33-group structure is used for other isotopes. The ECCO cell code relies on classic multi-group cross sections and scatter matrices, prepared with the NJOY code (NJOY-99.393 was used [4]), but also requires specific sub-group parameters prepared with the CALENDF code (CALENDF-2010 [5] was used). In the present work, cross sections and subgroup parameters are prepared with 1968 energy groups for each individual isotope. The individual libraries for the major isotopes are subsequently bundled into a complete ECCO library with 1968 energy groups. This library is used in a cell calculation to determine an appropriate weight spectrum for a metal-fueled fast reactor. The weight spectrum is used to collapse all 1968-group libraries to 33 groups; all 33-group libraries are subsequently combined into one ECCO library. The entire process has been automated and parallelized as much as possible; the interested reader is referred to [6] for more information.

Specific for the SHRT-45R benchmark is the presence of “fissium” in the fresh fuel. The elemental composition of this material was provided by ANL in scope of the SHRT-45R benchmark. Another specific feature is the use of lumped fission products (LFP) to represent the reactivity effect of the fission products; there are lumped fission products for U-235, U-238 and Pu-239. Cross sections for fissium and the LFP were created with ERANOS using the basic module MIXTURE_IN_AN_ECCO_INPUT_LIBRARY.

3. Simulations of the SHRT-45R Benchmark

The EBR-II core for SHRT-45R is shown in FIG.2. There are three types of fueled assemblies in the core, referred to as full-worth driver (FIG.3a), half-worth driver (FIG.3b), and control/safety (FIG.3c). Besides the fueled assemblies, the core contains stainless steel dummy assemblies as well as special instrumented assemblies. The core is surrounded by a reflector, and outside of the reflector there is a region of blanket assemblies (FIG.3d). Main parameters of the fuel assemblies and the core are listed in TAB.I. The fuel is highly enriched (approx. 66% U-235) metallic fuel. The blankets contain metallic uranium, mostly U-238. There are small amounts of Pu-239 due to conversion in both the core and the blanket. In the following sections an overview is presented of the modeling efforts for the SHRT-45R benchmark calculations with ERANOS v2.0.

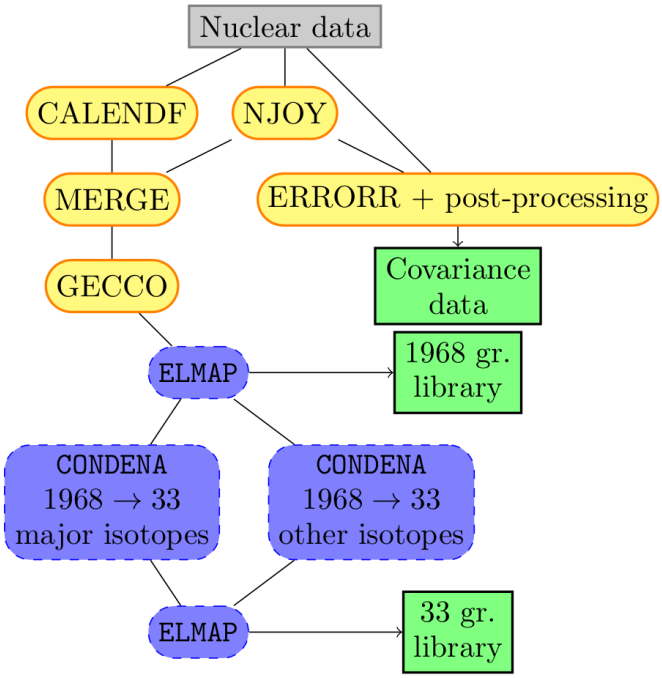


FIG 1. Flow chart for the calculation of a cross section library for ERANOS v2.0. Rectangles: input / output libraries. Solid frames: independent computer codes, striped frames: ERANOS modules.

