Validation of a cross-section interface for PARCS

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Abstract

This paper deals with the validation of a cross-section interface for the PARCS code. Such an interface, of which the development is reported in [1], allows providing realistic sets of material constants to PARCS, so that the full dependence of these data on history variables, instantaneous variables, and exposure can be accounted for. In order to check the proper implementation of this interface, the PARCS code was benchmarked against actual plant data (relative power distribution throughout the core and criticality condition). For that purpose, the Swedish Ringhals-3 Pressurized Water Reactor was considered. Different fuel cycles and within each cycle different core exposures were investigated. The cross-section data for each fuel/reflector assembly constituting the considered cores were created accordingly. The spatial distributions of the instantaneous conditions, of the history effects, as well as of the burnup, were taken from the results of SIMULATE-3 calculations. It was found that PARCS was able to reproduce the relative distribution of the power within the core. Both the measured axial and radial power profiles were correctly calculated by PARCS. On the average, the deviation between the calculated and measured power distributions is within acceptable limits. Concerning the determination of the core criticality, the deviation of the effective multiplication factor from unity is typically within ±200 pcm.

KEYWORDS: validation, core calculations, measurements, material constants

1. Introduction

In a companion paper [1], an interface allowing feeding the 3-D core simulator PARCS [2] with realistic material constants of any heterogeneous Pressurized Water Reactor (PWR) core was developed. Since the Studsvik Scandpower CASMO-4/SIMULATE-3 code package [3, 4] is used predominantly in Sweden, such an interface is based on the use of the binary library file created by CASMO-4 and read by SIMULATE-3. This binary library file contains the results of the 2-dimensional transport calculations of all the fuel/reflector assemblies loaded in a specific core and for all the possible operating conditions. More precisely, SIMULATE-3 is used for reading this file and for interpolating the data at the operating points necessary for representing the dependence of the material constants in PARCS. The full dependence of the material constants on history variables, instantaneous variables, and exposure can thus be reconstructed in

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a consistent way with the PARCS formalism.

The purpose of this paper is to check the proper implementation of the interface, i.e. to check that the cross-section data files (so-called PMAXS files, PMAXS standing for Purdue MAcroscopic Cross-Section) allow accurately modeling a PWR core. The validation task considered thereafter is a benchmark between PARCS and plant measured data. The paper is thus organized as follows. In the first part, the Ringhals-3 model is presented, with emphasis on the data functionalization of the material constants. The measured data are also described. Finally, the relative deviation of the calculated data from the measured ones is given for several fuel cycles and different exposures.

2. Presentation of the PARCS model and of the measured data sets

2.1 PARCS model

Since history effects are important to be taken into account while modeling a nuclear core, the complete history of the Ringhals-3 reactor had to be recovered. All the SIMULATE-3 input files modeling the history of the plant since the start of its commercial operation until December 2004 were obtained from Ringhals AB, i.e. the power utility operating the four Ringhals units, representing a total of 22 fuel cycles. Modeling the whole history of the Ringhals-3 PWR with PARCS would have been another alternative. Nevertheless, since Ringhals AB has been using SIMULATE-3 for in-core fuel management and core follow of Ringhals-3, using the history computed by SIMULATE-3 was preferred. The binary library file containing the results of the transport calculations for each of the fuel/reflector segments loaded in Ringhals-3 was also obtained, from which the PMAXS cross-section files were constructing using the interface mentioned previously. For each cycle considered in this benchmark, i.e. for each core loading, the PMAXS files had to be created accordingly.

The data functionalization was carried out differently for the fuel and reflector segments. For the fuel segments, the data functionalization of any parameter P was performed according to[1]:

$$\begin{aligned} & P\left(b, HD_m, HC_b, \alpha_{CR}, D_m, C_b, T_f\right) \\ & = P\left(b, HD_{m,0}, HC_{b,0}, \alpha_{CR,0}, D_{m,0}, C_{b,0}, T_{f,0}\right) + \left.\frac{\partial P}{\partial \alpha_{CR}}\right|_{\left(b, HD_m, HC_b, \alpha_{CR,ref}\right)} \times\left(\alpha_{CR} - \alpha_{CR,0}\right) \\ & + \left.\frac{\partial P}{\partial D_m}\right|_{\left(b, HD_m, HC_b, \alpha_{CR}, D_{m,ref}\right)} \times\left(D_m - D_{m,0}\right) + \left.\frac{\partial P}{\partial C_b}\right|_{\left(b, HD_m, HC_b, \alpha_{CR}, D_m, C_{b,ref}\right)} \times\left(C_b - C_{b,0}\right) \\ & + \left.\frac{\partial P}{\partial \sqrt{T_f}}\right|_{\left(b, HD_m, HC_b, \alpha_{CR}, D_m, C_b, T_{f,ref}\right)} \times\left(\sqrt{T_f} - \sqrt{T_{f,0}}\right) \end{aligned} \quad (1)$$

