ADVANCES IN THE CONCEPTUAL DESIGN OF A SMALL MODULAR REACTOR OF THE INTEGRATED PRESSURE WATER TYPE

AVANCES EN EL DISEÑO CONCEPTUAL DE UN PEQUEÑO REACTOR MODULAR DEL TIPO INTEGRADO DE AGUA A PRESIÓN

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Recibido 5/12/2023; Aceptado 1/5/2024

The development and deployment of small nuclear reactors (SMRs) as part of the new generations of nuclear reactors has gained significant importance in recent years. The advantages of SMRs is due not only to their ability to generate low-emission energy, but essentially to their modularity characteristics and their small dimensions. The TRI-structural-ISOtropic (TRISO) fuel, with proven advantages in graphite-gas type nuclear reactors, has been researched for use in PWRs. To obtain high proliferation resistance, extended fuel cycles for SMRs have been proposed. To obtain conceptual designs of SMR cores with a large cycle length, using low fuel enrichment, without shuffle, and with a relatively small core size is a challenge. In this work, a study was carried out to consider improvements in the behavior of the fuel cycles of a conceptual design of a SMR type iPWR, using TRISO fuel. These improvements are related to increasing reactor core power while maintaining extended fuel cycles and, on the other hand, considering different core zones with different fuel compositions, varying the packaging fraction, the last with the aim of to enlarge the fuel cycles and maintaining a flattened radial power distribution.

El desarrollo y despliegue de reactores modulares pequeños (SMR) como parte de las nuevas generaciones de reactores nucleares ha adquirido una importancia significativa en los últimos años. Las ventajas de los SMR se deben no sólo a su capacidad de generar energía baja en emisiones, sino principalmente a sus características de modularidad y a sus pequeñas dimensiones. El combustible TRI-estructural-ISOtrópico (TRISO), con ventajas comprobadas en reactores nucleares de tipo grafito-gas, ha sido investigado también para su uso .en los reactores de agua a presión (PWR). Para obtener una alta resistencia a la proliferación, se han propuesto ciclos de combustible extendidos para los SMR. Obtener diseños conceptuales de núcleos SMR con una larga duración del ciclo combustible, utilizando un bajo enriquecimiento, sin mover los conjuntos combustibles de posición, y con un tamaño de núcleo relativamente pequeño es un desafío. En este trabajo se realizó un estudio para considerar mejoras en el comportamiento de los ciclos de combustible de un diseño conceptual de un iPWR tipo SMR, utilizando combustible TRISO. Estas mejoras están relacionadas con aumentar la potencia del núcleo del reactor manteniendo ciclos de combustible extendidos y, por otro lado, considerar diferentes zonas materiales del núcleo con diferentes composiciones de combustible variando la fracción de empaquetamiento, esto último con el objetivo de ampliar los ciclos de combustible y mantener una distribución radial de energía liberada uniforme.

PACS: Nuclear reactors (Reactores nucleares). 28.41.-i; Theory and simulation of nuclear reactors (Teoría y simulación de reactores nucleares), 28.41.Ak; Nuclear engineering (ingeniería nuclear), 28.20.Ka.

I. INTRODUCTION

The development of Small Modular nuclear Reactors (SMR) has gained significant importance in recent years. Their compact size, the reduced initial capital values to be invested and the improvements in their safety represent an advantage over conventional nuclear power plants.

The interest in SMRs is not only related to their ability to generate low-emission energy, but essentially to their modularity characteristics and their small dimensions that make them more flexible and can be built in places with difficult access, where there is limited the power demand. They can also be used for non-electrical services such as heating and seawater desalination.

Within the SMR, pressurized water reactors (PWR) are the most promising in the short term. SMR-type integrated type pressurized water reactors (iPWR), are among the most important due to their advanced safety features.

