

PRATIC: A soluble-boron-free, pressurized water cooled, SMR core benchmark

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Abstract. Current nuclear reactor research is actively exploring small modular pressurized water reactors (PWRs), particularly soluble-boron-free (SBF) configurations. SBF designs utilize control rods and gadolinium-poisoned fuel rods to manage reactivity. Additionally, small modular reactors (SMRs) commonly integrate steel reflectors to minimize neutron leakage. However, the compactness of SMRs and the adoption of these technical solutions result in notable fluctuations in neutron flux within the core during normal cycle operation. Hence, comprehensive analysis is essential, especially concerning reactor performance under normal and accident conditions, the reliability of neutronics calculation assumptions, etc. Research into these issues requires reactor core neutronics benchmarks that are consistent with industrial concepts so that the analysis results can be applied to real reactors. In this context, this article introduces PRATIC, a SBF-PWR SMR core neutronics benchmark designed to match the global performances of industrial concepts. The development of PRATIC was conducted using a deterministic calculation scheme coupling the APOLLO2 and CRONOS2 codes. PRATIC features a thermal power of 350 MW_{th}, an equilibrium cycle length of 1.9 years, and an average discharge burnup of about 34 GWd/t, while maintaining controlled power distributions. The article elaborates on the design assumptions for PRATIC, then details the reactor core and its equilibrium cycle. Access to the PRATIC modeling data is available via a GIT repository, accessible upon request via email at pratic@cea.fr.

1 Introduction

In the face of global warming, the worldwide search for new clean, efficient and reliable energy sources continues apace, driven by the imperatives of decarbonization and energy security. Nuclear power, with its low carbon footprint and reliable electricity production, could have an important role to play in tomorrow's energy mix. In this context, small modular reactors (SMRs) are gaining in interest worldwide. Their smaller size compared to regular pressurized water reactors (PWRs) offers potential benefits such as streamlined construction in dedicated facilities (standardization), ease of deployment, low construction costs, etc. [1,2]. Numerous industrial SMR designs are currently being developed all over the world [3,4]. Within this array, some projects have focused on the development of soluble-boron-free (SBF) PWR cores. SBF reactor cores are generally chosen to avoid the side effects associated with the use of soluble boron, such as corrosion of structural materials, large volumes of liquid radwaste to manage, possible boron dilution accidents, deterioration of the

moderator temperature coefficient, requirement of boron control and water purification systems, etc. [5,6]. Consequently, removing soluble boron from the primary coolant system offers several advantages in terms of simplifying reactor operation and maintenance.

So far, in SBF reactor cores, one available method to compensate for excess reactivity is the use of burnable absorbers (such as gadolinium-poisoned fuel rods) and control rods. Despite the benefits of SBF operation, its reliance on control rods leads to significant variations in power distribution during the irradiation cycle, both axially and radially. Moreover, the wide employment of poisoned fuel rods results in an inhomogeneous dispersion of burnable poisons within the core. Achieving a uniform radial power distribution becomes more challenging in this scenario compared to large PWR cores that utilize soluble boron. These trends are further reinforced in SMRs by their smaller size and the widespread adoption of steel reflectors, also known as heavy reflectors, used to extend cycle length. Consequently, the manner in which SMR cores behave may vary notably from that of their larger PWR counterparts. This calls for a thorough examination of the assumptions used in neutronics

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calculation schemes. Furthermore, the potential future use of SBF-PWR type SMRs raises a number of questions that require analysis in various fields of scientific research. Among others, it is possible to mention the study of reactor behavior during normal operation, incidental or accidental transients, the exploration of prospective scenarios for fuel cycle management, sensitivity studies on the application of technological solutions, etc. To address these challenges, scientific research must be based on reactor core benchmarks aligned with current industrial concepts under development. This alignment must encompass technological choices and performance considerations, to ensure that study results can be seamlessly applied to reactors that will actually be deployed.

It is in this context and to meet these needs that PRATIC (which stands for “Petit REP Académique pour Tester, Innover et Concevoir”, meaning “Small Academic PWR for Testing, Innovation, and Design” in French) was developed at the French Atomic Energy and Alternative Energy Commission (CEA). PRATIC is a SBF-PWR type SMR core benchmark, built for scientific research, yet capable of approaching the performances of known industrial-grade SMR cores, in terms of power output, equilibrium cycle length, etc. [3,4]. The technological solutions used in PRATIC in terms of fuel type, nature of burnable absorbers, control rods, reflector, etc. are also consistent with those found in known industrial concepts [3,4].

First, Section 2 provides a comprehensive account of the assumptions employed to develop PRATIC and determine its equilibrium cycle characteristics. Second, Section 3 features a description of the reactor core. Then, Section 4 outlines the equilibrium cycle characteristics of PRATIC. Finally, conclusions are drawn in Section 5.

In addition to the content of this manuscript, a GIT repository is available, containing data files for core remodeling and various equilibrium cycle data (including core k_{eff} in several configurations, burnup distributions, power distributions, etc.). This repository will be regularly updated as the PRATIC database continues to grow. Access rights to this GIT repository will be distributed upon request by e-mail to the following address: pratic@cea.fr. The data shared in both this article and the GIT repository are licensed under CC BY-NC-SA 4.0, permitting data reuse solely for non-commercial purposes and requiring appropriate credit to the authors of this article.

2 Assumptions and codes used for the neutronics design of the core

2.1 Main assumptions

The development of the PRATIC core relied on neutronics calculations in order to find an SBF core design that minimizes 2D and 3D power peak factors during normal operation. Additionally, the aim was to limit the maximum reactivity achieved by the core when all absorber rod clusters are fully extracted. Before carrying out the optimization research, it was necessary to set several param-

eters in order to align them with those observed in established industrial concepts and/or to incorporate technological solutions already employed in the nuclear industry. Among these parameters, it is noteworthy to mention:

- The number and arrangement of assemblies in the reactor core, which are adopted from the Chinese ACP100 concept [7];
- The total thermal power of the core, set slightly below that of the ACP100 [6,8], resulting in a thermal output of 350 MW(thermal). Restraining the overall core power offers the advantage of reducing the average linear power (here 115.97 W/cm). This creates a margin relative to the fuel melting point, facilitating potential future studies on accidental transients;
- The layout of pins¹ in the assemblies, which follows the standard configuration of UOX fuel assemblies used in the French fleet [9]. These assemblies feature a 17×17 arrangement of pins, composed of 264 fuel rods, 24 guide tubes for inserting control rods and a central guide tube for instrumentation purposes. Refer to Figure 1 from reference [9] for an illustration;
- The type of fuel, based on the classic solution for French UOX assemblies, i.e., UO_2 with an enrichment in ^{235}U of 5 wt.% or less [10];
- The incorporation of gadolinium-poisoned fuel rods, aligning with a commonly employed solution in SBF-PWR SMRs designs [6]. All fuel rods containing gadolinium poison are of the $\text{UO}_2\text{-Gd}_2\text{O}_3$ type. They feature an 8 wt.% gadolinium content and a 2.5 wt.% ^{235}U enriched UO_2 support, aligning with the composition of poisoned fuel rods outlined in reference [11];
- The use of two types of absorber rod clusters: “grey” and “black” clusters. Grey clusters are made of 16 silver-indium-cadmium alloy ($\text{AgInCd} = \text{AIC}$) rods and 8 steel rods. Black clusters are made of 24 AIC rods;
- The cold active height (i.e., at 20°C) was arbitrarily set to 200 cm, so that the core is roughly as high as it is wide, thus minimizing neutron leakage;
- The moderator pressure in the primary circuit, set to 155 bars, corresponding to that of French PWRs [12]. The moderator pressure value remains constant for all core power levels;
- A neutron reflector mainly made of steel, also known as “heavy reflector”, is used in PRATIC. This type of reflector is chosen for its ability to limit neutron leakage at the core edges, thereby increasing cycle length compared to employing a reflector primarily composed of water. This technological solution is already used in some PWR-type SMRs, as indicated in reference [13];
- The moderator temperature program is set to achieve an average core temperature of 300°C, with a temperature rise of 30°C across the core’s active height at full power. This results in a moderator inlet temperature of 285°C (at nominal power) and a flow rate of $1550 \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. It also ensures an isothermal core at 300°C during hot zero power conditions. These parameters were chosen arbitrarily by the authors without

¹ A pin refers to a fuel rod, guide tube, or instrumentation tube.

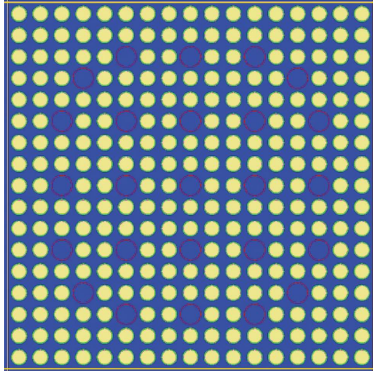


Fig. 1. Radial cut of a 17×17 UOX fuel assembly [9]. The UO_2 fuel rods are shown in yellow. The instrumentation tube and guide tubes are represented by black circles filled with blue, which stands for water holes.

specific studies or sensitivity analysis, but the thermal-hydraulic conditions are similar to those in PWR-type SMR concepts referenced in references [3,4].

- The end of the cycle is reached when the core reactivity reserve is equal to 100 pcm;
- The core operates under a 2-batch cycle², a strategy outlined in reference [14] as suitable for achieving a cycle length of about 2 years while flattening power distributions.