where b represents the burnup, HD_m and HC_b represent the history of the moderator density and of the boron concentration, respectively, C_b represents the instantaneous boron concentration, T_f represents the instantaneous effective fuel temperature, D_m represents the moderator density,

[1] The data functionalization is actually slightly simpler for the fission yields. The interested reader is referred to [1] for the details related to the functionalization of these parameters.

and α_{CR} represents the effective rodded fractions. The subscript 0 denotes the base case, whereas the subscript *ref* represents the reference point, defined as the midpoint between the instantaneous value and the base value. This can be written in a generic form as:

$$v_{ref} = \frac{v + v_0}{2} \tag{2}$$

For the reflector segments, the data functionalization of any parameter P was performed according to:

$$P(C_b) = P(C_{b,0}) + \left.\frac{\partial P}{\partial C_b}\right|_{(C_{b,ref})} \times (C_b - C_{b,0}) \tag{3}$$

It has to be noted that the cross-section interface reconstructs for the reflector segments the dependence of the material data on the instantaneous moderator density as well [1]. Nevertheless, a limitation in PARCS prevents using the instantaneous moderator density from the SIMULATE-3 results for the reflector nodes [5].

History variables (such as the history of the moderator density and of the boron concentration) and exposure distributions were then transferred from SIMULATE-3 to PARCS for the fuel cycle and exposure corresponding to each of the sets of measured data. Although PARCS has the ability to calculate the spatial distribution of the moderator density and of the fuel temperature throughout the core, once the core inlet temperature and thermal power are given, the spatial distribution of these instantaneous parameters was also obtained from SIMULATE-3 calculations. SIMULATE-3 thus provides the full 3-dimensional spatial distribution of the history of the moderator density, of the history of the boron concentration, of the burnup, of the instantaneous moderator density, and of the instantaneous fuel temperature throughout the core. The knowledge of these parameters allows retrieving the correct material data for each fuel/reflector segment in the PARCS model, provided that the remaining instantaneous conditions (control rod insertion, and boron concentration) can also be known. The concentration of the poisons was calculated by PARCS, based on the corresponding microscopic cross-sections and fission yields stored in the PMAXS files.

Concerning the PARCS model itself, the 157 fuel assemblies constituting the active core were represented. An explicit treatment of the bottom, top, and radial reflectors was carried out. The radial reflector region is constituted by 2 different segments (one segment only taking the baffle into account, and another segment taking both the baffle and the core barrel into account). Axially, each fuel/reflector assembly in PARCS is modeled by an active region corresponding to the core active height, surrounded by a bottom reflector and a top reflector. Some fuel assemblies even present an axial zoning of the core active height. The core is actually represented by 5746 regions [26 axial nodes x 221 radial nodes (157 fuel assemblies and 64 reflector assemblies)]. Concerning the options for the calculations, zero incoming current was assumed as boundary condition for the neutron flux. A hybrid neutronic solver was used for determining the neutron flux. This hybrid solver is based on the Analytic Nodal Method (ANM) and on the Nodal Expansion Method (NEM) [6].

2.2 Measured data sets

Several sets of measured data were obtained from Ringhals AB. These measurements are representative of steady-state conditions and were recorded at different core exposures and for different fuel cycles. The operating conditions for each of the measurements analyzed in the

following of this paper are summarized in Table 1.

Table 1: Operating conditions corresponding to the measured data sets.

