CONCEPTUAL DESIGN UPDATE OF A SMALL MODULAR REACTOR CORE USING TRISO FUEL

ACTUALIZACIÓN EN EL DISEÑO CONCEPTUAL DEL NÚCLEO DE UN REACTOR MODULAR PEQUEÑO USANDO COMBUSTIBLE TRISO

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In recent years, the design of new prototypes of small modular reactors has generated a growing interest in the international scientific community. Their applications and versatility make them an attractive option among candidates considered in generation III+ and IV. The use of TRi-structural ISOtropic fuel (TRISO) in integral pressurized water reactors (iPWR) constitutes a challenge to achieve extended fuel cycles. To obtain high proliferation resistance, extended fuel cycles for the iPWRs have been proposed. Obtaining such a large cycle length, using low fuel enrichment, without shuffle, and with a relatively small core size, is a challenge for the neutronic design of the reactor core. Previous works have analyzed the characteristics of an iPWR using TRISO fuel with a power of 25 MWt. In this work, a full-core neutronic computational model based in SERPENT code was developed, allowing to describe the performance of the proposed reactor core configurations. The core neutronic update is made with the aim of increasing the thermal power. The radial power distributions, fuel cycle length and other parameters for the different variants are analyzed and compared.

En los últimos años, el diseño de nuevos prototipos de reactores modulares pequeños ha generado un creciente interés en la comunidad científica internacional. Sus aplicaciones y versatilidad los convierten en una opción atractiva entre los candidatos considerados en la generación III+ y IV. Por otro lado, el uso de combustible tipo TRISO en reactores integrales de agua a presión (iPWR) constituye un desafío para lograr ciclos de combustible extendidos. Para obtener una alta resistencia a la proliferación, se han propuesto ciclos de combustible extendidos para los iPWR. Obtener una longitud del ciclo tan grande, utilizando un bajo enriquecimiento de combustible, sin mover los conjuntos combustibles y con un tamaño del núcleo relativamente pequeño es un desafío para el diseño neutrónico del núcleo del reactor. Trabajos previos han analizado las características de un iPWR que utiliza combustible TRISO con una potencia de 25 MWt. En este trabajo, se desarrolló un modelo computacional neutrónico del núcleo completo basado en el código SERPENT, que permitió simular el desempeño de las configuraciones del núcleo del reactor propuestas. La actualización neutrónica del núcleo se realiza con el objetivo de aumentar la potencia térmica. Se comparan las distribuciones de potencia radial, la duración de los ciclos de combustible y otros parámetros, para las diferentes variantes analizadas.

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I. INTRODUCTION

The study of small modular reactors (SMR) has recently attracted a growing interest in the international scientific community. SMRs are characterized by their diverse applications and versatility, making them an interesting option among the possible candidates for Generation III+ and IV of new nuclear reactors.

The analyses of the performance of SMRs both for energy production and other applications is at the cutting-edge of nuclear energy due to the potential it represents in terms of safety, economy and energy flexibility.

Additionally, the use of TRISO fuel in PWR type reactors opens new possibilities in nuclear energy production. Each TRISO particle has a kernel where fuel is located. The kernel is surrounded by three layers of carbon and ceramic-based materials that prevent the release of radioactive fission products. TRISO fuels are structurally more resistant to neutron irradiation, corrosion, oxidation and high temperatures than traditional reactor fuels. Specifically, its use in iPWR type modular reactors constitutes a challenge to obtain extended fuel cycles. One of the goals of the design of SMR is to achieve extended fuel cycle lengths, greater than the duration of the fuel cycles of standard nuclear reactors, which allows an increased proliferation resistance.

Previous works have analyzed the characteristics of an iPWR reactor using TRISO fuel with a power of 25 MWt. The main design features of this reactor are presented in [1,2].

In [2] a neutronic analysis was performed for a two effective full power years' operating cycle of a small PWR using TRISO fuel with a novel composition. The theoretical investigation of the use of TRISO fuel particles in PWR assemblies was originally reported in [3], where graphite was used as a moderator in a light water cooled PWR.

In [1], it was proposed a core design capable of operating for approximately four effective full power years (1400 days) without needing refueling. The influence of some design parameters of the TRISO fuel (packing fraction –i.e, the volumetric fraction that TRISO particles occupy within the encapsulation material– enrichment, and kernel radius) on the effective neutron multiplication factor (Keff) value was evaluated and a 2n multifactorial analysis was performed.

In [4], the neutronic performance of the SMR of 25MWt PWR-type, using Thorium in TRISO fuel in the form of duplex configuration was studied, considering 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 very good neutronic performance of the proposed SMR of 25MWt PWR-type allows redesigning the core to achieve higher thermal powers while maintaining the same power density.