The TRI-structural-ISOtropic (TRISO) fuel, with proven advantages in graphite-gas type nuclear reactors, has been researched for use in PWRs, with the aim of increasing safety barriers in extreme scenarios. For this type of fuel, there are minor risks of releasing fission products in extreme events, and it is possible to retain them safely up to temperatures of 1600°C. A TRISO fuel particle is composed of a fuel core (in the standard variant enriched uranium dioxide) that is surrounded by successive layers of alternating pyrolytic carbon (PyC) and silicon carbide (SiC). TRISO fuels are structurally more resistant to neutron irradiation, corrosion, oxidation and high temperatures than traditional reactor fuels.

In [1], [2] and [3] the conceptual design of a small PWR core was carried out, with a thermal power of 25 MWt, which it reached an extended fuel cycle of approximately 4 years and that uses TRISO fuel. Variants of enrichment, packing fraction and TRISO fuel particle size were studied with the aim of optimizing the fuel cycle. The packing fraction (PF) is defined as the volumetric ratio of the volume occupied by TRISO particles to the total volume occupied by the packing material.

An important goal to achieve for SMRs is the so-called extended fuel cycles, that is, reactor working times at nominal power of around four years without refueling. This aspect strengthens its resistance to the proliferation of nuclear weapons. That is why the design of the SMR seeks to achieve this performance.

In [4], the neutronic performance of the SMR of 25 MWt PWR-type, using thorium in TRISO fuel in the form of duplex configuration was studied, in terms of the following parameters: cycle length, main isotopes' mass transmutation, moderator temperature coefficient, fuel temperature coefficient, and power distributions. To achieve this goal, three distribution cases of ThO_2 and UO_2 in TRISO particles inside the fuel rods were compared.

The particularly good neutron behavior of the proposed 25 MWt iPWR type SMR [5] allowed the core to be redesigned to achieve higher thermal powers and maintain the rest of its advantageous characteristics, including a long life fuel cycle.

In [5], the neutron redesign of the reactor core was conducted with the aim of increasing thermal power. The core redesign study was done by increasing the axial and radial dimensions. The radial power distributions, the length of the fuel cycle and other parameters for the different variants analyzed were compared.

In [6], in order to evaluate the behavior of the fuel cycle, several computational models of fuel burnup were analyzed, dividing the reactor core into three, two and a single burnup zones. The model using a single burnup zone does not adequately describe the fuel cycle parameters. The models that used two and three burnup zones did not present major differences in the main results.

In this work, a study is carried out to consider improvements in the behavior of the fuel cycle of the updated design of the proposed reactor core. These improvements are related to increasing reactor core power while maintaining extended fuel cycles and, on the other hand, considering different core zones with different fuel compositions, by varying the packaging fraction, with the aim of enlarging the fuel cycles and maintaining a flattened radial power distribution. The structure of the paper is as follows: In the next section, the main design parameters of the proposed SMR and the characteristics of the developed neutronic model are shown. In section 3, the results obtained for all the studied cases are presented. Finally, the conclusions are summarized in section 4.

II. MATERIALS AND METHODS

II.1. Reactor design and parameters

The proposed redesigned reactor core consists of 157 fuel assemblies [5], whose layout is shown in Figure 1. Each fuel assembly (FA) is made up of a 5×5 arrangement of fuel rods. The location in the core of the fuel assemblies that use control rods is shown, as well as their position in the lattice. Inside each fuel rod, the encapsulating material contains a lattice of TRISO particles. Depending on the value of the packaging fraction used, the pitch of the lattice takes different values.

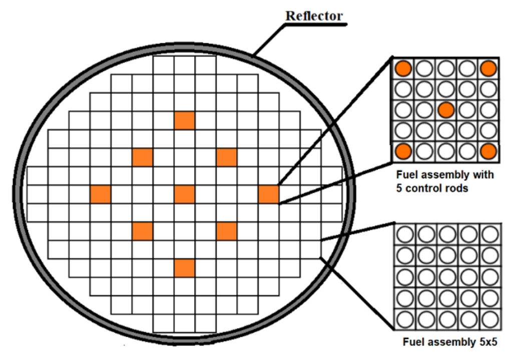

Figure 1. Scheme of the proposed reactor core with 157 fuel assemblies.