Fuel cycle	Core-averaged cycle exposure (GWd/tHM)	Relative power (%)	Core-averaged coolant temperature (ºC)	Control rod insertion	Critical boron concentration (ppm)
10	0.2208	99.8	303.3	All rods out	965
10	4.8136	99.8	303.0	All rods out	524
10	9.5929	99.8	303.2	All rods out	79
19	0.3694	100.0	301.4	All rods out	915
19	4.5983	100.0	301.4	All rods out	519
19	9.8300	100.1	301.2	All rods out	25
22	0.1442	99.1	301.2	All rods out	1270
22	4.6668	100.1	301.3	All rods out	828

Traveling In-core Probes (TIPs) were used to map the relative power distribution throughout the core. These detectors, which are actually fission chambers, can only be positioned in the central instrumentation tube of 50 out of 157 fuel assemblies, as represented in Fig. 1. For each of these fuel assemblies, the axial distribution of the detector signal is determined. The conversion of the detector signal into power fraction as well as the interpolation of the data for the remaining fuel assemblies were carried out by using SIMULATE-3, so that the full 3-dimensional relative power distribution can be recovered throughout the entire active core. Since PARCS does not contain any detector data, the conversion of the detector signals into relative power fraction is impossible using PARCS.

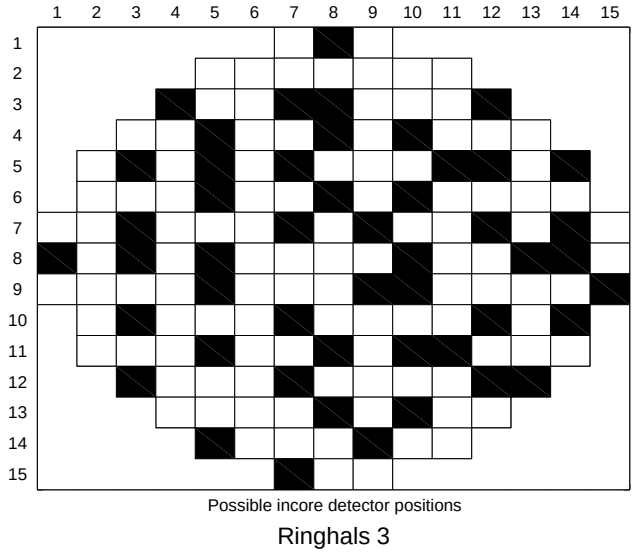


Figure 1: Position of the TIPs (the black squares are possible radial locations of the TIPs in Ringhals-3).

3. Results

In this paper, the relative power distribution calculated by PARCS and the effective multiplication factor are the only parameters compared to the measurement data for the sake of brevity. Complementary results will be presented at the conference. The relative deviation of the Relative Power Fraction (RPF) is calculated as:

$$\frac{RPF^{PARCS} - RPF^{measured}}{RPF^{measured}}$$

The radial distribution of the exposure is given in Fig. 2 for each of the cycles analyzed in this paper. This burnup distribution is representative of the first set of measurements for each cycle (i.e. close to the beginning of each cycle). The relative deviation of the calculated RPF from the measured one is given in Figs. 3, 4, and 5 for the fuel cycles 10, 19, and 22, respectively. In each of these Figures, the radial deviation of the RPF is given on the left hand-side, whereas the calculated and measured axial power profiles are given on the right hand-side.

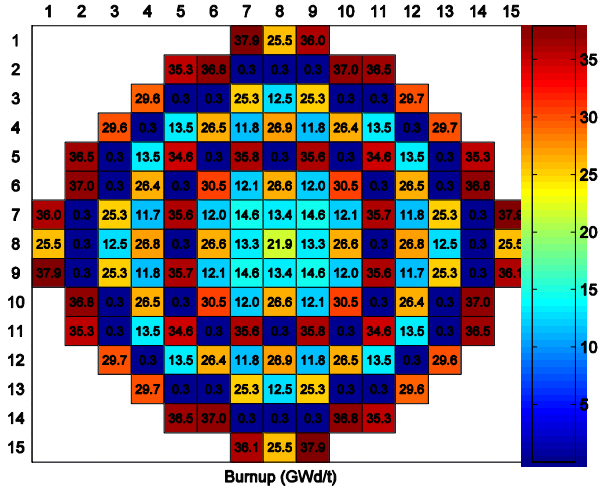
Axially, a systematic deviation of the PARCS results from the measurement data can be noticed. As mentioned in Section 2, PARCS is currently not able to use the moderator density provided by SIMULATE-3 for the reflector nodes. Assuming density-independent material data for the top reflector is an assumption that might not be valid. This approximation could explain the larger discrepancy of the RPF close to the top of the active core. The axial leakage of neutrons through the top reflector might therefore be erroneously estimated, resulting in an underestimation of the RPF by PARCS. PARCS is nevertheless able to correctly reproduce the overall axial power profiles.