2.2 Deterministic calculation scheme

PRATIC was developed through core-depletion calculations employing a deterministic approach that couples the APOLLO2 [15] and CRONOS2 codes [16]. Firstly, version 2.8-5 of the APOLLO2 code is employed to generate 2-group homogenized macroscopic cross-section data for fuel assemblies. Secondly, the CRONOS2 code, version 2.15, uses this data as a multi-parametric database (since energy group cross-sections depend on moderator density, fuel temperature, etc.) to perform complete neutron modeling of the reactor core.

2.2.1 APOLLO2

On the APOLLO2 side, the SHERM-MOC package [17] is utilized to solve the 2D stationary transport equation (with the axial dimension considered infinite) for assemblies in an infinite lattice, employing a 281-group data library based on the JEFF-3.1.1 evaluation [18]. For the current study, resonant upscattering and fuel temperature correction to account for crystallographic effects in UO_2 were disabled, in order to facilitate code-to-code comparisons. The calculation of macroscopic cross-sections is carried out in two steps. A depletion calculation of the

² In a 2-batch cycle, fuel assemblies are reloaded only once during their operational lifetime in the core. Consequently, half of the fuel assemblies are discharged from the core at the end of each irradiation cycle.

fuel assembly is first performed using constant parameters derived from preliminary CRONOS2 calculations (here, fuel temperature of 430°C , moderator temperature of 300°C , and primary pressure of 155 bars were considered). Next, the isotopic concentrations of evolving materials (only the fuel in this study) are reloaded for several burnup steps, and calculations are performed for multiple configurations (variations in fuel temperature, moderator temperature, control rod insertion, etc.) to assess the corresponding cross-sections. Following this, spatial homogenization is conducted on a 17×17 radial mesh (one cell per pin), and cross-section energy condensation is performed on a two-group mesh with a cut-off energy of 0.625 eV.

2.2.2 Equivalence calculations and reflectors modeling

Prior to using the data produced by the APOLLO2 code in the CRONOS2 code, SPH equivalence calculations are performed, as described in reference [19]. These calculations are employed to determine pin-level equivalence coefficients, which are then applied to adjust neutron flux predictions in CRONOS2 to better align them with those of APOLLO2. An albedo equivalence treatment is also performed to evaluate the effective cross-sections of the homogenized reflectors [20].

2.2.3 CRONOS2

On the CRONOS2 side, the diffusion equation is solved by the MINOS solver [21] with 2 energy groups and on 17×17 assembly radial mesh, so that each pin is described radially by a calculation cell. Axially, the entire height of the fuel, encompassing the reflector, is initially divided into 28 meshes. This distribution comprises 20 meshes, each 10 cm high, within the active zone and 4 meshes, each 5 cm high, in each axial reflector. This axial mesh is adjusted on the fly as the rods are inserted, to define a calculation plane at the end of the absorber rods. Consequently, a few extra meshes (of the order of 1–3) are added to the standard grid as the absorber clusters are inserted. During core-depletion calculations, the ^{135}Xe concentration in each calculation cell is fixed using a “xenon equilibrium” model. Thus, in CRONOS2 calculations, the ^{135}Xe concentration in the core is not zero at the start of the equilibrium cycle (i.e. cycle burnup = 0 GWd/t). CRONOS2 also takes into account simplified thermal-hydraulic feedbacks. Thermal-hydraulic calculations are performed on a coarser radial mesh, with 4 calculation meshes per assembly. From an axial perspective, the calculation grid used for neutronics calculations is also used for thermal-hydraulics.

It is also worth noting that the following assumptions are made in the CRONOS2 calculations:

- The pellet-cladding gap is considered closed throughout the cycle and for all pin cells. This is represented by a thermal conductance value of $1 \text{ W}/^\circ\text{C}$;
- In a fuel cell, the fraction of fission energy deposited outside the fuel and its cladding is fixed at 2.5%;
- In non-fissile cells, the energy created by neutron capture is not taken into account, leading to zero power values in the guide tubes and control rods.

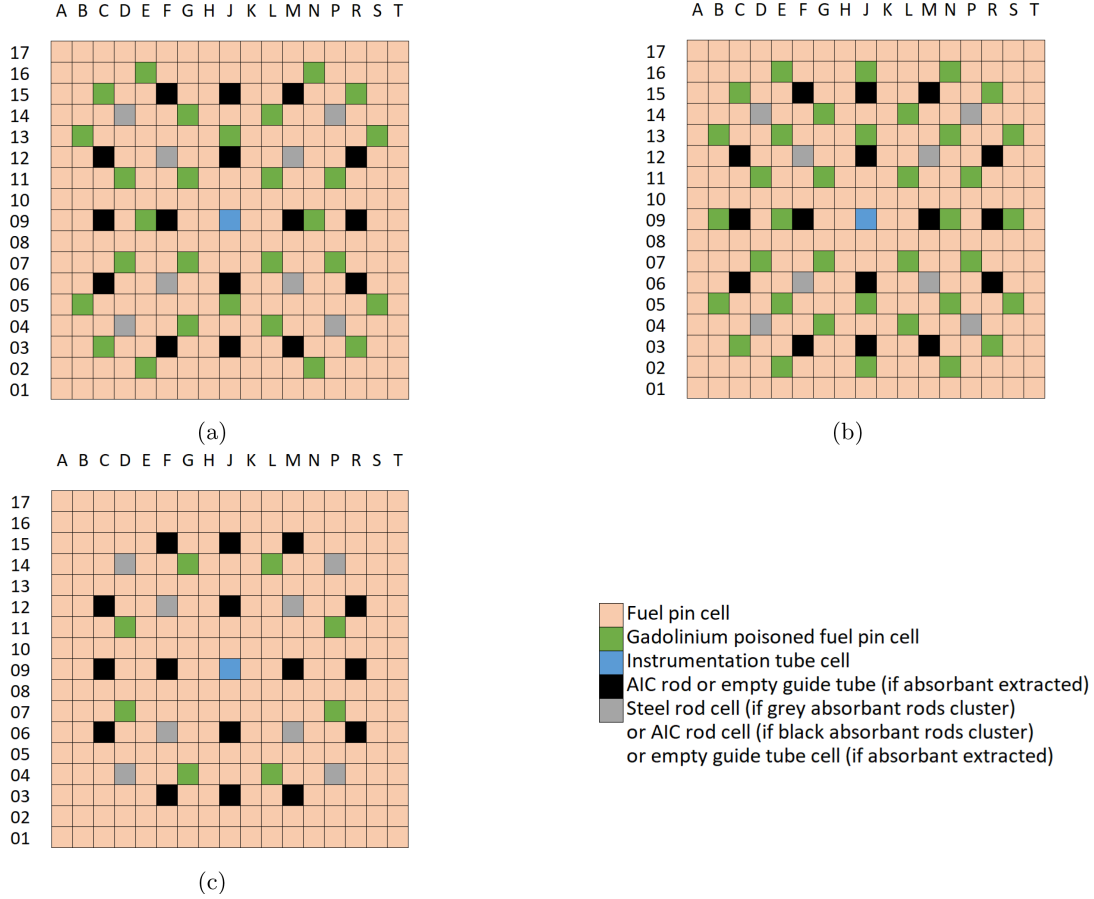


Fig. 2. Schematic view of rod type distribution in external (a), internal (b) and central (c) assembly types.

3 The PRATIC core

3.1 Fuel assemblies

Within PRATIC, three classifications of fuel assemblies are employed, namely: “external”, “internal”, and “central”. The specifications for each of these fuel assembly types are detailed as follows:

- Central: fuel enrichment in ^{235}U equal to 2.5 wt.% and 8 gadolinium-poisoned fuel rods;
- Internal: fuel enrichment in ^{235}U equal to 3.5 wt.% and 36 gadolinium-poisoned fuel rods;
- External: fuel enrichment in ^{235}U equal to 5.0 wt.% and 28 gadolinium-poisoned fuel rods.

As explained before, all fuel rods containing gadolinium poison are of the $\text{UO}_2\text{-Gd}_2\text{O}_3$ type, with a gadolinium content of 8 wt.% and a ^{235}U support of 2.5 wt.%. The spatial distribution of poisoned rods within the three types of assemblies is shown in Figure 2 and are the result of optimization work carried out at CEA. The aim of this optimization was to achieve a uniform distribution of poisoned fuel rods in the assemblies while preserving their eighth symmetry. This choice of homogeneous distributions is based on reference [14], which indicates that this solution is well suited for ensuring robust safety performance with 2-batch cycles.

The data necessary for modeling PRATIC assemblies, including component dimensions, isotopic densities, material densities, thermal expansion data, etc., are available in the accompanying GIT repository. The data file on which this work is based is revision 1.6 of the equilibrium core: PRATIC_EquilibriumCore.InputDataFile_V1.6.xlsx. These data are provided for two temperature conditions: 20°C, representing the core’s cold state, and 300°C, representing its isothermal state. The materials and dimensions in this repository have been carefully selected from benchmarks such as VERA core physics [22] and BEAVRS [23].

3.2 Core configuration

PRATIC is a 350 MW_{th} SBF-PWR SMR core, loaded with 57 fuel assemblies. The core is radially surrounded by a heavy reflector, approximated in the present work by a homogeneous mixture primarily consisting of steel and a small amount of H₂O. The thickness of this reflector is set equal to the hot fuel assembly pitch (considered at 300°C). Similarly, the axial reflectors (upper and lower) are modelled by a mixture of approximately half steel and half water, with a thickness of 20 cm (regardless of the temperature). As previously mentioned, the cold active height of the fuel is set to 200 cm (increasing to 200.5613 cm at

Table 1. General data and dimensions of PRATIC.

