High-fidelity modelling of the ETRR-2 research reactor

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Abstract. This study forms part of the on-going International Atomic Energy Agency (IAEA) Coordinated Research Project (CRP) which primarily focuses on benchmarking computational tools against experimental data for research reactors. It is important to benchmark these tools against experimental data as part of evaluating their capabilities in simulating physical phenomena which take place during reactor operation. Necsa has recently developed a framework for performing nuclear reactor core calculations, which integrates both stochastic and deterministic modelling methods in a consistent way. In this work, this calculational system is applied to the ETRR-2 benchmark problem in aid of code validation. In particular, a series of control rod calibration experiments are modelled as initial qualification of the model, whereafter a series of cycle depletion analysis is conducted to validate the burn-up capability of the package.

1. Background and motivation

This work forms part of the on-going IAEA CRP which primarily focuses on benchmarking computational tools against experimental data for research reactors. In the general run of the IAEA CRP projects for research reactors, a platform is made available for interested institutions to submit their reactor specifications, experiment descriptions and experimental data for benchmark studies. A previous IAEA CRP 1496 [1] mainly focused on benchmarking neutronics and thermal-hydraulics computational methods and tools against experimental data for operation and safety analysis of research reactors, whereas the current IAEA CRP [2] focuses on burn-up and activation calculations. Research reactors are widely used for material/fuel testing, neutron activation studies, silicon doping, medical and industrial isotope production and other applications. For safe and efficient reactor operation, reactor core planning and core-follow calculations are to be performed for every operational cycle. It is therefore important to benchmark computational tools against experimental data as part of evaluating their capabilities in simulating physical phenomena which take place during reactor operation. With the ever increasing computing power, the capabilities of computational tools have been considerably improved over the years. However, before any computational tool can be licensed to perform routine reactor calculations, it must have been extensively verified and validated against experimental data. The nuclear industry is strictly regulated and for this reason the CRP project was primarily initiated to promote/ensure safe and efficient operation of research reactors through the use of computational tools which are validated against experimental data. Necsa has recently developed a tool which integrates both Monte-Carlo and deterministic based codes in a consistent way. For instance, it allows the creation of detailed unified heterogeneous 3D models, which can then be deployed to generate input for various underlying codes such as MCNP [3], Serpent [4] and also the OSCAR-4 [5] nodal diffusion solver. In this particular work, the tool was used to prepare detailed models for the Egyptian 2nd Testing Research Reactor (ETRR-2) benchmark, which is part of the current CRP on multi-cycle core depletion and material activation analysis. The models were then employed in the Monte-Carlo criticality and burn-up code, Serpent II, to simulate ETRR-2 benchmark experiments.

2. Facility overview

ETRR-2 is a 22 MW open pool tank type, multi-purpose research reactor in Egypt. The facility has been successfully utilized for material testing, silicon transmutation, medical radioisotope production, neutron activation analysis and neutron radiography. It is fuelled with low-enriched (19.7%) fuel elements, cooled and moderated with light water and reflected by beryllium blocks. The core configuration consists of a 6 × 5 array of 29 fuel elements, six neutron absorbing control blades, two control guide boxes and a central position for cobalt irradiation. The core is surrounded by four chambers that can be filled with gadolinium solution which is used as a secondary shutdown mechanism. The ex-core region consists of a configurable aluminium grid with beryllium blocks, hollow aluminium boxes and aluminium blocks which make up the last row of the grid positions.