Radially, differences can be seen between the PARCS calculations and the measurements. When looking at the results from cycles to cycles, the following trend can be noticed. The RPF is systematically overestimated at the core centre and underestimated at the core periphery at the beginning of cycle, whereas the opposite behavior can be noticed close to the end of cycle. At middle of cycle conditions, the deviation of the PARCS results from the measured data does not exhibit any systematic behavior. An asymmetry in the radial relative deviation can also clearly be noticed in some cases, notably for the fuel cycle 19. When looking at the corresponding exposure distribution in Fig. 2, such an asymmetry is not present in the loading pattern. Since the asymmetry in the relative deviation of the RPF comes exclusively from the measured data, measurement errors can be suspected.

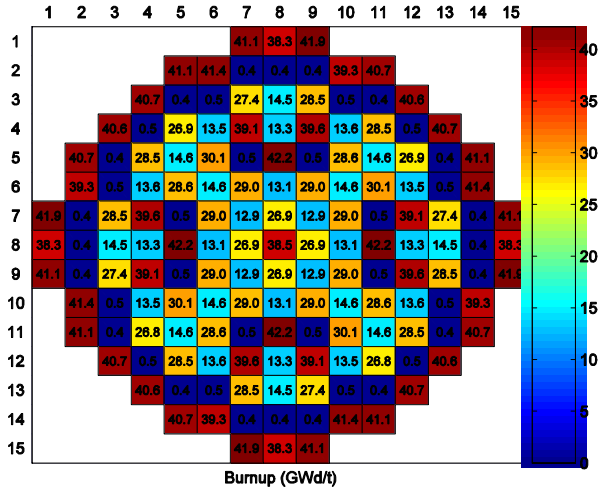
The main results of the comparisons between the calculated RPF and the measured ones are summarized in Table 2. As can be seen in this Table, PARCS is able to reproduce the RPF for rather well, although minor discrepancies exist for some isolated cases as pointed out previously. Concerning the calculation of the effective multiplication factor, the deviation of the PARCS estimate is within typically ±200 pcm.

Figure 2: Radial distribution of the exposure.

a) fuel cycle 10, core-averaged cycle exposure of 0.2208 GWd/tHM.



b) fuel cycle 19, core-averaged cycle exposure of 0.3694 GWd/tHM.



c) fuel cycle 22, core-averaged cycle exposure of 0.1442 GWd/tHM.