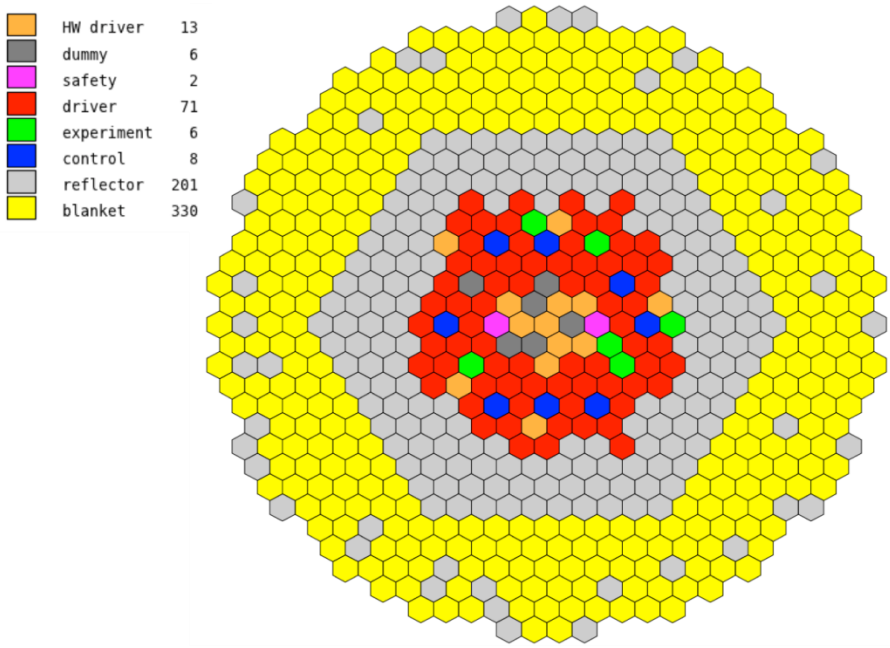


FIG 2. EBR-II core layout for the SHRT-45R experiment.

3.1.Cell Calculations and Preparation of Homogeneous Cross Sections

The benchmark provides isotopic compositions for each fuel assembly and each blanket assembly. The EBR-II core is approximately 36 cm high, and for each assembly, 3 compositions are provided for the bottom, center and top part of the fuel. This results in a total of about 1200 unique isotopic compositions. In ERANOS, the management of the material compositions is fully integrated and if one wants to use 1200 different fuel mixtures, the simplest method would be to perform 1200 ECCO calculations, which represents a considerable computational burden.

TABLE I. SOME PROPERTIES OF THE EBR-II REACTOR

Parameter	Value
Power (MW)	18 MW for 4 days and 60 MW for 1.6 days
Inlet temperature (K)	616
Outlet temperature (K)	716
Subassembly data at 20ºC (driver/blanket)	
Subassembly pitch (cm)	5.89
Na gap thickness (mm)	0.38
Duct wall thickness (mm)	1.02
Structural material	SS316 / SS304
Lower shield height (cm)	55.32 / 3.46
Fuel height (cm)	34.29 / 139.70
Gas plenum height (cm)	24.90 / 11.348
Upper shield height (cm)	38.69 / 0.0
Pin data at 20ºC (driver/half-worth/safety/blanket)	
# pins	91 / 45 / 61 / 19
Fuel slug diameter (cm)	0.34 / 0.34 / 0.34 / 1.11
Cladding inner diameter (cm)	0.38 / 0.38 / 0.38 / 1.16
Cladding outer diameter (cm)	0.44 / 0.44 / 0.44 / 1.25

The EBR-II core contains 4 categories of fueled assemblies: full-worth driver, half-worth driver, control / safety, and blanket assemblies. It was decided to perform cell calculations for one representative assembly of each category; this gives a total of 12 cell calculations since there are three fuel compositions for each SA.