Table 1 shows the main parameters of the updated core design of the SMR reactor of the iPWR type using TRISO fuel. The thermal power considered for the new design was 65 MWth, which corresponds to the power density of the reference core of 25 MWth [3].

Table 1. Main design parameters of the proposed core.

Parameters	Value/unit
Thermal power	65 MWt
Core height	220 cm
Beryllium reflector thickness	10 cm
Fuel pitch	3 cm
Fuel rod diameter	2 cm
Clad thickness (Zircaloy)	0.15 cm
Number of fuel assemblies	157
Fuel rods pattern	5×5
Number of control rods	45
Standard packing fraction	30 % cm
Fuel enrichment	15 % by weight

The composition of the TRISO particles are given in Table 2 [2].

Table 2. Composition of the TRISO particle.

Material	Density (g/cm^3)
Kernel	10.88
Buffer	1.1
IPyC	1.9
SiC	3.2
OPyC	1.9
SiC packing matrix	3.2

II.2. Computational model

To carry out the simulations that will allow knowing the neutronic performance of the core (effective neutron multiplication factor (Keff), axial and radial power distributions, as well as the fuel burnup) the Serpent code, Version 2.1.27, was used [7].

Serpent is a multi-purpose, three-dimensional continuous energy Monte Carlo particle transport code, which was developed at the VTT Technical Research Center of Finland, Ltd. Although it started as a simplified code for calculating reactors, today its scope extends beyond the simulation of reactors. It can solve multiple problems, including coupled reactors, burnup and fuel cycle analysis, etc. [8]. The code includes ACE format cross-section libraries based on JEF-2.2, JEFF-3.1, JEFF-3.1.1, ENDF/B-VI.8, and ENDFB/B-VII evaluated data files. The nuclear data library used for the cross-sections in these calculations was the JEFF-3.1 at the different temperatures of the materials. All the calculations were performed with a statistic of 10,000 neutrons per cycle and 500 cycles, skipping the first 100. This setting guarantees standard deviation values (SD) below 100 pcm in Keff.

To perform fuel burnup calculations, the Bateman equations were solved, using two methods [7]. The first: transmutation trajectory analysis, gives the analytical solution of the linearized decay chains, and the second: Chebyshev rational approach, which consists of a solution of advanced exponential matrices developed in VTT itself.

The Bateman equations are a set of first-order differential equations that describe the time evolution of concentrations of the nuclei undergoing a linear or serial decay chain [8].

For the burnup calculations in the built computational model, a variable burnup step was considered, which divides the total burnup interval into 80 subintervals, with a step of 0.1 MWd /KgU for the first interval, which is increased for higher values of burnup.

III. RESULTS AND DISCUSSION

III.1. Analysis of the fuel cycle for higher power values

The conceptual design of the reference reactor core considered a thermal power of 25 MWth [3]. For the conceptual redesign of the larger core, a higher power value was considered (65 MWth), proportionally increasing the thermal power according to the increase made to the volume of the core, keeping constant the power density. The volume of the core was increased with the variation of the number of fuel assemblies from 89 to 157 and the increase of the core height from 150 to 220 cm [5].

However, in the results obtained from the thermo-hydraulic simulation of the 25 MWth reactor [3], a large reserve of the maximum temperature values with respect to the critical values was obtained. Taking into account the above, it was considered to study the fuel cycle in the updated core design for higher power values, with the objective of assessing how much its duration is shortened, and checking if it maintains the characteristic of an extended fuel cycle with a sufficiently flattened radial power distribution.

Figure 2 shows the variation of Keff vs EFPD (effective full power days) for the power values of 65, 80 and 100 MWth. For fuel burnup a model was used dividing the reactor core into two zones [6]. In the case of 100 MWth of power, the cycle length is reduced from 1,215 to 790 EFPD, for a produced energy of 79,000 MWd, versus 78,975 MWd for de reference cycle. In the case of 80 MWth, the cycle duration was reduced to 990 EFPD with an approximately equal value of the energy produced.