Data	Value
Reactor type	SBF-PWR SMR
Nominal power (NP)	350 MW _{th}
Average linear power at 100% NP	115.97 W/cm
Specific power density	24.73 W/g
Number of fuel assemblies	57
Fuel assembly pitch at 300°C	21.5313 cm
Inter-assembly half-gap at 300°C	0.04035 cm
Active height at 300°C	200.5613 cm
Heavy radial reflector thickness at 300°C	21.5313 cm
Axial reflectors thickness (temperature-independent)	20.0 cm
Primary circuit pressure	155 bar
Moderator inlet temperature at 100% NP	285°C
Moderator inlet temperature at 0% NP	300°C
Moderator average temperature (identical for all power levels)	300°C
Moderator flow rate (identical for all power levels)	1550 kg.m ⁻² .s ⁻¹
Moderator cross-sectional area in the core (identical for all power levels)	1.41 m ²

300°C), making the reactor core approximately as high as it is wide, thereby minimizing neutron leakage. The moderator temperature program was designed so as to have an average moderator temperature in the core of 300°C and a moderator temperature rise over the entire active height of 30°C, at full power. Primary circuit pressure is 155 bar. These and other general data about PRATIC are provided in Table 1 as well as in the GIT repository.

Note that in Table 1 and in the data available in the GIT repository, the moderator flow rate in the primary circuit assumes no fluid circulation in the guide tubes, for modeling simplification. Moreover, mixing grids are neither explicitly modeled nor diluted in the primary circuit water, whether in the core or axial reflectors. As a result, they are not considered in the analysis.

3.3 Fuel management

Three types of fuel assemblies are used in PRATIC, distributed as follows: an external fuel zone of 40 assemblies, an internal fuel zone of 16 assemblies, and a central assembly. As previously discussed, PRATIC features a 2-batch equilibrium cycle to align with the recommendations of reference [14]. This implies that all assemblies are reloaded once before their ultimate removal from the core, except for the central assembly, which completes a single cycle in the core before being discharged. The fuel zoning and reloading patterns exhibit rotational symmetry per quarter-core and are depicted in Figures 3 and 4 respectively. These figures also illustrate the naval coordinate system used to locate the assemblies in the GIT repository.

At the end of each equilibrium cycle, 28 fuel assemblies are reloaded at new locations in the core to undergo

a second irradiation cycle. The remaining 29 fuel assemblies, comprising 8 inner assemblies that have completed two cycles, 20 outer assemblies that have completed two cycles, and the central assembly that has completed one cycle, are permanently discharged from the core. The location of these is shown in Figure 5. The removal of these 29 assemblies induces the loading of 29 fresh assemblies at the beginning of each equilibrium cycle. These are denoted as “Cycle 1” assemblies in Figures 3–5.

3.4 Core control

All assemblies of the PRATIC core are equipped with absorber rod clusters used for core control or shutdown. The control rods are divided into three banks (alternatively called “groups”) of grey absorber rod clusters (G1, G2, and G3) and one bank of black absorber rod clusters (G4). As previously mentioned (see Sect. 2.1), grey rod clusters are made up of 16 AIC rods and 8 steel rods, while black rod clusters are made up of 24 AIC rods. Therefore, grey rod clusters have a lower impact on reactivity than black rod clusters. Assemblies without piloting control rods (i.e., those where G1, G2, G3, or G4 banks are not inserted) are equipped with shutdown rods (S bank). These rods, made of AIC and identical to black absorber rod clusters, are used for reactor core shutdown. The locations of the control and shutdown banks in the reactor core are depicted in Figure 6. The control rods are inserted in increments of 1 cm (also referred to as “steps”) across the active part of the core, with up to 200 cm per group, in the sequence of G1, G2, G3, and then G4. The overlap between pilot group insertions is 50%, meaning group G2 begins its insertion when group G1 is halfway through its maximum insertion, group G3 starts its insertion when

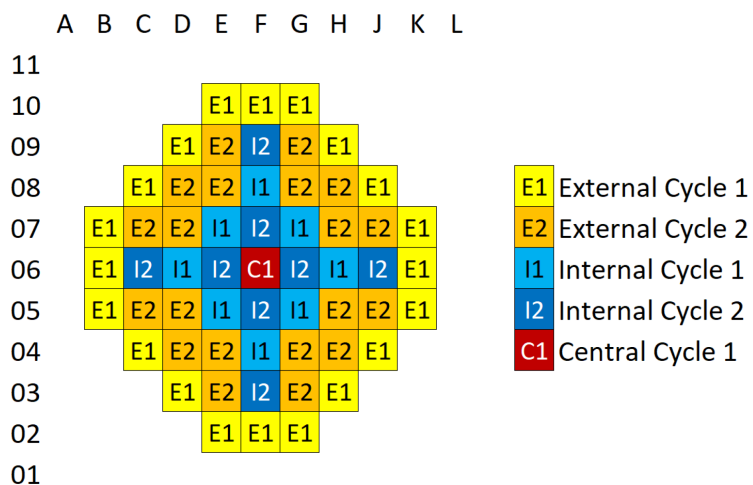


Fig. 3. Fuel zoning.

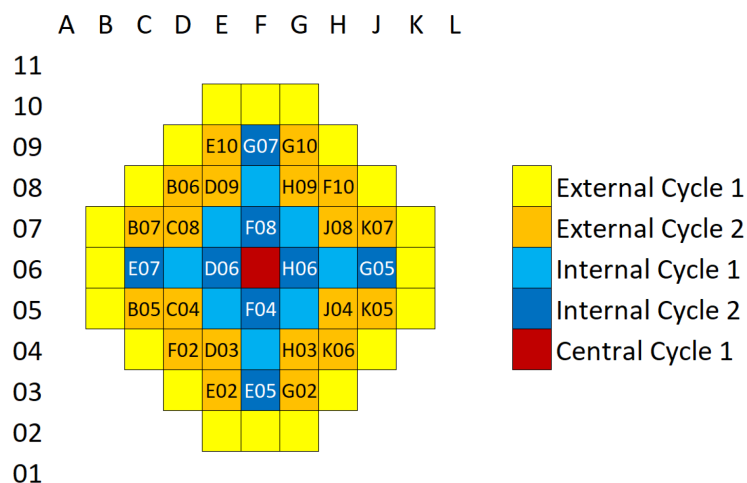


Fig. 4. Fuel reloading pattern. Text in each assembly indicates where the assembly was located during the previous cycle.

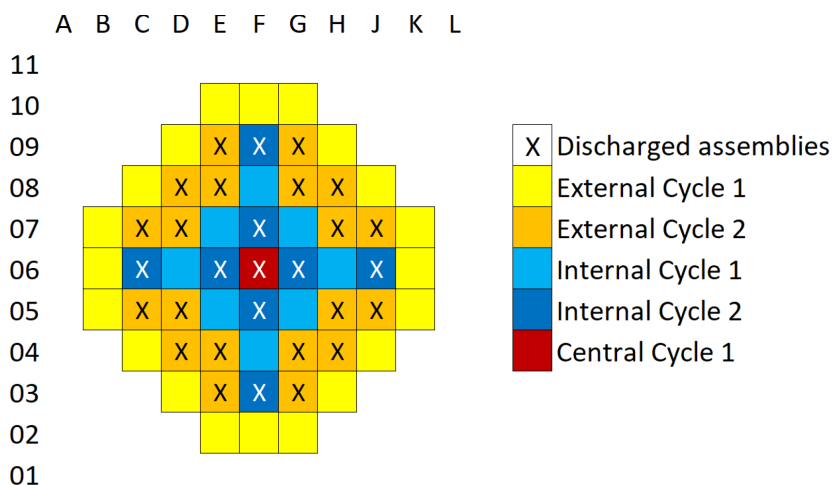


Fig. 5. Fuel assembly discharge pattern. Assemblies marked with an “X” correspond to those discharged at the end of the equilibrium cycle.

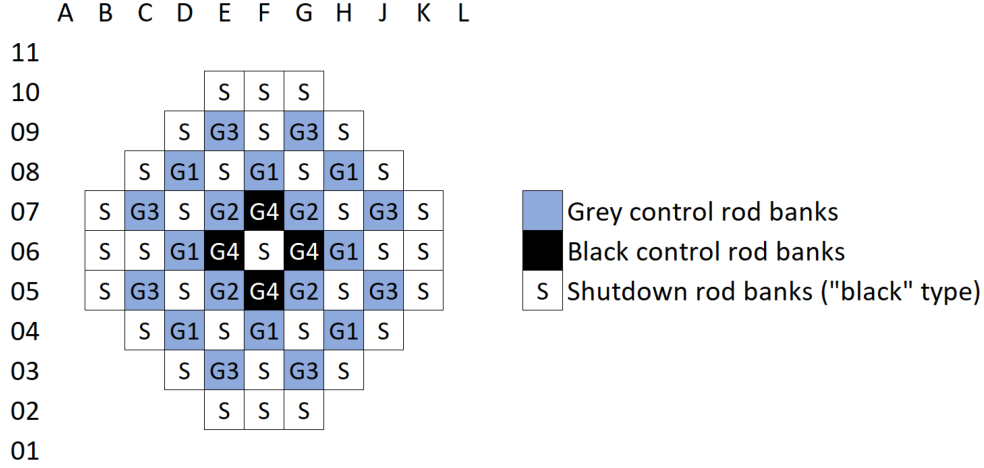


Fig. 6. Location of control rod banks and shutdown rod banks. The text in each assembly indicates the assignment of an absorber cluster to a specific rod bank.

group G2 is halfway through its maximum insertion, and so on. Consequently, the cumulative insertion of control rods I_{cumul} is defined by equation (1).

$$I_{\text{cumul}} = \min(I_{G1}; 0.5 \cdot H) + \min(I_{G2}; 0.5 \cdot H) + \min(I_{G3}; 0.5 \cdot H) + I_{G4} \quad (1)$$

where I_X is the insertion of the control rod bank X (cm) and H is the maximum insertion of control rods banks (i.e. 200 cm for PRATIC).