For fueled assemblies, cell calculations are performed in 2D geometry as illustrated in FIG.3a – 3d. Cell calculations are performed with the recommended "ECCO reference route" [7]; this entails calculations in heterogeneous geometry using 1968 and 33 groups for the fueled assemblies. Non-fuel regions are homogenized based on the assembly design data specified in the benchmark documentation, and cross sections are prepared as infinite homogeneous medium in 33 energy groups. EBR-II control assemblies feature a reduced fuel bundle in a guide thimble (FIG. 3c). The fueled part can be lowered out of the core to obtain the desired control effect. Some control assemblies are so called "high-worth" control assemblies, which have an absorber bundle (B4C) above the fuel bundle. When the fueled part is lowered out of the core, the absorber section is inserted into the core region, giving a strong reactivity effect. Cross sections for the absorber section were prepared with the so-called reactivity equivalence method in ERANOS.

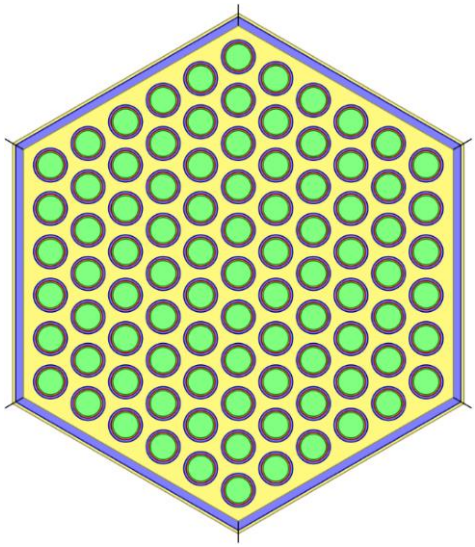
For the fuel-bearing mixture, he 12 cell calculations produce 12 libraries with microscopic cross sections. For each mixture in the benchmark, the specified mixture composition is used with the corresponding microscopic cross sections to generate macroscopic cross sections. Since there are so many mixtures, a special ERANOS module was programmed directly in the ESOPE programming language. Taking into account the presence of non-fuel mixtures in the core, the total number of unique mixtures is 1324.

3.2.Core Calculations

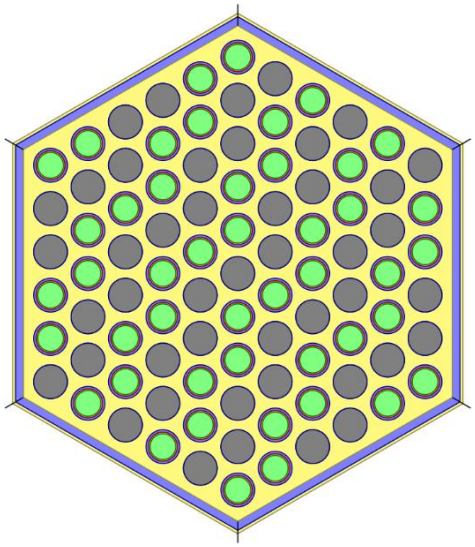
The benchmark documents specify precisely the geometry of each type of assembly in the EBR-II core, and also specify the insertion depth of the control rods. Taking into account the axial dimensions of each type of assembly and effects of axial expansion, a unified axial mesh results with many "small" meshes. This mesh was "thinned out" by hand, removing small meshes (e.g.

meshes of height less than 1 cm) but making sure that the total mass of fuel remains unchanged. Core calculations were done as follows:

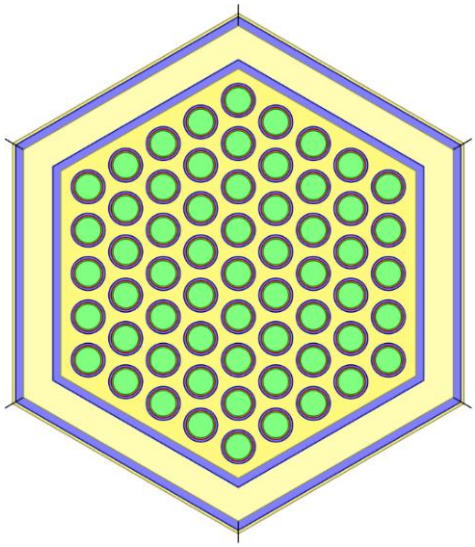
- For the multiplication factor, TGV-VARIANT was used with transport theory, 33 energy groups, P_5 flux expansion and P_1 scatter cross sections. This proved to be a demanding calculation. The flux distribution from TGV-VARIANT is used to determine the power distribution in the core as well as the fission rates in U-235, U-238 and Pu-239, which are needed for the decay heat calculation in subsequent thermal-hydraulic analysis.
- Diffusion theory with Hex-Z geometry was used to calculate forward and adjoint fluxes for S/U analysis and the determination of the point kinetics parameters.
- The control rod worth curve was determined with a series of core calculations, varying the insertion depth of the control rods.



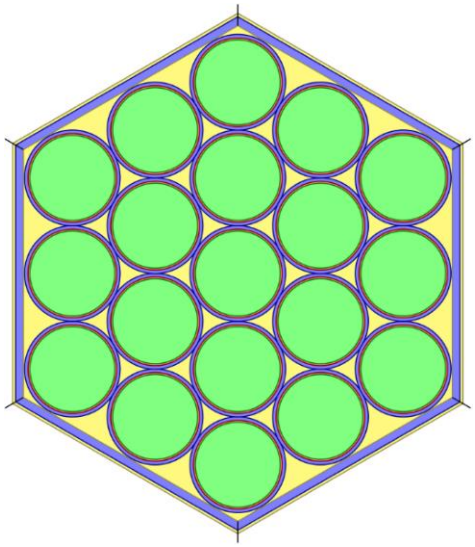
3a. Full worth driver SA (91 fuel pins)



3b. Half-worth driver SA (45 fuel pins, 46 steel pins)



3c. Control / safety SA (fueled part, 61 pins)



3d. Blanket SA (19 pins)

FIG 3. The 4 categories of fuel-bearing assemblies in the EBR-II core. These are the models used in the cell calculations with ECCO. Note: this is the actual size of the assemblies (pitch 5.89 cm).

3.3.Reactivity Feedback Coefficients

The main purpose of the neutronics benchmark is the determination of the reactivity feedback coefficients for the thermal-hydraulic calculations. The benchmark description requests the following feedback coefficients: Doppler effect, sodium void effect, radial expansion, axial expansion, control rod drive expansion. The benchmark does not define these coefficients in more detail, and as a result, some interpretation is necessary. In line with discussions at the benchmark coordination meetings, the reactivity coefficients were determined as described below. In all cases, direct calculations were used, where all cross sections are re-evaluated at each expansion state of the reactor.

Doppler Effect

The Doppler effect is calculated by increasing the temperature of the fuel by 1000 K from the reference state, and then

$$\alpha_D = \frac{\rho(T_0 + \Delta T) - \rho(T_0)}{\Delta T}$$

Note that the geometry does not change in this calculation; it is thus an artificial (not physically possible) state of the reactor. The EBR-II core has a special configuration, where the core is surrounded by a steel reflector, which in turn is surrounded by the blanket (mostly U-238). The core has high enrichment (66% of U-235) and thus has a negligible Doppler effect. Since the blanket is far away from the core, any power increase in the core does not directly increase the temperature in the blanket and thus the blanket was not taken into account for the determination of the Doppler effect.

Sodium Void Coefficient

In any fast reactor the reactivity is more or less sensitive to the coolant density. In the current work, the sodium temperature was assumed to increase by 100 K, and the corresponding density was calculated. The reduced density was used, ceteris paribus, to determine the sodium void effect. Two calculations were performed: one case where the coolant density in the core region was reduced, and one calculation where the coolant density was reduced throughout the reactor.