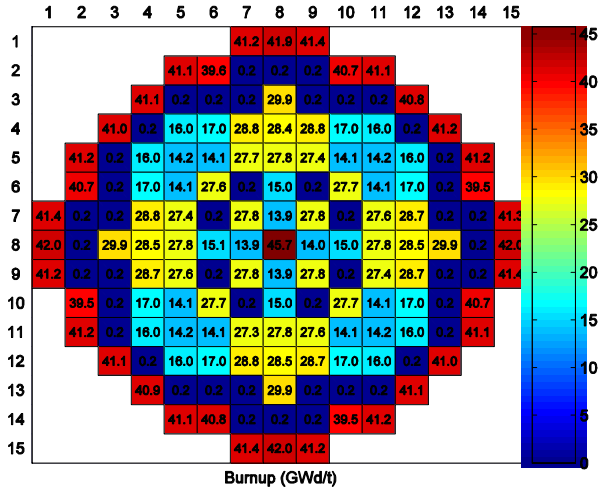
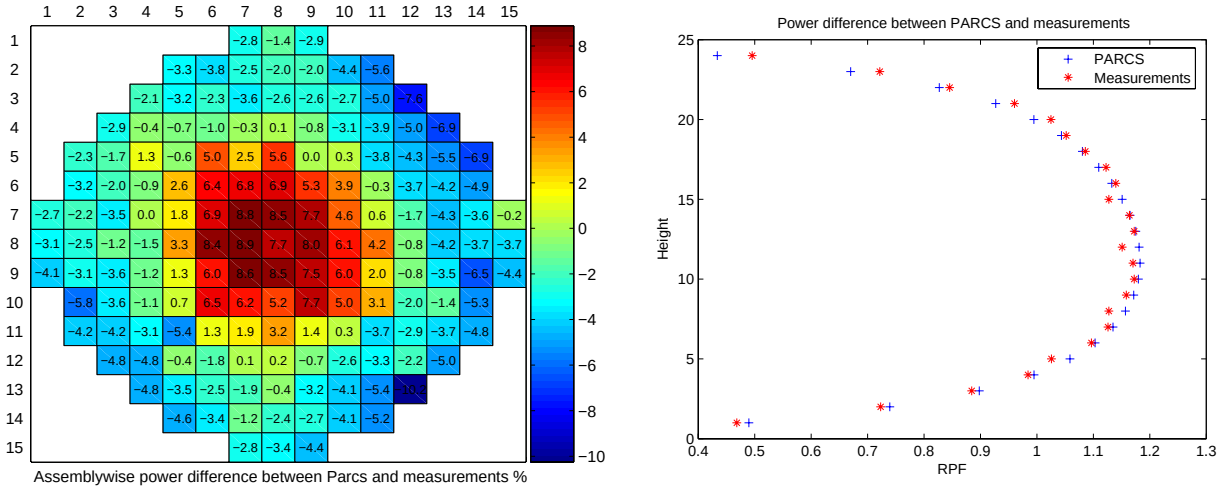
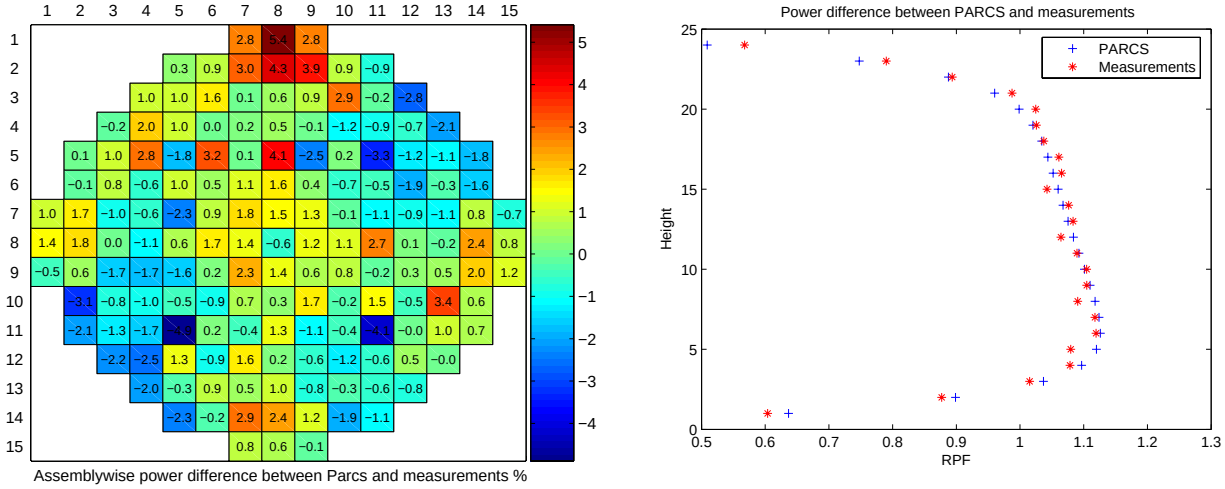


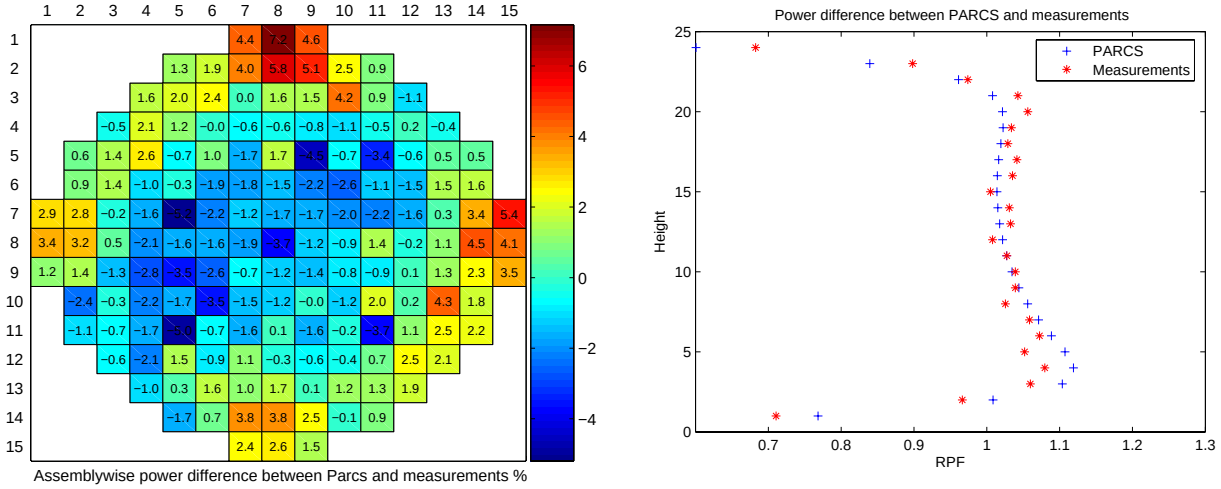
Figure 3: Deviation of the calculated RPF from the measured one for the fuel cycle 10.



a) results for a core-averaged cycle exposure of 0.2208 GWd/tHM.