3. Experimental description

3.1. Control rod experiment

The facility was commisioned in the early 90s and its first criticality was achieved in 1997 [6]. During the commisioning stage, a series of control rod calibration experiments were performed for which the results and experimental descriptions were made available in a previous IAEA CRP [7]. Typically, these experiments are perfromed at low reactor power to avoid feedback effects. The reactor core is adjusted to be at a super-critical state by withdrawing control rod to be calibrated by a certain distance and reactivity is measured. The reactor is then brought back into a critical state by inserting a rod which is not being calibrated. This procedure is repeated over and over again until the calibrated rod is fully extracted from the core. From such experiments, differential and integral rod worth curves can be derived. These curves are often used to charaterize the absorbing capability of control rods as a function of extraction position. Since the commisioning cores and corresponding experiments consist of fresh fuel elements, such experiments provide a good platform to verify and validate calculational models without having to deal with extra uncertainties associated with burn-up and cycle modelling. Core SU-29-2SO was choosen from the previous CRP as a basic core configuration to test the models before doing the multi-cycle core depletion analysis for four burn-up cycles. In particular, control rod 5 calibration was simulated using control rods 3 and 6 to compensate for change in reactivity.

3.2. Fuel burn-up experiment

From the four operating cycles, three irradiated fuel elements were removed at different operational cycles from the core for experimental burn-up measurements. Burn-up is usually determined by measuring the content/concentration of a particular fission product of interest which results from prompt fission. Burn-up measurement techniques which yield high quality results are usually costly and time consuming [8]. A low-cost technique which is still relatively efficient is the gamma spectrometry method. This technique is widely used to calculate burn up by measuring the activity of the particular fission product of interest. In this study, Cs-137 was also used as a fission monitor/counter to calculate % burn-up for the three spent fuel elements using the following Equations 1 and 2, respectively.

$$\% \, \text{Burn up} = \frac{\text{number of fissioned atoms}}{\text{intial number of U} - 235 \, \text{atoms}} \tag{1}$$

where,

$$\text{Number of fissioned atoms} = \frac{\text{number of Cs} - 137 \, \text{atoms}}{\% \, \text{yield of Cs} - 137 \, \text{from fission}}. \tag{2}$$

Cs-137 fission % yield was determined from the mass distribution curve of fission products for all actinides (the yield is very similar for U-235 and Pu-239). In addition, calculated burn-up results for the three irradiated/spent fuel elements were also provided for comparison by the benchmark suppliers.

4. Calculational approach adopted and model description

Using the code independent pre-processor, detailed heterogeneous models are created in preparation of the ETRR-2 benchmark problem. The models are created based on the ETRR-2 facility specifications document [9] which include material specifications and geometric description of the reactor components. A library of in-core and ex-core reactor components is built which is later on used to create a complete core layout. With this new modelling approach, an attempt is made to model the reactor as accurate as possible. In this work, the models are then deployed to generate Serpent input for Monte-Carlo based calculations. Figure 1 illustrates a 3D model of the ETRR-2 reactor with fuel elements, control rods, cobalt irradiation device and the second shutdown system surrounding the core.

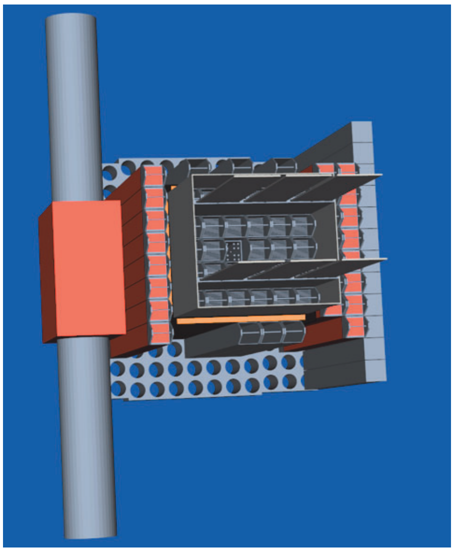

Figure 1: 3D model of the ETRR-2 reactor

However, it must be pointed out that some assumptions had to be made in the modelling process, especially where certain material, structural and operational descriptions were not given. For instance, in the case of cobalt irradiation device no description was given for the spacer element, cobalt pellets, material specifications for the top and bottom structure and cobalt has negative reactivity effects. No plant operational history with control rod positions was given and as a result a rod search method was implemented and used, assuming two rods are fully extracted from the core throughout the operational cycles. No indication of reactor power delivered and as result a constant power per cycle was assumed.