Axial and Radial Expansion Coefficients

Physically, axial and radial expansion are driven by (a change of) temperature. The radial expansion of the core is mostly determined by the temperature of the grid plate, whereas the axial expansion is mainly determined by the state of the fuel. Since the geometrical description in ERANOS only allows for uniform meshes, a uniform expansion must be calculated. Reactor materials were grouped into solids and fluids. The thermal expansion coefficients provided in the benchmark for the metallic fuel and the cladding are very similar; thus, the thermal expansion coefficient of stainless steel was used for all solids. For radial and axial expansion a uniform temperature change of 100 K was adopted and material densities were appropriately reduced; for radial expansion, the cell calculations were appropriately changed.

Control Rod Driveline Expansion

The benchmark requested that the reactivity change to due control rod driveline expansion was evaluated. However, the benchmark does not detail the control rod drivelines and thus it is difficult to model this effect. Ultimately, it was decided to calculate the control worth curve.

3.4.Energy Deposition due to Gamma Rays

For the thermal-hydraulic evaluations, it is important to know the power distribution in the reactor, with specific attention to the non-fueled assemblies, where power is deposited due to neutron capture and the absorption of gamma rays. In ERANOS v2.0 the transport of gamma rays can be calculated with the 2D BISTRO transport code. For this calculation, one needs cross sections for gamma transport, the source of gamma rays, and the KERMA factors which determine the energy deposition due to absorption of gamma rays. A set of gamma cross sections was kindly provided by the CEA; KERMA factors are part of the standard ERANOS v2.0 distribution. For the gamma transport calculation an RZ equivalent core model was developed. The source distribution of gamma rays was determined from the neutron flux, taking into account gamma ray production from fission and capture reactions. The resulting power deposition due to gamma rays was then normalized with the fission power to give the requested total reactor power.

4. Results

Note the following: in the present work, three sets of cross sections were produced, i.e. one set based on JENDL-4.0, one set based on JEFF-3.1.2, and one set based on ENDF/B-VII.1. In some figures, results are given for all three data sets, although the discussion in this paper mostly concerns the results obtained with JENDL-4.0. The main results are listed in TAB.II; the uncertainty due to nuclear data on the reported parameters was calculated when possible. Uncertainties were calculated with conventional perturbation methods; covariance data was taken directly from the nuclear data files, i.e. the covariance data is not “adjusted”. In FIG.4a the contribution to the uncertainty of the multiplication factor due to individual isotopes is given. As expected, U-235 is the most important isotope. In FIG.4b the isotopic contribution to the Doppler effect is given. Note the strong positive influence due to U-235 fission: broadening of the fission resonances leads to an increase of the fission. Also note that the contribution from U-238 is large, even if U-238 is only 33% of the fuel material. The uncertainty of the Doppler effect is dominated by Fe-56, and, rather surprisingly, Mn-55, as illustrated in FIG. 4c. Finally, in FIG.4d the contribution to the uncertainty of the void effect is given. As expected, Na-23 and U-235 contribute most to this uncertainty. From TAB.II it is immediately clear that only geometric feedback effects are available in EBR-II; the Doppler coefficient is basically zero.

TABLE II: RESULTS OF THE ERANOS ANALYSES, COMPARISON WITH BENCHMARK PARTNERS

Parameter	**Value**	**KIT**	**PSI**	**ANL**
Multiplication factor	0.9923 ± 0.44%	0.9876	1.001	0.9885
β_{eff} [pcm]	691	691	694	705
Feedback parameters [pcm / K]				
Axial expansion	-0.84	-0.68	-0.48	-0.65
Radial expansion	-2.10	-2.42	-1.72	-1.67
Axial + radial expansion	-2.94			
Sodium expansion core only	-0.71			
Sodium expansion throughout	-1.90 ± 1.71%	-2.15	-1.68	-1.49
Doppler	-0.024 ± 5.81%	-0.04	-0.05	-0.06
Control rod expansion	-0.8 (determined from CR worth curve)			