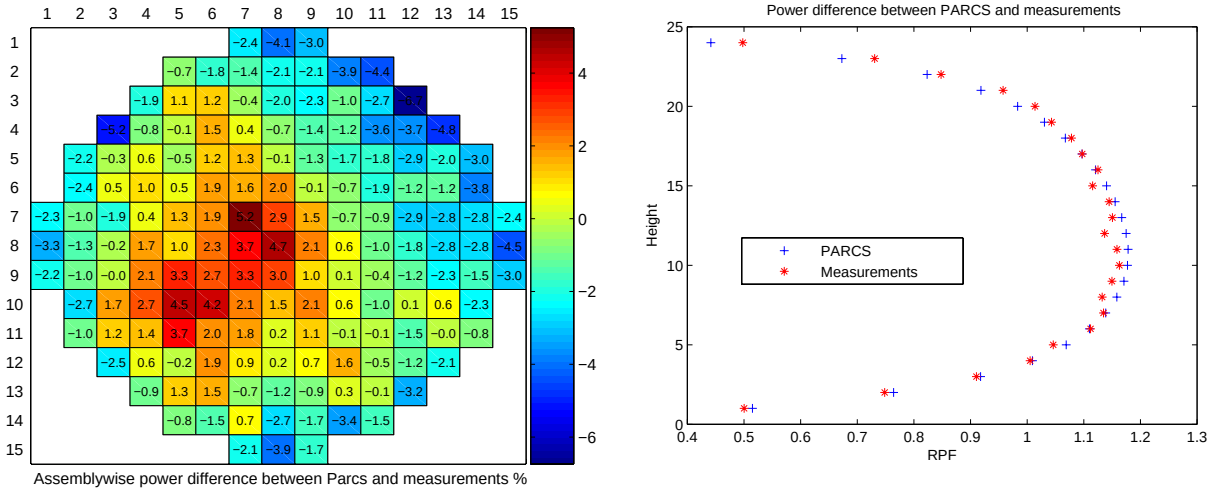


b) results for a core-averaged cycle exposure of 4.8136 GWd/tHM.

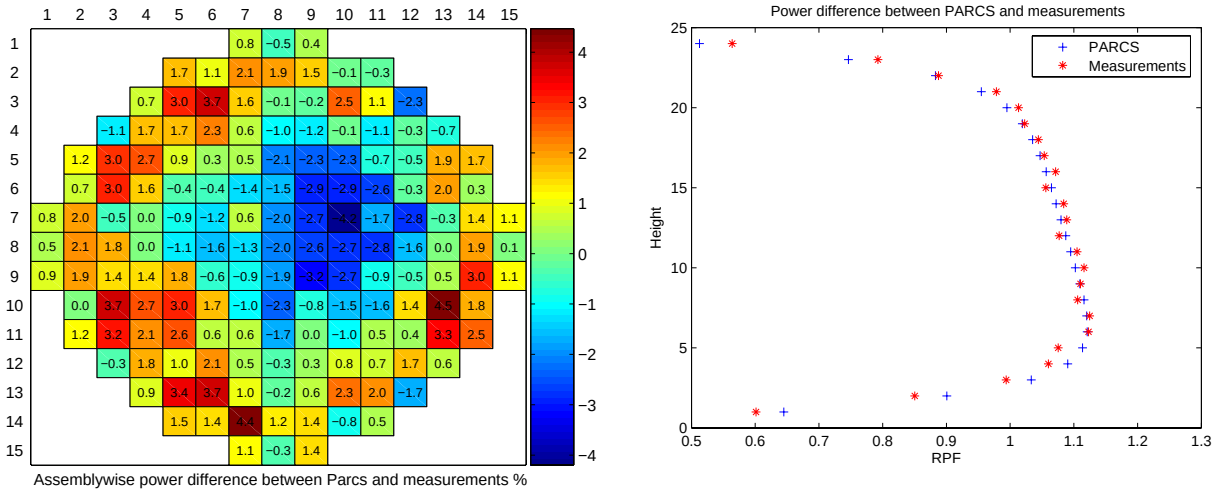


c) results for a core-averaged cycle exposure of 9.5929 GWd/tHM.