5. Results and discussion

5.1. Control rod calibration

Figure 2 shows the calculated and measured control rod 5 differential rod worth curves from the selected core SU-2SO. It must be noted that for the first 13 steps, control rod 5 was calibrated using rod 3 to compensate for the change in reactivity and rod 6 was used to compensate for the remaining cases untill rod 5 was fully extracted from the reactor core. It is clearly seen from Figure 2 that our model over-estimated the measured values in most cases and under-estimated in few. Some of the calculated points are way off and this could be attributed to the model convergence, fission source term not fully converged for those cases. Our model was also overly sensitive to reactivity changes hence in some cases it over-estimated the measured valules. Conceptually, the differential rod worth curve is expected to peak towards the center of the core where there is high neutron flux but in this case the flux profile is suppresed and this could be due to the presence of Co-59 pellets in the irradiation device. Since no description was provided for the cobalt loading pattern and the spacer element, this could have also contributed to the offset observed towards the center of the core. However, moving from the center towards the top of the core, our model agrees with the measured values except for the last value.

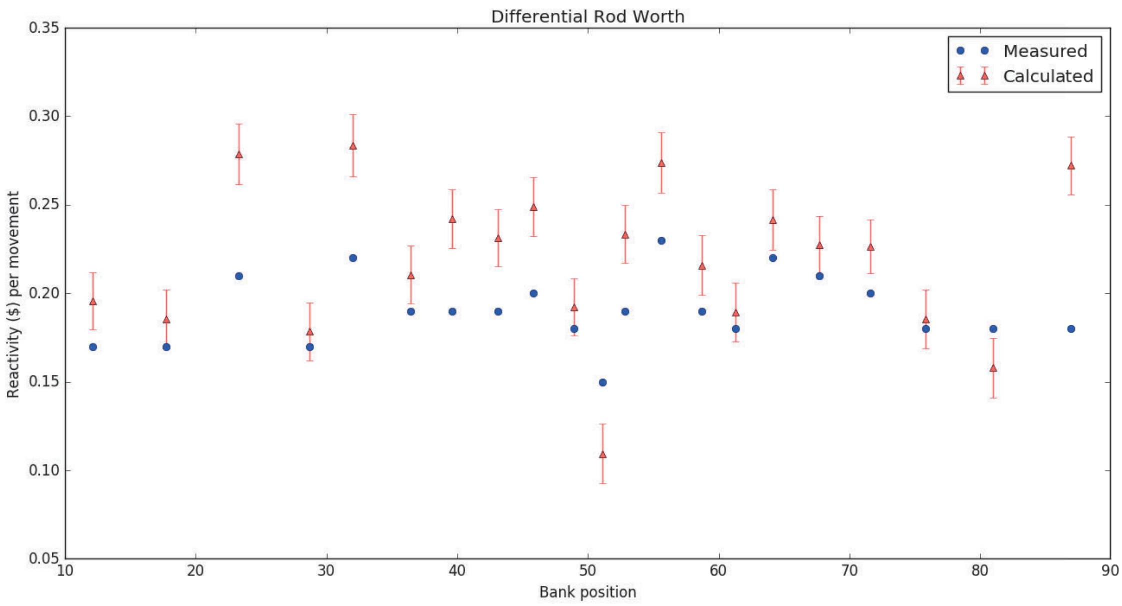

Figure 2: A comparison between the calculated and measured differential rod worth curves for control rod 5 calibration

From the differential rod worth curves in Figure 2, corresponding integral rod worth curves were derived as shown in Figure 3. Once again it can be clearly observed from Figure 3 that our model deviated from the measured values, more especially moving towards the center of the core all the way the top of the core.