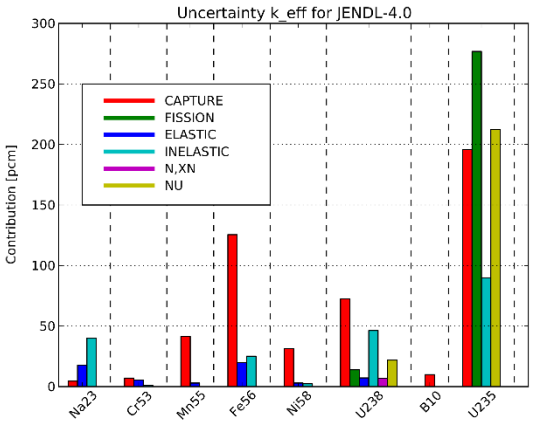


FIG.4a. Isotopic contributions to Δk

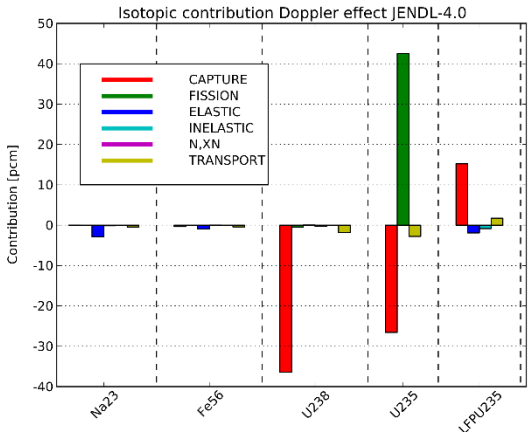


FIG.4b. Isotopic contributions to the Doppler effect.

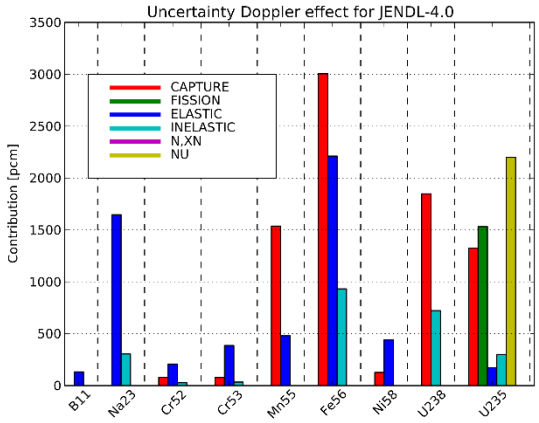


FIG.4c. Isotopic contributions to the uncertainty of the Doppler effect.

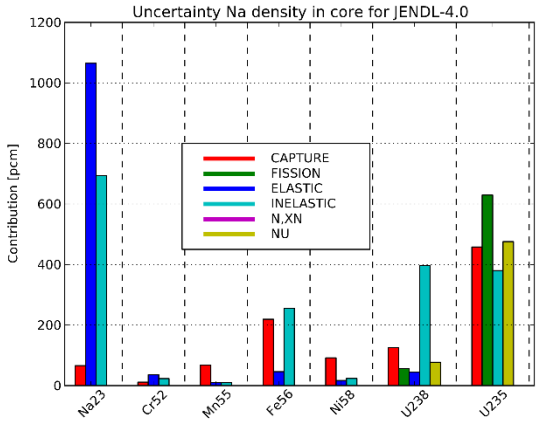


FIG.4d. Isotopic contributions to the uncertainty of the void effect.

FIG.4 Isotopic contributions to the reactivity effects.

The power distribution is shown in FIG.5a (units of kW per SA). The power distribution for SHRT-45R is also supplied as part of the benchmark documents, and in FIG.5b the error between our calculations and the benchmark data is shown. The error in the power distribution is on the order of a few percent for most assemblies, in other words, a rather good result, but there are a few assemblies with errors of 50% or more (position 05A03 being the worst, with an error of 89.51%). The positions with the largest errors all contain stainless steel dummy assemblies. Power is produced in these assemblies due to neutron capture and gamma ray absorption. Disregarding the contribution of gamma rays the energy deposition in the steel assemblies is too low, but with the correction for gamma ray transport the energy deposition is much too high.