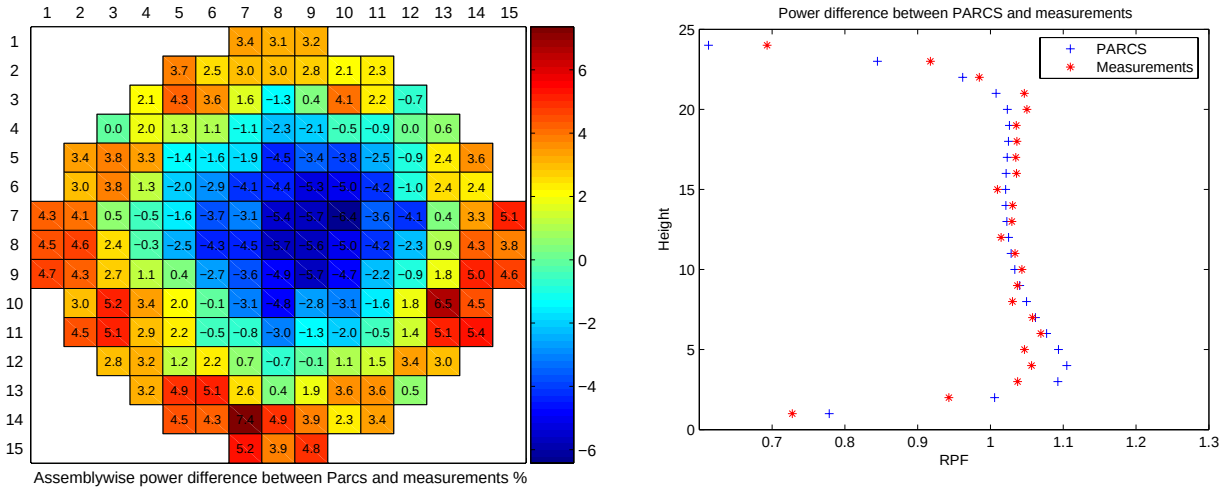
Figure 4: Deviation of the calculated RPF from the measured one for the fuel cycle 19.



a) results for a core-averaged cycle exposure of 0.3694 GWd/tHM.

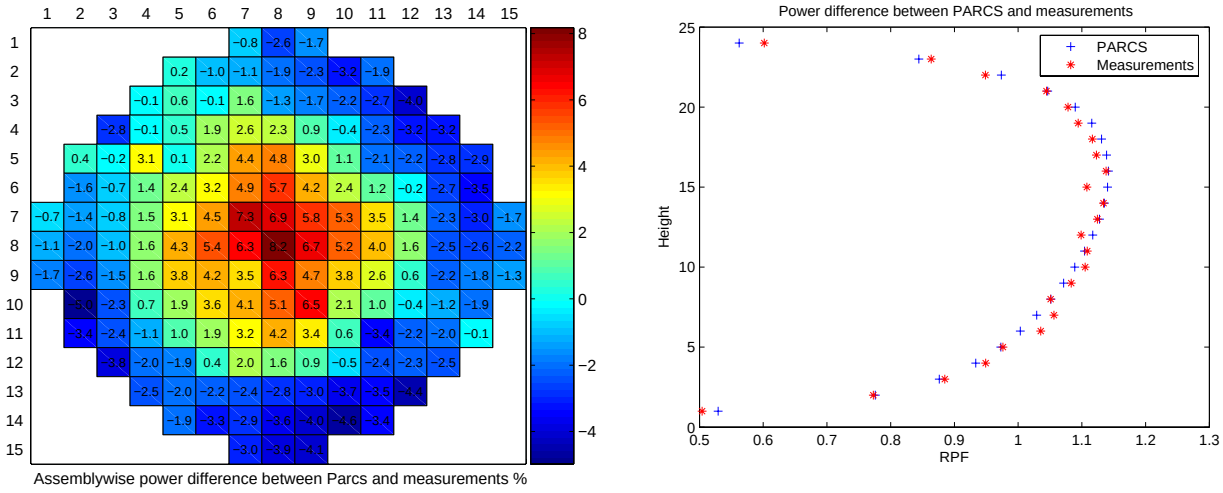


b) results for a core-averaged cycle exposure of 4.5983 GWd/tHM.