An increase in the absolute power value implies an increase in the power density value. Therefore, the possibility of using it implies a detailed thermo-hydraulic analysis of the core and possibly considering higher values of the cooling parameters of the thermodynamic cycle.

For the above, it is necessary to know the radial and axial power distributions. Figure 3 shows the radial distributions of energy released at the beginning and end of the cycle (BOC and EOC) with different power values for a quarter of the reactor core. The radial power distributions are given through the values of the radial peak factors (pf). In the radial power distributions presented, it is observed that there is no significant difference when a fuel cycle is carried out with higher power values.

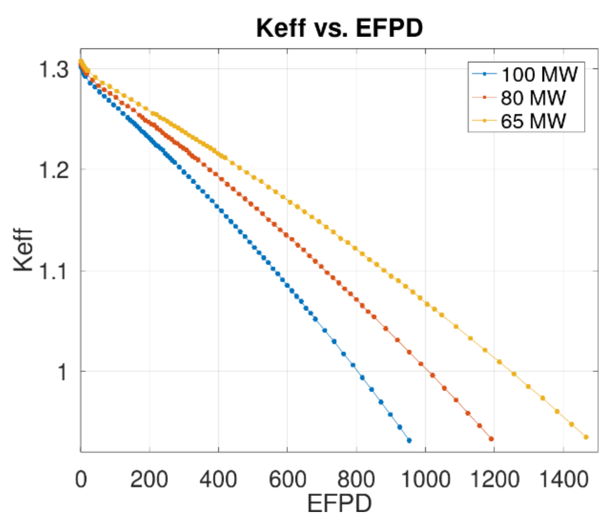

Figure 2. Keff vs. EFPD for different values of core thermal power.

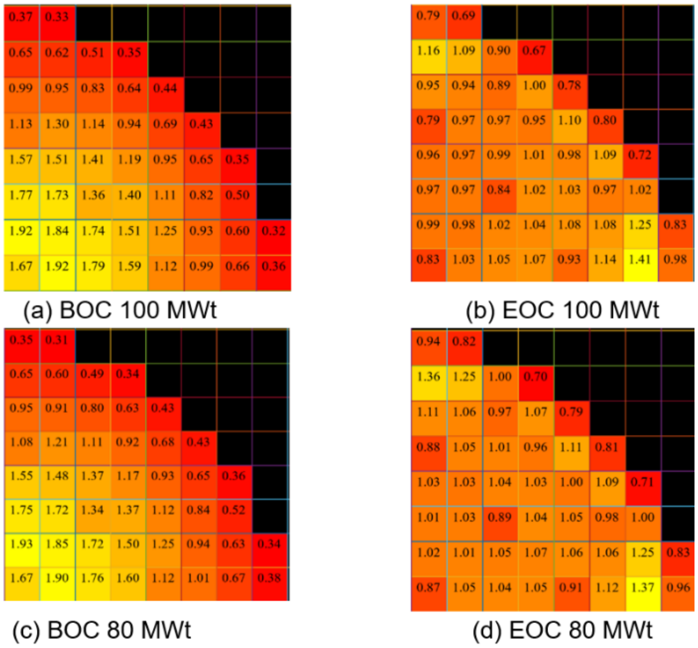

Figure 3. Radial power distributions at BOC and EOC for fuel cycles with difference power values.

III.2. *Analysis of the core fuel cycle, using zones with different packing fractions*

As said before, one of the main objectives of the SMR is to achieve extended fuel cycles using total refueling.