It should be noted here that there is no actual measured data for the power distribution in the EBR-II core. The benchmark documentation gives the calculated power for each assembly prior to the SHRT-45R experiment. It is unknown how this map was calculated, and it is unknown how reliable the numbers are; it is unknown whether or not a correction for energy deposition due to gamma rays was taken into account. As a result, it is not possible to judge “right” and “wrong” in this case.

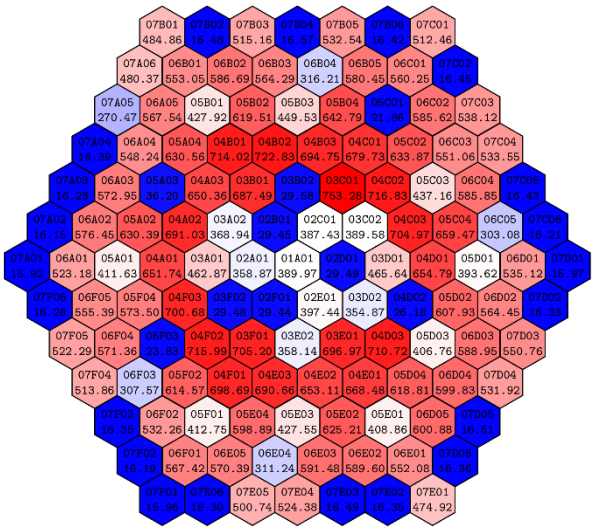


FIG.5a. Power distribution [kW]

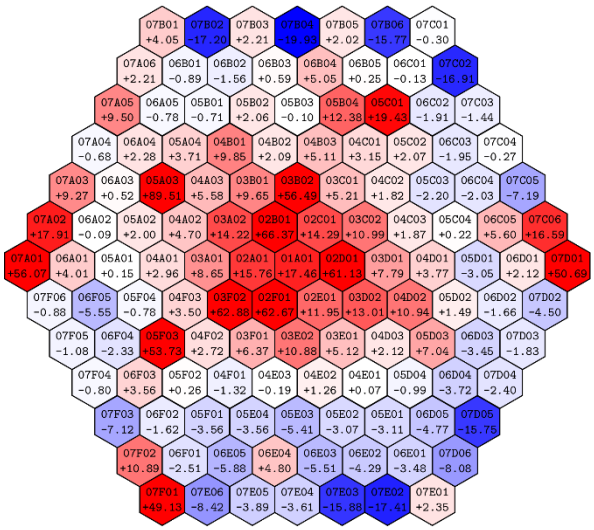


FIG.5b. Error of power distribution vs benchmark [%]

FIG.5. Power distribution in the EBR-II core

The control rod worth curve is presented in FIG.6a. To determine the effect due to control rod drive expansion, separate calculations were done where the control rod position is varied around the critical position (FIG.6b). Interestingly, the graph shows that the reactivity would decrease if the control rod is extracted past the critical position. Whether this is a true or an artifact of our modeling is unclear.