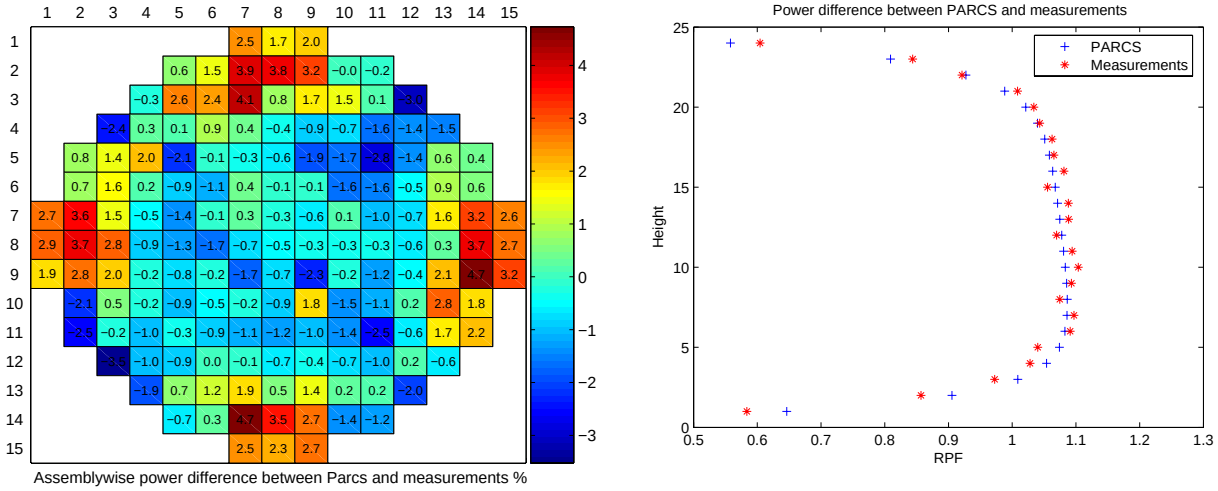


c) results for a core-averaged cycle exposure of 9.8300 GWd/tHM.

Figure 5: Deviation of the calculated RPF from the measured one for the fuel cycle 22.



a) results for a core-averaged cycle exposure of 0.1442 GWd/tHM.



b) results for a core-averaged cycle exposure of 4.6668 GWd/tHM.

Table 2: Summary of the results of the different benchmark cases.

Fuel cycle	Core-averaged cycle exposure (GWd/tHM)	PARCS k_{eff}	Mean deviation for the radial RPF (%)	Standard deviation for the radial RPF (%)	Maximum deviation for the radial RPF (%)	Minimum deviation for the radial RPF (%)
10	0.2208	0.99865	-0.82	5.64	8.88	-10.25
10	4.8136	1.00116	0.18	2.19	5.41	-4.89
10	9.5929	1.00189	0.28	3.00	7.16	-5.19
19	0.3694	0.99986	-0.51	2.91	5.24	-6.74
19	4.5983	1.00052	0.38	2.37	4.46	-4.20
19	9.8300	1.00120	0.34	3.70	6.37	-5.72
22	0.1442	0.99764	0.12	4.17	8.17	-4.98
22	4.6668	1.00017	0.28	2.33	4.73	-3.52

4. Conclusion

In this paper, the validation of the PARCS code together with a cross-section interface allowing feeding PARCS with realistic sets of material data was carried out. Several fuel cycles and core exposures were considered. The 3-dimensional spatial distributions of the history of the moderator density, of the history of the boron concentration, of the exposure, of the instantaneous moderator density, and of the instantaneous fuel temperature were obtained from SIMULATE-3. Based on these distributions, together with the position of the control rod and the instantaneous boron concentration, the material data can be retrieved. These validation tasks demonstrated that PARCS was able to reproduce the main variations of the power distribution within the core. Nevertheless, some minor discrepancies and systematic deviations were also noticed. Further investigations are thus necessary for pointing out the root cause of these discrepancies. An additional benchmark is planned for checking whether these deviations come from the data stored in the PMAXS files or from the PARCS algorithms. For the purpose of the former, the reconstruction of the material data from Eq. (1) would be compared to the original data used to create the PMAXS files.

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