However, when we increase the power of the reactor, there is a decrease in the fuel cycle length. One way to increase it is by placing a greater mass of fissile fuel at BOC. The above is achieved in two ways: increasing the enrichment in U^{235}, or increasing the packing fraction. Increasing the initial enrichment is an impractical option because the enrichment value of the TRISO fuel used is already a high value (15 %). Therefore, it was preferred to study the use of higher values of packing fraction within the permissible range, which according to the literature, it is between 0.24 and 044 [1].

With the aim to obtain a radial power distribution as flattened as possible, it was considered to load the inner zone of the reactor core with lower values of PF and the peripheral area with higher values.

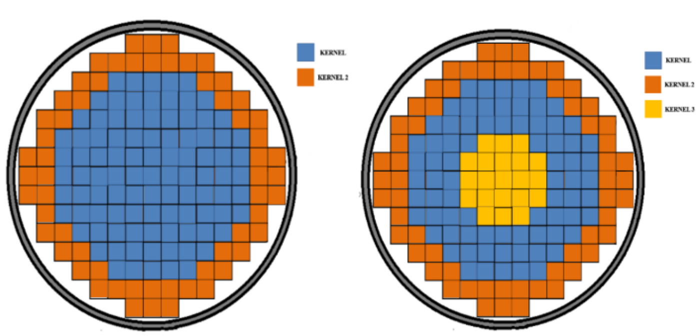

Figure 4. Fuel assemblies' layout for two and three zones core.

Figure 4 shows the radial distribution of the fuel assemblies for two and three zones with different PF.

III.3. *Reactor core analysis with two zones*

Fuel cycles were studied for three cases of core compositions with two zones with fuel assemblies of different PF values. The inner zone with the lowest value of PF and the outer zone with the highest value, which is equivalent to placing a higher value of mass of fissile fuel in the outer zone and a lower value in the inner zone. The PF values used were 0.30, 0.35 and 0.40.

Calculated TRISO particle lattice pitch values for a body-centered square lattice for the used values of PF are given in Table 3.

Table 3. TRISO particle lattice pitch values.

PF	TRISO particle lattice pitch (cm)
0.30	0.1288
0.35	0.1224
0.40	0.1170

The core compositions studied were inner zone with PF 0.30 and outer 0.35 (Z1-0.30 and Z2-0.35), and 0.35 inner and 0.40 outer (Z1-0.35 and Z2-0.40). The results were compared with the standard composition of a single PF value (Z1-0.30 and Z2-0.30). Table 4 shows the Keff values and their SD in pcm at BOC for each case, the fuel cycle length values in EFPD, and the final burnup values, averaged for the full core and averaged for each zone.

Table 4. Main parameters of fuel cycles for two-zone cores.

Parameters	Z1-0.30 and Z2-0.30
Keff BOC ± SD (pcm)	1.30643 ± 27
Length fuel cycle (EFPD)	1200
Total burnup EOC (MWd/kgU)	58.00
Inner zone burnup EOC (MWd/kgU)	69.63
Outer zone burnup EOC (MWd/kgU)	39.39

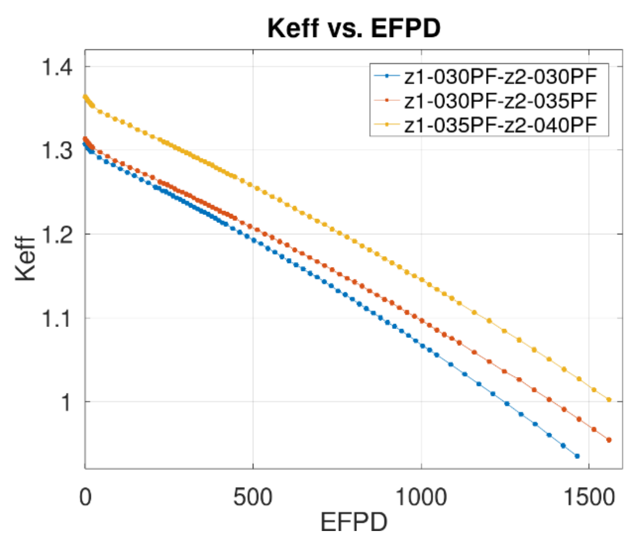

Figure 5. Keff vs. EFPD for different core compositions with two zones.