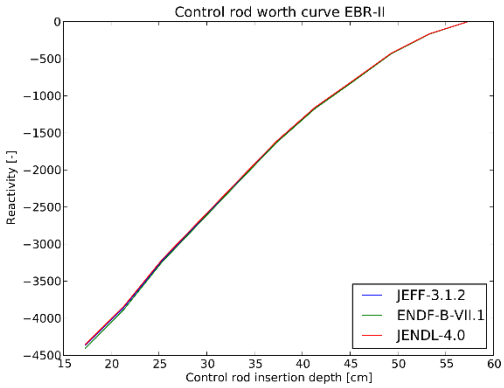


FIG.6a. Integral control rod worth curve

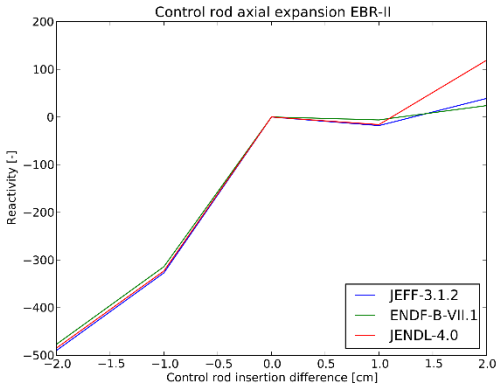


FIG.6b. Reactivity effect of control rod movement around critical position

FIG.6. Reactivity effects due to the control rods.

5. Discussion and Lessons Learnt

In general, the performance of ERANOS v2.0 for the EBR-II benchmark was very satisfactory. From a practical point of view, there were only two problematic areas: (1) the large number of unique mixtures (> 1200 fuel mixtures) required the creation of a special module to calculate macroscopic cross sections from pre-calculated microscopic cross sections and user-supplied material compositions, and (2) the memory footprint of TGV-VARIANT. Despite the small size of the EBR-II core and the high level of heterogeneity, core calculations were successful,

accurate and converged without failure. The power distribution in the presence of gamma ray transport requires a more detailed investigation.

The overall experience of this benchmark exercise also highlighted a shortcoming in traditional reactor physics calculations. It is clear from this work that the Doppler effect is negligible in EBR-II, and all feedbacks are purely due to expansion effects. However, classic reactor physics codes, such as TGV-VARIANT, can only handle rectilinear coordinate systems, in other words, even if one can (theoretically) calculate the precise deformation of the core due to thermal expansion, the neutronics analysis code cannot perform a calculation in the actual, deformed geometry. A similar observation concerns the temperature (and thus the density) distribution of the coolant. In other words, the calculated feedback coefficients are only approximate, in the sense that they correspond to a hypothetical state of the reactor. Note also that the application of Monte Carlo (MC) calculations does not improve the situation, since MC codes cannot treat arbitrarily deformed geometries.

In the scope of the benchmark, many participants obtained very detailed results for the thermal-hydraulic (TH) properties; some participants succeeded in resolving the flow and temperature distribution inside individual fuel assemblies with CFD calculations. Compared to such detail, the classic approach of cell calculations – homogenization – core calculation of ERANOS seems very crude. Furthermore, since most TH codes rely on point kinetics in combination with more or less sophisticated reactivity feedback models, the neutronics calculations should be able to provide detailed distributions of feedback effects – which is not possible for expansion effects since ERANOS can only perform perturbation theory if the reference and perturbed geometries are identical. The EBR-II benchmark has shown that there is much to be gained in the area of coupled analysis of nuclear reactors.

Acknowledgment

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References

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Benchmark Analyses of EBR-II Shutdown Heat Removal Tests, IAEA-TECDOC, IAEA, Vienna (2017, under review).

[2] RIMPAULT, G. et al., “The ERANOS code and data system for fast reactor neutronics analyses”, Proc. Int. Conf. PHYSOR2002, Seoul, South Korea, October 7 – 10 2002 (2002).

[3] SHIBATA, K. et.al., “JENDL-4.0: A new library for nuclear science and engineering”, Journal of Nuclear Science and Technology, **48**(1), 1 – 30 (2011).

[4] MACFARLANE, R.E., MUIR, D.W., LANL Report LA-12740-M (1994).

[5] SUBLET, J.-C., RIBON, P., COSTE-DELCLAUX, M., “CALENDF-2010: User Manual”, Rep. CEA-R-6277 (2011).

[6] VAN ROOIJEN, W.F.G., YAMANO, N., “Analysis of the neutronics properties of the prototype FBR Monju based on several evaluated nuclear data libraries”, Nuclear Data Sheets **118**, 426 – 429 (2014).

[7] RIMPAULT, G., SUTEAU, C., “Lattice calculation with ECCO”, ERANOS User Workshop 2006, CEA Cadarache (2006)