Moreover, the insertion of each bank of control rods can be deduced from I_{cumul} using equations (2–5).

$$I_{G1} = \min(I_{\text{cumul}}; H) \quad (2)$$

$$I_{G2} = \min(\max(0; I_{\text{cumul}} - 0.5 \cdot H); H) \quad (3)$$

$$I_{G3} = \min(\max(0; I_{\text{cumul}} - H); H) \quad (4)$$

$$I_{G4} = \min(\max(0; I_{\text{cumul}} - 1.5 \cdot H); H) \quad (5)$$

where I_{cumul} is the cumulative insertion of control rods, I_X is the insertion of the control rod bank X (cm) and H is the maximum insertion of control rod banks.

It is worth mentioning that 42% of PRATIC assemblies incorporate rod clusters used for core piloting, and that 35% of the rod clusters loaded in the core (including shutdown rods) are grey rod clusters.

4 Characteristics of the equilibrium cycle of PRATIC

The search for the equilibrium cycle involves connecting successive depletion calculations. In each calculation, time steps of 1000 MWd/t are modeled, except at the beginning of cycle where the time steps are refined. During depletion calculations, the control rod banks are inserted so that the core reaches criticality (i.e. critical control rods insertion). The cycle ends when the reactivity reserve of the core is equal to 100 pcm (i.e. k_{eff} with all control rods fully extracted = 1.001). When the end of the cycle is reached, cycle length is measured as the difference between the

average burnup of the core at the end of the cycle and at the beginning of the cycle.

The iterative process to find the equilibrium cycle is as follows: when the end of cycle is reached, the cycle length is compared to that of the previous cycle. If it differs by more than 15 MWd/t, the core is reloaded according to the fuel reloading pattern described in Figure 4, and a new depletion calculation is performed. Otherwise, the cycle is considered to have reached equilibrium. It should be noted that the initial depletion calculation employs an arbitrary burnup distribution to initialize the cycle calculation: the burnup of all “Cycle 1” assemblies is set at 0 GWd/t, while that of all “Cycle 2” assemblies is set at 15 GWd/t.

The following sections describe the equilibrium cycle length, the evolution of core reactivity and control, power distributions, and burnup distributions throughout the equilibrium cycle. In addition, Table A.1 in Appendix compiles relevant macroscopic data at several burnup steps throughout the equilibrium cycle. All the results discussed in the subsequent sections are related to the reference equilibrium cycle, which means that the core is operating at 100% NP during the entire cycle.

4.1 Equilibrium cycle length

The equilibrium cycle length was calculated using the approach outlined at the beginning of Section 4. The resulting value is 17.148 GWd/t, corresponding to 692 equivalent full power days (EFPD). This cycle duration, equivalent to 1.895 years, is comparable to those reported for several established industrial SBF-PWR SMR designs, which are typically around 2 years [3].

4.2 Reactivity and control rods insertion

In the characterization process of a reactor core, it is usual to assess the core k_{eff} in two specific configurations: one

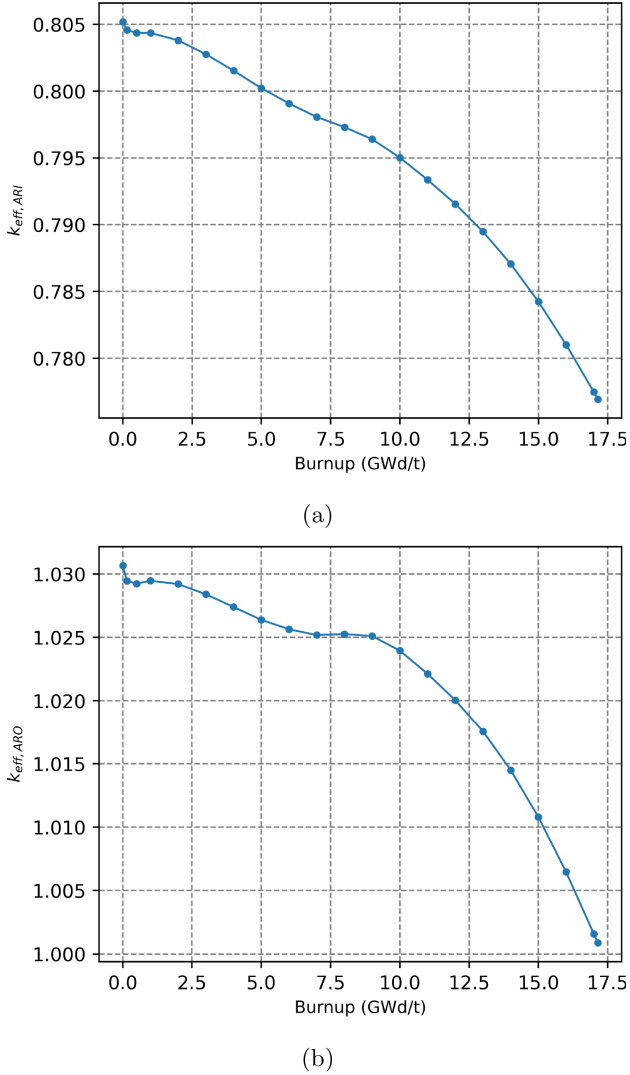


Fig. 7. Core k_{eff} evolution during the reference equilibrium cycle in ARI (a) and ARO (b) configurations.

configuration where all absorber clusters are in their maximum insertion position (noted $k_{\text{eff,ARI}}$, with ARI meaning All Rods In), and another where they are in their maximum extraction position (noted $k_{\text{eff,ARO}}$, with ARO meaning All Rods Out). The calculation of $k_{\text{eff,ARI}}$ offers a way to assess whether the anti-reactivity from the absorber rod clusters (control and shutdown) is sufficient for core shutdown, while considering safety margins. In contrast, $k_{\text{eff,ARO}}$ is often used to determine the reactivity reserve of the core. In the present work, the calculation of $k_{\text{eff,ARI}}$ and $k_{\text{eff,ARO}}$ was performed at several stages of the equilibrium cycle, while maintaining its thermal-hydraulic conditions (also referred to as “hot thermal-hydraulic conditions”). The evolution of the $k_{\text{eff,ARI}}$ and $k_{\text{eff,ARO}}$ throughout the reference equilibrium cycle of PRATIC are presented in Figure 7.

In Figure 7a, it should be noted that the maximum value of $k_{\text{eff,ARI}}$, in hot thermal-hydraulic conditions, is

equal to 0.80519. This value is far below the typical limit value of 0.95 [12] used to ensure that the studied system will remain subcritical despite biases and uncertainties affecting the calculations. This provides an indication that the anti-reactivity introduced by the absorber rod clusters is sufficient to shutdown the core at any point in the equilibrium cycle. One limitation of this analysis is that the limit value of 0.95 is generally considered under cold thermal-hydraulic conditions (i.e. an isothermal temperature of 20°C). Such thermal-hydraulic conditions result in higher k_{eff} values compared to hot conditions. Therefore, the analysis on $k_{\text{eff,ARI}}$ could be revisited in the future by imposing a moderator temperature of 20°C. However, such an investigation falls beyond the scope of this paper.

Figure 7b shows that the maximum value of $k_{\text{eff,ARO}}$ is equal to 1.03066. To compensate for this excess reactivity, the control rods are inserted at a critical level. Figure 8 presents the evolution of the critical cumulative control rod insertion and its distribution across various control rod groups over the reference equilibrium cycle.

Figure 8 shows that only groups G1 and G2 are inserted into the core during the equilibrium cycle. Please note that numerical values depicted in Figures 7 and 8 are provided in Table A.1, in Appendix of this paper.