Figure 5 shows the Keff dependence of the EFPD for the studied compositions. The thermal power considered was the standard value for the updated design of 65 MWth.

In relation to the standard composition with PF of 0.30, an increase of 340 EFPD is observed for the composition Z1-0.35 and Z2-0.40 and of 120 days for Z1-0.30 and Z2-0.35, which corresponds to the additional amount of fuel fissile placed in the reactor core. However, in the case of the composition Z1-0.30 and Z2-0.35, the initial reactivity value in the hot state to be compensated is slightly higher than that of the reference composition. For composition Z1-0.35 and Z2-0.40 this value increases by approximately 18 %.

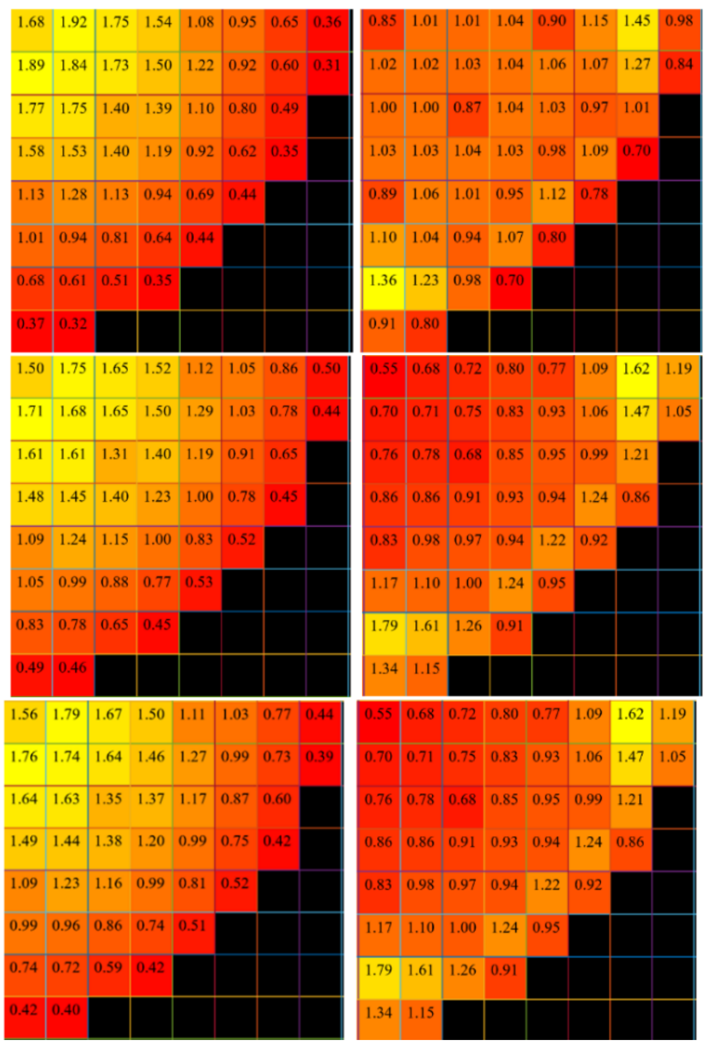

Figure 6. Radial power distributions at BOC and EOC for the different reactor core compositions. Up to down: a) Z1-0.30 and Z2-0.30 (BOC and EOC) b) Z1-0.30 and Z2-0.35 (BOC and EOC) c) Z1-0.35 and Z2-0.40 (BOC and EOC)

Table 5 shows that for the composition Z1-0.30 and Z2-0.35, a final burnup value of the fuel discharged in the inner zone is obtained, that is slightly higher than that corresponding to the composition standard (Z1-0.30 and Z2-0.30), although they have the same initial composition. This means an advantage of composition Z1-0.30 and Z2-0.35 compared to the reference one. For the outer zone in Z1-0.30 and Z2-0.35 case, it is observed, as expected, that the burnup value increases when the PF increases; the increase in the burnup value is almost linear with respect to the increase in the PF value. In the case when the PF value goes from 0.30 to 0.35 (Z1-0.35 and Z2-0.40) in the inner zone, an increase in the burnup value of the discharged fuel of 18 % is obtained.