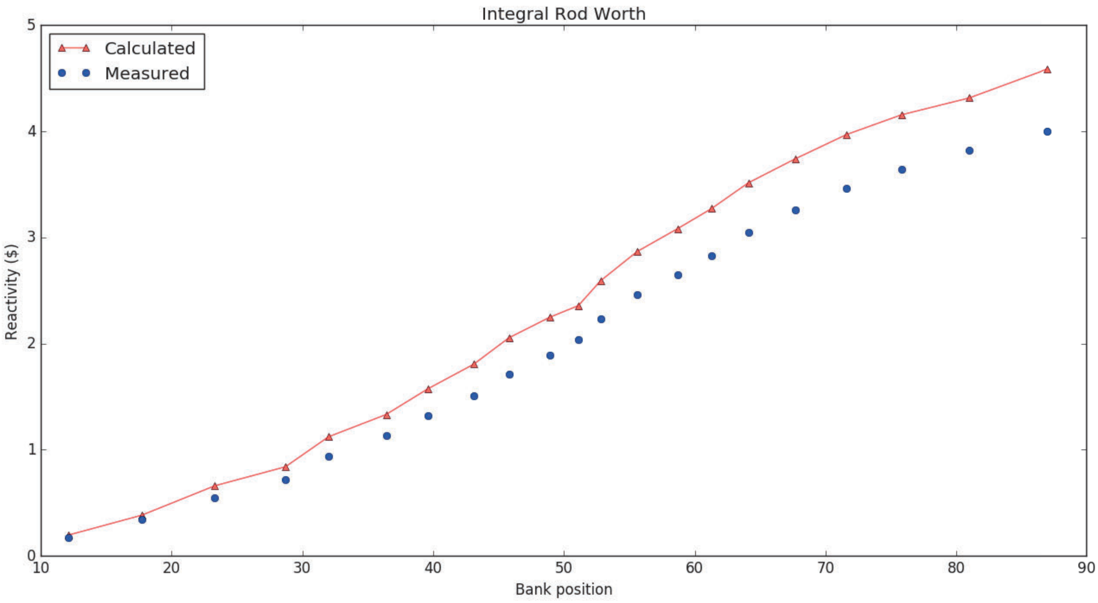

Figure 3: A comparison between the calculated and measured integral rod worth curves for control rod 5 calibration

5.2. Fuel burn-up calculations

Table 1 shows the results of the calculated and experimentally measured % burn up for the three selected spent fuel elements. In our case, Equations 1 and 2 were used to calculate % burn up for the three spent fuel elements using Cs-137 as fission monitor. For elements 1FE001 and 2FE001, our model was relatively closed to the measured % burn up as compared to what the benchmark supplier predicted/calculated. The low burn-up values are more sensitive to rod positions. However, it turned out that for element 1FE007 prediction by the benchmark supplier was closer to the measured value as compared to what our model predicted. It must be noted that the benchmark supplier calculated their % burn up with all rods out, whereas in our model a rod search method was utilized with two rods fully extracted and the remaining four rods moving as a bank. It is more accurate to use a rod search method to perform reactor calculations than to do them with all rods out.

Table 1: Comparison between measured and calculated % burn-up for the three irradiated fuel elements

Fuel element ID	**Mass of U-235** (gram)	**Measured burn-up**	**Calculated burn-up** (benchmark providers)	**Calculated burn-up** (Necsa)
1FE001	148.2	3.26 %	4.23 %	3.60 %
1FE007	148.2	10.70 %	11.10 %	11.70 %
2FE001	209	20.92 %	22.61 %	20.11 %

6. Conclusion

As far as control rod calibration are concerned, our model mostly over-predicted the measured values and under-predicted them in few cases. However, the model at least followed the trend of the experimental data even though there was an offset between the calculated and measured values. On the other hand, the calculated % burn up results were in good agreement with the measured values and therefore the burn up capability of the Serpent code was successfully validated for this ETRR-2 benchmark exercise. For future work, further studies are to be conducted more specifically in the case of control rod calibration experiments. This work forms part of our submission to the current IAEA CRP on benchmarking computational tools against experimental data for research reactors.

7. References

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