4.3 Power distribution

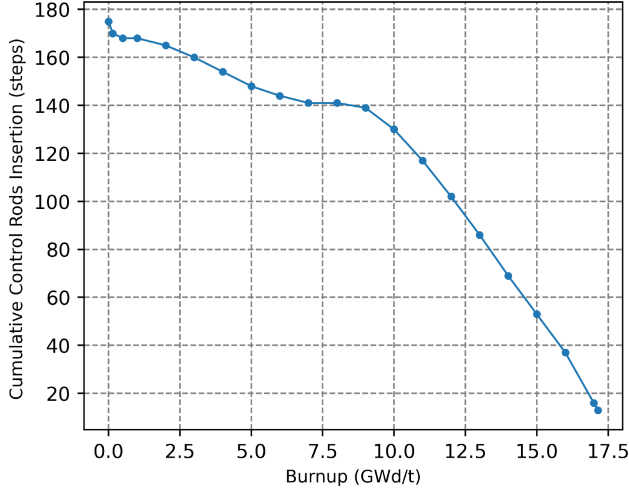
As previously discussed, a key goal in the development of PRATIC was to minimize the 2D and 3D power peaks (respectively noted $\text{MAX} F_{XY}$ and $\text{MAX} F_Q$) reached during the cycle, with critical control rods insertion. The definitions of $\text{MAX} F_{XY}$ and $\text{MAX} F_Q$ are recalled by equations (6) and (7).

$$\text{MAX} F_{XY} = \max \left(\frac{P_{\text{th,surf}}(x, y)}{\text{AVE} P_{\text{th,surf}}} \right) \quad (6)$$

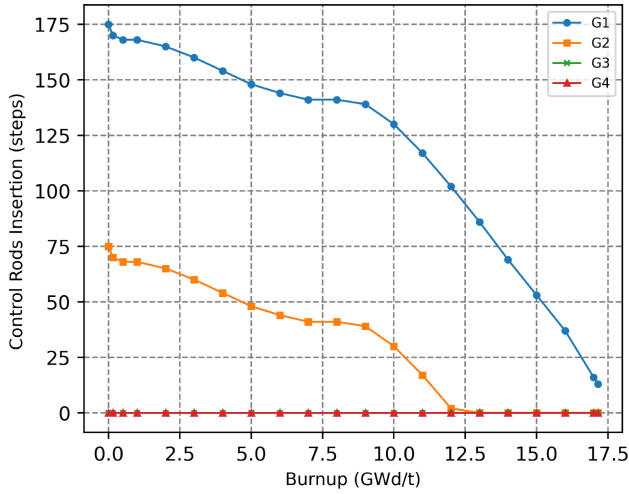
$$\text{MAX} F_Q = \max \left(\frac{P_{\text{th,vol}}(x, y, z)}{\text{AVE} P_{\text{th,vol}}} \right) \quad (7)$$

where:

- $P_{\text{th,vol}}(x, y, z)$ represents the thermal power density (W/cm^3) of the mesh located at coordinates (x, y, z) , where x and y denote the coordinates in the (X, Y) plane, and z denotes the axial position along the Z -axis;
- $\text{AVE} P_{\text{th,vol}} = \sum_{X,Y,Z} \frac{V(x,y,z) \cdot P_{\text{th,vol}}(x,y,z)}{\sum_{X,Y,Z} V(x,y,z)}$ (expressed in W/cm^3). Here, $V(x, y, z)$ represents the volume (cm^3) of the mesh located at coordinates (x, y, z) .
- $P_{\text{th,surf}}(x, y) = \sum_Z P_{\text{th,vol}}(x, y, z) \cdot \Delta z(x, y, z)$ (expressed in W/cm^2). Here, $\Delta z(x, y, z)$ denotes the height (cm) of the mesh located at coordinates (x, y, z) ;
- $\text{AVE} P_{\text{th,surf}} = \sum_{X,Y} \frac{S(x,y) \cdot P_{\text{th,surf}}(x,y)}{\sum_{X,Y} S(x,y)}$ (expressed in W/cm^2). Here, $S(x, y)$ is the area (cm^2) of the radial mesh located at coordinates (x, y) .



(a)



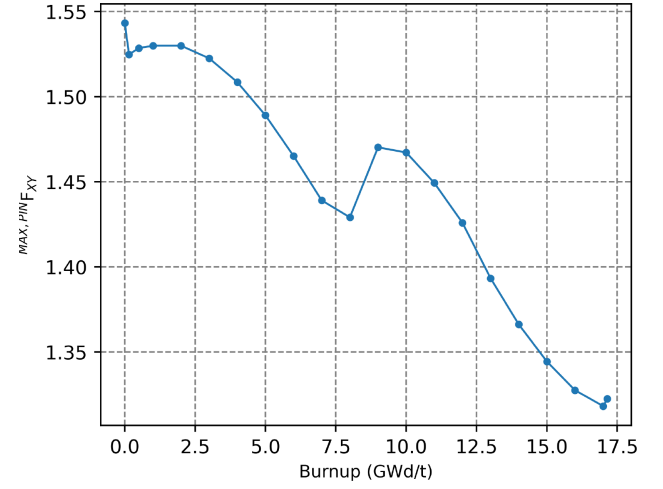
(b)

Fig. 8. Evolution of the cumulative insertion of the control rods (a) and of the insertion of each control rods bank (b) along the reference equilibrium cycle.

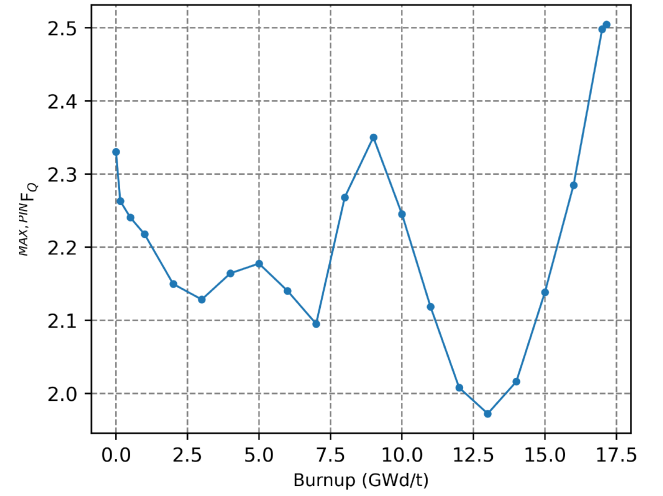
The notations $^{MAX,PIN}F_{XY}$ and $^{MAX,PIN}F_Q$ indicate that the radial mesh used for computing power factors is at the pin scale, while the notations $^{MAX,FA}F_{XY}$ and $^{MAX,FA}F_Q$ signify that the radial mesh used for power factor calculations is at the assembly scale. The present study primarily focused on pin scale power factors, as they result in higher maximum values.

The evolution of $^{MAX,PIN}F_{XY}$ and $^{MAX,PIN}F_Q$ along the equilibrium cycle is depicted in Figure 9. Firstly, Figure 9a shows that the maximum value of $^{MAX,PIN}F_{XY}$ is reached at the beginning of cycle and is equal to 1.543.

To put this value into perspective, it is possible to draw a comparison with the radial power factor associated with a primary water temperature that may result in boiling (i.e. primary water saturation). This saturation power factor, written $^{SAT}F_{XY}$, can be derived from equation (8).



(a)



(b)

Fig. 9. Evolution of the radial (a) and three-dimensional (b) power peak factors along the reference equilibrium cycle.

$$^{SAT}F_{XY} = \frac{\dot{m} \cdot C_P}{P_{th,core}} (T_{mod,sat} - T_{mod,in}) \quad (8)$$

where $P_{th,core}$ is the thermal power of the core (350e6 W for PRATIC), $\dot{m}$ is the water flow in the primary circuit (2185.39 kg.s⁻¹ calculated with a moderator cross-sectional area in the core equal to 1.41 m²), C_P is the specific heat capacity of water under primary circuit conditions (5458.34 J.kg⁻¹.K⁻¹ for water at 300°C and 155 bar [24]), $T_{mod,sat}$ is the water saturation temperature (617.94 K = 344.79°C for water at 155 bar [24]) and $T_{mod,in}$ is the temperature of the primary water at the core inlet (558.15 K = 285.00°C for PRATIC).

Using the parameters of PRATIC, application of equation (8) gives a value of $^{SAT}F_{XY}$ equal to 2.038. As a result, the maximum value of $^{MAX,PIN}F_{XY}$ reached during the equilibrium cycle is 24.29% below the $^{SAT}F_{XY}$, providing a safety margin against boiling water in the primary circuit. As a complement, Figures A.1–A.3, provided in

Appendix, show the assembly and pin scale distributions of the radial power factor F_{XY} at the beginning, middle and end of the equilibrium cycle. The color scales used in the assembly-scale figures (Figs. A.1a, A.2a and A.3a) are consistent across all three. Likewise, the pin-scale figures (Figs. A.1b, A.2b and A.3b) maintain uniform color scales.

Secondly, as depicted in Figure 9b, there is a consistent rise in $^{MAX,PIN}F_Q$ from 13.0 GWd/t to the end of the cycle at 17.148 GWd/t. The observed phenomenon is attributed to the upward motion of the control rods towards the end of the cycle. This action leads to a gradual increase in power in the upper part of the core, corresponding to areas of lower burnup. As a result, the maximum value of $^{MAX,PIN}F_Q$ over the equilibrium cycle is reached at the very end of the cycle and is equal to 2.505. This maximum value of $^{MAX,PIN}F_Q$ can be used to deduce the maximum value of linear power reached during the equilibrium cycle (noted $^{MAX}P_{lin}$), according to equation (9).

$$^{MAX}P_{lin} = ^{MAX,PIN}F_Q \cdot ^{AVE}P_{lin} \quad (9)$$

where $^{MAX,PIN}F_Q$ is the three-dimensional power peaks (unit-less) and $^{AVE}P_{lin}$ is the average linear power (W/cm), calculated over the whole core. For PRATIC, $^{AVE}P_{lin}$ is equal to 115.97 W/cm.

The application of equation (9) leads, in the case of PRATIC, to a value of $^{MAX}P_{lin}$ equal to 290.48 W/cm. This $^{MAX}P_{lin}$ value is significantly below the threshold linear power level above which the risk of cladding rupture becomes a concern, which is of the order of 420–430 W/cm according to reference [10]³. Moreover, it remains significantly below the critical linear power limit which must not be exceeded to prevent the fuel from reaching its melting point, specified at 590 W/cm in reference [10]. The elements listed above demonstrate that the power distribution in PRATIC is well controlled, despite the absence of soluble boron.