For the outer areas of the compositions analyzed, when comparing the final burnup value when going from PF 0.30 to 0.35, it increases by 14 %, and when changing from 0.35 to 0.40 it increases by 18 %. On the other hand, the increase in the value of the average total final burnup of the discharged fuel when comparing the case Z1-0.30 and Z2-0.30, and the case Z1-0.30 and Z2-0.35, is only 2 MWd/kgU. However, for the case Z1-0.35 and Z2-0.40 it increases by 10 MWd/kgU with respect to the standard case. This greater increase is explained by the larger number of FAs located in the interior zone (97) with respect to the exterior zone (60).

Figure 6 shows the radial power distributions at BOC and EOC for the compositions studied with two zones of the reactor core.

For the case Z1-0.30 and Z2-0.35, where a greater amount of fuel is placed in the outer zone, a lower maximum value of the radial peak factor is obtained, which indicates a flatter radial power distribution. This is because the concentration of the fissile fuel increases with the radius of the core.

For the case Z1-0.35 and Z2-0.40, the behavior of the radial power distribution is similar to that of the composition Z1-0.30 and Z2-0.35, although the maximum values of the radial peak factor are a little higher, and are found located in FA of the outer zone with a border to FA of the inner zone.

III.4. Analysis for a reactor core with three zones

For this analysis, the fuel cycle was studied for a core with three different compositions, with PF values in the inner zone of 0.30, an intermediate zone with 0.35 and an outer zone with 0.40. (Z1-0.30 - Z2-0.35 - Z3-0.40). In Figure 4 it was shown the layout of FAs in the core: 60 FA in the outer zone with PF equal to 0.40 (orange), 72 FA in the intermediate zone with PF equal to 0.35, (blue), and 25 typical FA with PF equal to 0.30 in the interior area (yellow).

The fuel cycle for the three-zone core was compared to the standard single-zone fuel cycle with PF equal to 0.30. Figure 7 shows the dependence of Keff vs EFPD for the two cases analyzed.

Table 5 shows the Keff values and their SD in pcm at BOC for each case, the fuel cycle length values in EFPD, and the final burnup values, averaged for the full core and averaged for each zone for the reactor core with three zones.

When comparing the composition of the core with three zones with different PF values (0.30 inner, 0.35 intermediate and 0.40 outer) with the composition of only one PF value (0.30) it is observed that an increase in the length of the fuel cycle of 550 EFPD, with an increase in the final value of the average burnup of 10 MWd/kgU.

The average burnup value of the outer zone is lower than the total average burnup value but higher than the average value of the outer zone of the two-zone core, case Z1-0.35 and Z2-0.40.

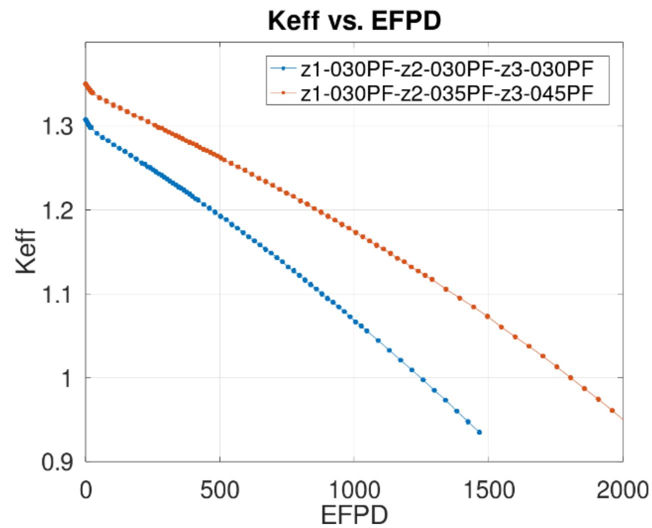

Figure 7. Keff vs. EFPD for different core compositions with three zones.