To complement the explanations of the previous paragraphs, it is interesting to examine the evolution of power axial offset of the core (AO) throughout the equilibrium cycle. In neutronics, the core AO (expressed in %) represents the difference in thermal power between the upper and lower regions of the core and can be expressed as:

$$AO = \frac{P_{th,top} - P_{th,bottom}}{P_{th,top} + P_{th,bottom}} \cdot 100 \quad (10)$$

where $P_{th,top}$ and $P_{th,bottom}$ represent the thermal power of the half-upper and half-lower axial regions of the core, respectively (expressed in W).

Figure 10 details the AO evolution throughout the equilibrium cycle. It shows that the core AO exhibits significant variability during base operation. Beginning at -21.31%, it decreases slightly to a minimum of -23.71% near 9.0 GWd/t, then rapidly rises to a maximum of +37.93% at the conclusion of the equilibrium cycle. This behavior highlights the substantial change in axial power

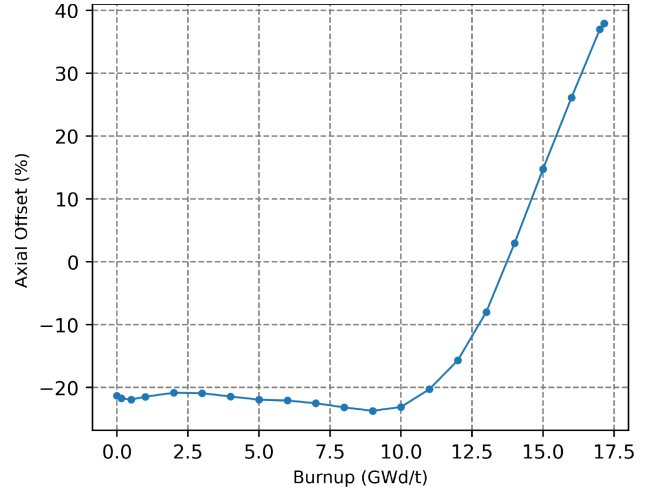


Fig. 10. Evolution of the power axial offset of the core throughout the reference equilibrium cycle.

distribution over the equilibrium cycle. Initially tilted towards the lower portion of the core, this distribution quickly shifts upwards with the extraction of control rods. This results in the strong power peak observed towards the top of the core at the end of the cycle (cf. Fig. 9b).

Please note that numerical values depicted in Figures 9 and 10 are provided in Table A.1, in Appendix of this paper.

4.4 Burnup distribution

The assembly and pin burnup radial distributions at the beginning, middle and end of the equilibrium cycle are presented, in Appendix, by Figures A.4–A.6 respectively. Firstly, the average burnup of assemblies at the start of the equilibrium cycle is about 7.29 GWd/t. By the end of the equilibrium cycle, this value rises to 24.44 GWd/t. The average burnup of the discharged assemblies, whose locations are shown in Figure 5, is recorded at 33.70 GWd/t. Finally, the maximum radial burnup of discharged assemblies is equal to 36.48 GWd/t. This value rises to 43.06 GWd/t at the pin scale. The central assembly, discharged at the end of each cycle, achieves a radial burnup of 20.39 GWd/t.

5 Conclusion

In the field of nuclear reactor design, there is active research and development dedicated to exploring soluble boron free small modular pressurized water reactors (SBF-PWR type SMRs). To ensure the effective applicability of scientific research findings on SBF-PWR type SMRs to emerging reactor designs, it is crucial to utilize core benchmarks that are in line with the industrial concepts currently under development.

In this context, this paper presents the PRATIC (“Petit REP Académique pour Tester, Innover et Concevoir”, meaning “Small Academic PWR for Testing,

³ This value was obtained for a UO₂ rod, with Zircaloy-4 cladding and pre-irradiated for 2 cycles in a PWR [10].

Innovation, and Design” in French) benchmark. PRATIC is an SBF-PWR type SMR core, designed for scientific research purposes but with performance levels close to those of industrial reactor cores concepts referenced in the literature. Indeed, PRATIC operates with cycle length of 1.895 years ($17148 \text{ MWd/t} = 692 \text{ EFPD}$) at a nominal power of $350 \text{ MW}_{\text{th}}$. Throughout its equilibrium cycle, it maintains well-controlled power distributions both radially and axially ($^{\text{MAX,PIN}}F_{XY} = 1.543$ and $^{\text{MAX,PIN}}F_Q = 2.505$). This value of $^{\text{MAX,PIN}}F_{XY}$ is 24.29% lower than the power factor leading to a risk of boiling water in the primary circuit, giving an acceptable margin for this type of accident. Moreover, the maximum linear power reached by the core during its equilibrium cycle is 290.48 W/cm , significantly below the linear power at which cladding fails could occur and even further from the fuel melting point. Finally, the average discharge burnup of the fuel assemblies is equal to 33.70 GWd/t .

Future developments related to PRATIC could include the creation of a start-up core, the design of a core variant incorporating MOX fuel or the validation of data obtained from the deterministic model against a Monte Carlo reference. Additionally, PRATIC could be used to analyze common assumptions in neutronics calculation schemes, SBF-PWR SMR core behavior during incidental or accidental conditions, nuclear scenario studies, and more. Finally, in-depth analyses of the core’s thermohydraulics could be conducted to confirm the choices made by the authors regarding the associated parameters (moderator inlet temperature, moderator flow rate, etc.) and to adjust them if necessary.

The GIT repository accompanying this article encapsulates the data required in order to model PRATIC using neutronics codes, enabling the scientific community to employ it for research activities concerning SBF-PWR-type SMRs. Moreover, some equilibrium cycle data such as core power distributions, burnup distributions, etc. are also provided in this GIT repository, for benchmarking purposes. The GIT repository will be updated as additions are made to the PRATIC database.

Abbreviations

The following abbreviations are used in this manuscript:

AIC	AgInCd
AO	Axial Offset
ARI	All Rods In

ARO	All Rods Out
CEA	French Atomic Energy and Alternative Energy Commission
EFPD	Equivalent Full Power Day
MOX	Mixed Uranium and Plutonium Oxide-based fuel
NP	Nominal Power
PRATIC	Petit REP Académique pour Tester, Innover et Concevoir
PWR	Pressurized Water Reactor
SMR	Small Modular Reactor
FA	Fuel Assembly
UOX	Uranium Oxide-based fuel

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Conflicts of interest

The authors declare that they have no competing interests to report.

Data availability statement

This article is accompanied by a GIT repository that includes the information needed to model PRATIC with neutronics codes, as well as various data relating to the equilibrium cycle. Updates to the PRATIC database will be reflected in this GIT repository. Access to this GIT repository will be granted on request by e-mail to the following address: pratic@cea.fr. The data shared in both this article and the GIT repository are licensed under [CC BY-NC-SA 4.0](https://creativecommons.org/licenses/by-nc-sa/4.0/), permitting data reuse solely for non-commercial purposes and requiring appropriate credit to the authors of this article.

Author contribution statement

R. Vuiart: Conceptualization, Methodology, Investigation, Formal Analysis, Visualization, Writing – original draft, Writing – review & editing. **A. Eustache:** Conceptualization, Methodology, Investigation, Formal Analysis, Writing – review & editing. **S. Eveillard:** Conceptualization, Methodology, Investigation, Formal Analysis, Writing – review & editing. **G. Prulhière:** Conceptualization, Methodology, Investigation, Formal Analysis, Final Results, Writing – review & editing. All authors have read and agreed to the published version of the manuscript.

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Appendix A

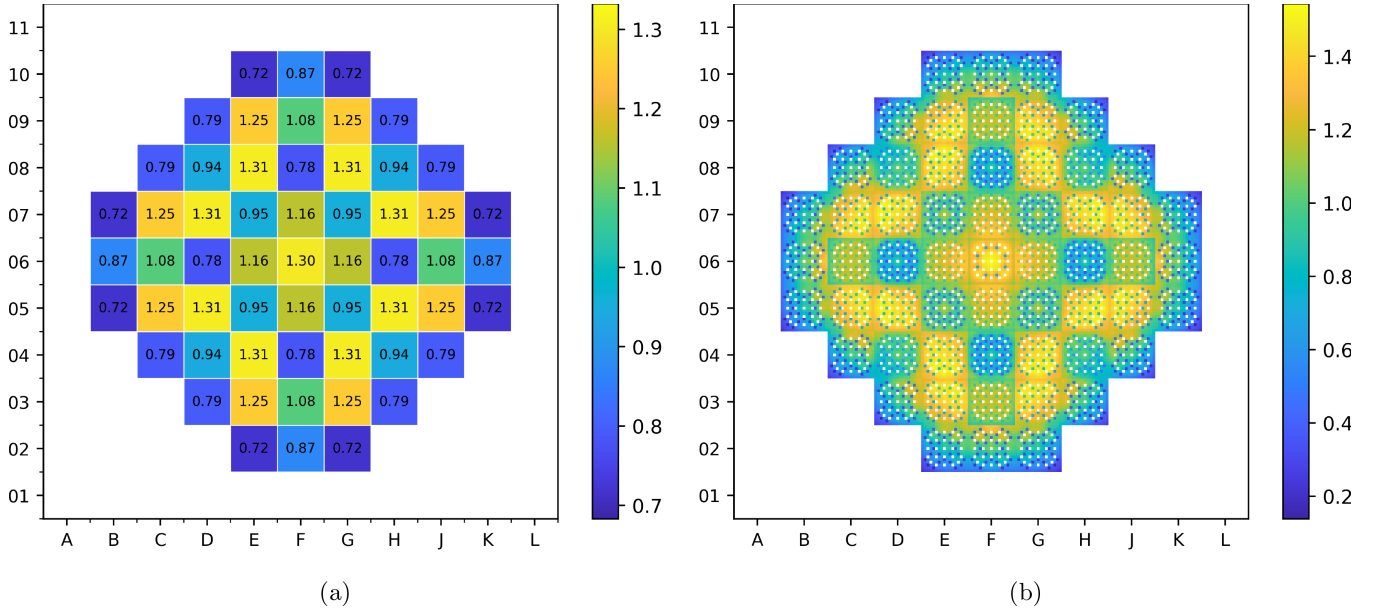


Fig. A.1. Fuel assembly scale (a) and pin scale (b) distributions of the normalized radial power in PRATIC for a cycle burnup of 0.0 GWd/t, corresponding to the beginning of the reference equilibrium cycle.