Table 5. Main parameters of fuel cycles for three-zone cores.

Parameters	Z1-0.30-Z3-0.30
Keff BOC ± SD (pcm)	1.30609 ± 26
Length fuel cycle (EFPD)	1200
Total burnup EOC (MWd/kgU)	58.00
Inner zone burnup EOC (MWd/kgU)	73.71
Intermediate zone burnup EOC (MWd/kgU)	66.97
Outer zone burnup EOC (MWd/kgU)	41.079

In Figure 8 it is observed that at BOC the maximum radial peak factor is located in an FA located in the intermediate zone of the core, and is a lower value (1.47) than that obtained for a single composition (1.92), or those obtained for two zones with different compositions (1.75 for two zones 0.30-0.35) and (1.79 for two zones 0.35-0.40).

At EOC for the three-zone composition, a maximum value of the radial peak factor of 1.73 was obtained and is located in an FA of the peripheral zone. That value is higher than that obtained for a single composition (1.45), and of the order of the values obtained for the cases with two zones with different compositions (1.79).

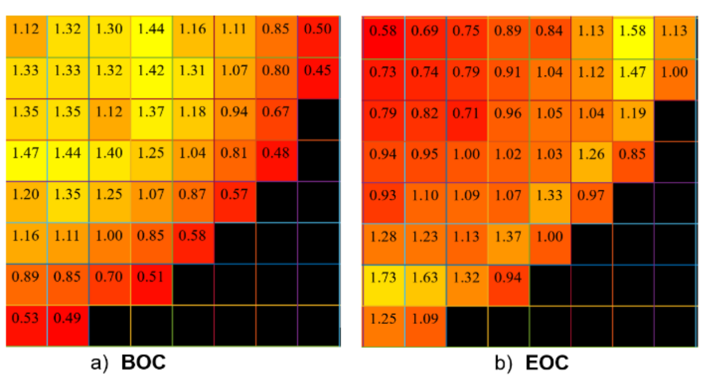

Figure 8. Radial power distribution at BOC and EOC for the core with three-zone composition, PF values of 0.30, 0.35 and 0.40 in the inner, middle, and outer zone respectively.

IV. CONCLUSION

An increase in the thermal power value produces a considerable decrease in the duration of the extended fuel cycle of the proposed SMR, compared to the case of 65 MWth. In the case of a power value of 80 MWth it is reduced by 225 EFPD, while in the case of a value of 100 MWth it is reduced by 425 EFPD. A detailed thermo-hydraulic analysis is necessary to justify the use of higher power density values in the proposed SMR.

For core compositions using a PF value larger than the standard value of the proposed conceptual design, a considerable increase in fuel cycle length was obtained. For the case of a reactor core with two zones Z1-0.30 and Z2-0.35, the cycle duration was increased by 120 EFPD, and for the case Z1-0.35 and Z2-0.40, by 340. In both cases, a radial power distribution similar to the one of the standard case was obtained.

For the case Z1-0.35 and Z2-0.40, the value of the final average burnup of the discharged fuel increased by 12 MWd/kgU with respect to the reference composition.

In the case of three zones with different PF values (Z1-0.30 - Z2-0.35-Z3-0.40), an increase in the duration of the fuel cycle of 550 EFPD was obtained, with a value of the final burnup that increases by 10 MWd/ kgU in relation to the reference case. Furthermore, the power radial distribution at BOC is flatter than in the reference case, although the value of the maximum peak factor at EOC increases to approximately 1.7.

New studies must be done to complete the analysis of the neutronic physical characteristics of the proposed cores, such as the study of the management of excess reactivity using burnable poisons and the calculations of the control rods worth, among others.

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