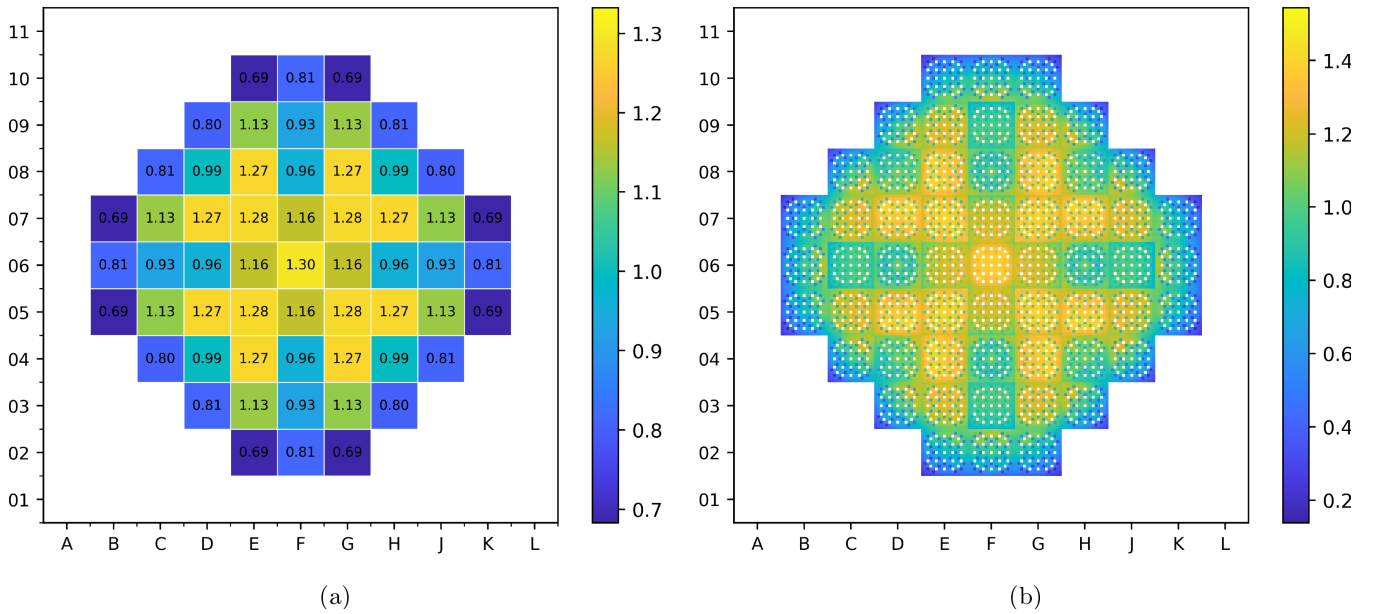


Fig. A.2. Fuel assembly scale (a) and pin scale (b) distributions of the normalized radial power in PRATIC for a cycle burnup of 8.0 GWd/t, corresponding to the middle of the reference equilibrium cycle.

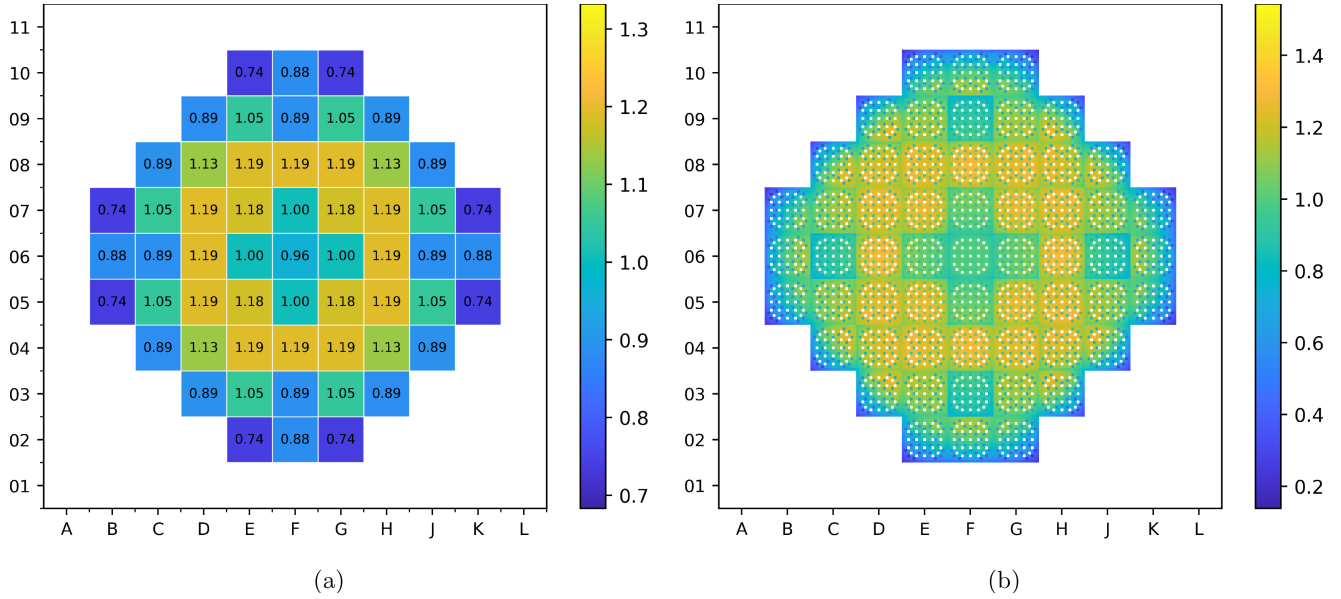


Fig. A.3. Fuel assembly scale (a) and pin scale (b) distributions of the normalized radial power in PRATIC for a cycle burnup of 17.148 GWd/t, corresponding to the end of the reference equilibrium cycle.

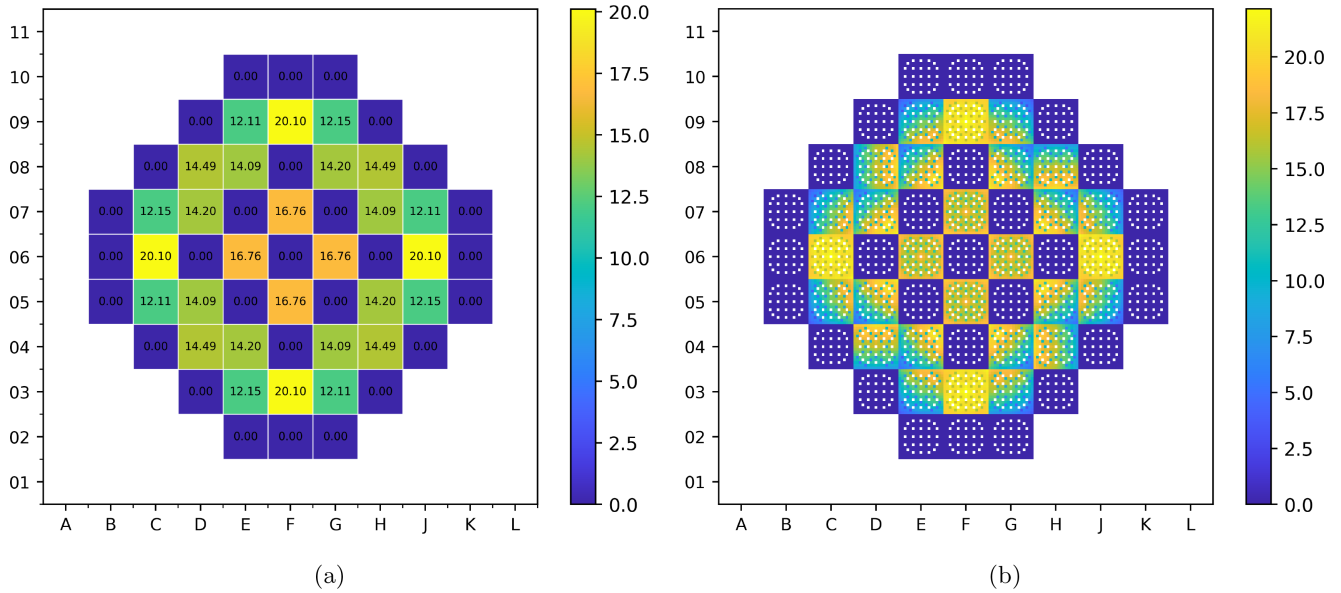


Fig. A.4. Fuel assembly scale (a) and pin scale (b) distributions of the radial burnup in PRATIC for a cycle burnup of 0.0 GWd/t, corresponding to the beginning of the reference equilibrium cycle.

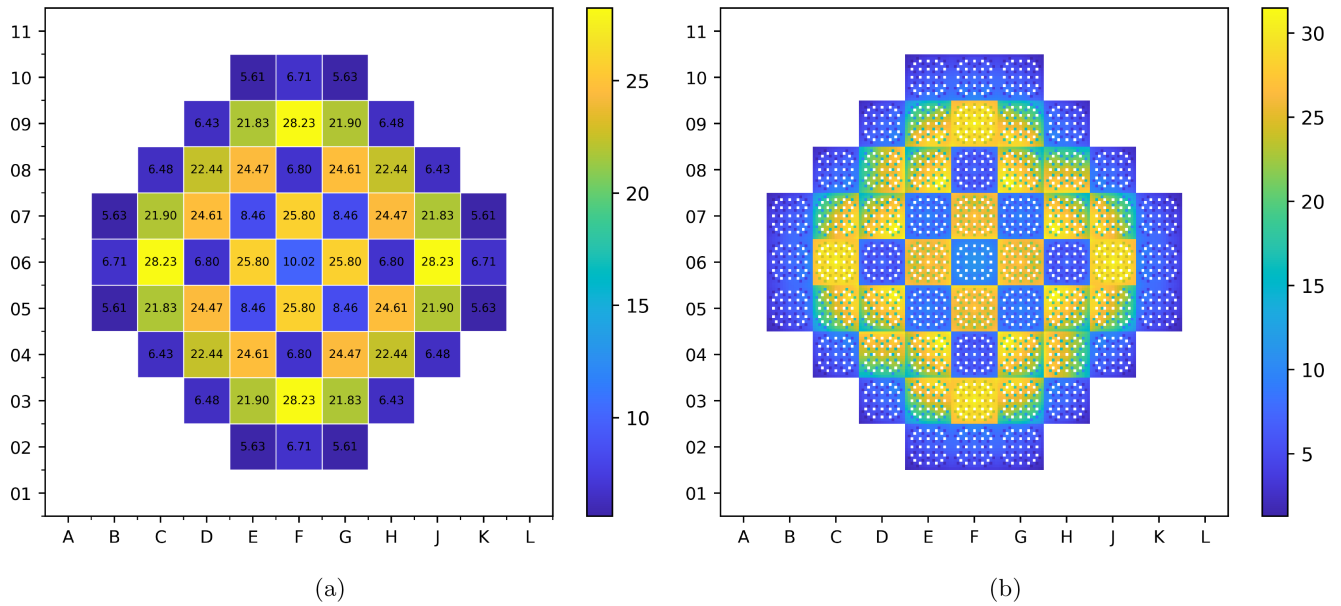


Fig. A.5. Fuel assembly scale (a) and pin scale (b) distributions of the radial burnup in PRATIC for a cycle burnup of 8.0 GWd/t, corresponding to the middle of the reference equilibrium cycle.

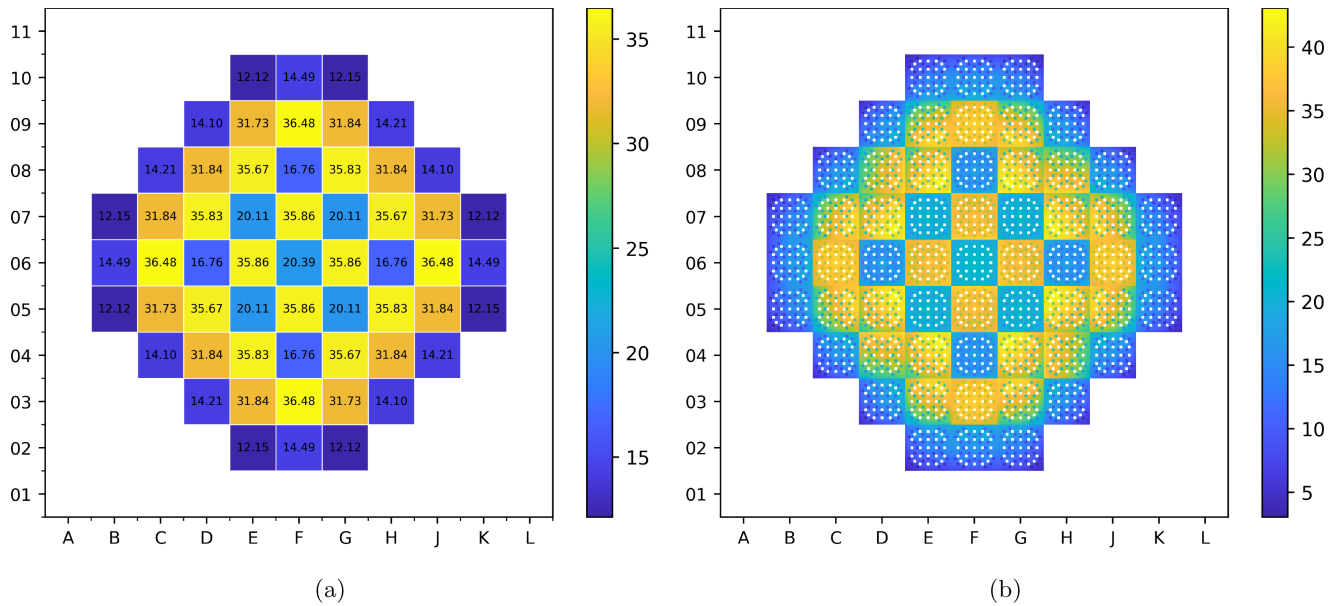


Fig. A.6. Fuel assembly scale (a) and pin scale (b) distributions of the radial burnup in PRATIC for a cycle burnup of 17.148 GWd/t, corresponding to the end of the reference equilibrium cycle.

Table A.1. Evolution of relevant physical quantities throughout the PRATIC equilibrium cycle.

Cycle Burnup (MWd/t)	Equivalent Full Power Days	$k_{\text{eff,ARO}}$	$k_{\text{eff,ARI}}$	Cumulative Insertion of Control Rods (steps)	Control Rod Banks Insertion (steps)				AO (%)	MAX,FA F_{XY}	MAX,FA F_Q	MAX,PIN F_{XY}	MAX,PIN F_Q	MAX P_{in} (W/cm)
					G1 G2 G3 G4									
					G1	G2	G3	G4						
0.0	0.0	1.03066	0.80519	175	175	75	0	0	-21.31	1.307	1.968	1.543	2.330	270.27
150.0	6.1	1.02944	0.80458	170	170	70	0	0	-21.72	1.314	1.925	1.525	2.263	262.46
500.0	20.2	1.02923	0.80436	168	168	68	0	0	-21.93	1.319	1.910	1.528	2.241	259.85
1000.0	40.3	1.02945	0.80436	168	168	68	0	0	-21.46	1.318	1.884	1.530	2.218	257.20
2000.0	80.7	1.02920	0.80380	165	165	65	0	0	-20.84	1.312	1.815	1.530	2.150	249.31
3000.0	121.0	1.02839	0.80277	160	160	60	0	0	-20.91	1.306	1.793	1.522	2.128	246.84
4000.0	161.3	1.02739	0.80153	154	154	54	0	0	-21.43	1.300	1.836	1.508	2.164	250.99
5000.0	201.7	1.02638	0.80022	148	148	48	0	0	-21.94	1.294	1.856	1.489	2.178	252.55
6000.0	242.0	1.02564	0.79907	144	144	44	0	0	-22.07	1.286	1.853	1.465	2.140	248.21
7000.0	282.4	1.02518	0.79806	141	141	41	0	0	-22.50	1.290	1.852	1.439	2.095	242.98
8000.0	322.7	1.02525	0.79730	141	141	41	0	0	-23.16	1.296	2.015	1.429	2.268	263.05
9000.0	363.0	1.02511	0.79640	139	139	39	0	0	-23.71	1.326	2.104	1.470	2.350	272.58
10000.0	403.4	1.02395	0.79502	130	130	30	0	0	-23.10	1.332	2.021	1.467	2.245	260.40
11000.0	443.7	1.02213	0.79336	117	117	17	0	0	-20.27	1.315	1.863	1.449	2.119	245.68
12000.0	484.0	1.02005	0.79155	102	102	2	0	0	-15.67	1.291	1.768	1.426	2.008	232.86
13000.0	524.4	1.01756	0.78947	86	86	0	0	0	-8.00	1.260	1.737	1.393	1.972	228.74
14000.0	564.7	1.01450	0.78706	69	69	0	0	0	+2.97	1.234	1.775	1.366	2.016	233.82
15000.0	605.1	1.01080	0.78423	53	53	0	0	0	+14.75	1.213	1.885	1.344	2.139	248.01
16000.0	645.4	1.00647	0.78101	37	37	0	0	0	+26.10	1.196	2.046	1.327	2.285	264.98
17000.0	685.7	1.00159	0.77747	16	16	0	0	0	+36.98	1.193	2.230	1.318	2.498	289.70
17147.8	691.7	1.00089	0.77694	13	13	0	0	0	+37.93	1.192	2.236	1.323	2.505	290.48