In this work, the neutronic redesign of the reactor core is analyzed with the aim of increasing the thermal power. The core is redesigned by increasing the axial and radial dimensions and both. The radial power distributions, the length of the cycles and other parameters for the different variants analyzed are compared. A computational model based on the Serpent code was developed to simulate the neutronic behavior of the reactor core designs.

II. MATERIALS AND METHODS

The reference reactor core is the SMR 25 MWt iPWR-type studied by other authors [1, 2, 5]. The distribution of fuel assemblies and fuel rods is depicted in Fig. 1. The reference core is composed of 89 fuel assemblies (FA), with the rods located in four different patterns. The design has 45 control rods to reduce the peak power factor, also help to keep the uniformity in fuel burnup, neutron flux, power distributions and the control of the reactivity. The diameter of the reference reactor core is 220 cm, with an active height of 150 cm. The core has three reflectors: a radial one composed of beryllium with a thickness of 8 cm and two axial ones of water with a thickness of 10 cm.

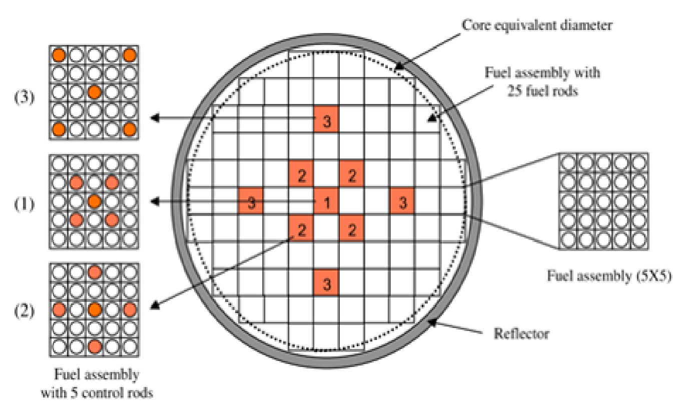

Figure 1. Schematic of the reference reactor core. The main reference design characteristics are summarized in Table 1.

Table 1. Reference core design parameters.

Parameter	Value/Unit
Power	25 MWth
Core height	150 cm
Core diameter	220 cm
Fuel pitch	3 cm
Fuel rod diameter	2 cm
Zircaloy Clad thickness	0.15 cm
No. of assamblies	89
Pattern	5x5
No. of control rods	45
Packing fraction	30 %
Enrichment (by weight of U-235)	15 %

The code used to perform the neutronic simulation of the core is Serpent, version 2.1.27 [6]. This is a multi-purpose, three-dimensional continuous energy Monte Carlo particle transport code. It is used to perform neutronic calculations like eigenvalue, burnup, fuel cycles, etc. Detailed information on the possibilities of the Serpent code can be found at [6–8]. Evaluated data files like JEF-2.2, JEFF-3.1, JEFF-3.1.1, ENDF/B-VI.8, and ENDFB/B-VII are included in the code. In the particular case of our work, the nuclear data library JEFF-3.1 was used.

To increase the thermal power of the core, first the influence of increasing axial dimensions of the core in Keff values was studied, maintaining the rest of the standard design parameters. The increase values in the axial dimensions of the core was chosen taking as reference height values of other SMR reactor cores of the iPWR type. Table 2 shows the Keff values at the beginning of the life (BOL) for the different values of the analyzed core height.

Table 2. Keff values vs. core height, keeping constant the number of FA (89).

Cases	Core height (cm)	Initial Keff
1	150	1.28915 ± 0.00031
2	160	1.29182 ± 0.00031
3	170	1.29388 ± 0.00030
4	180	1.29729 ± 0.00028
5	190	1.29878 ± 0.00027
6	200	1.30007 ± 0.00028
7	210	1.30175 ± 0.00027
8	220	1.30363 ± 0.00030

To accomplish burnup studies by increasing the thermal power, five configurations were studied, besides the reference one 89 FA and 150 cm in height, varying axial and radial dimensions of reactor core. Two cases of axial elongation, that of 190 cm in height and that of 220 cm in height were analyzed. In addition, the radial increase in the dimensions of the core was considered, increasing the number of FA to 121 and 157. This allowed us to analyze three more cases, one with 121 FA and 150 cm in core height, another with 157 FA and 150 cm in height, and one case where the core dimensions' increase axially and radially, this is 157 FA and 220 cm in core height.

The core thermal power was increased proportionally to the reactor core volume. The distribution of fuel assemblies and fuel rods is shown in Fig. 2 to the 157 FA and 220 cm core height case.

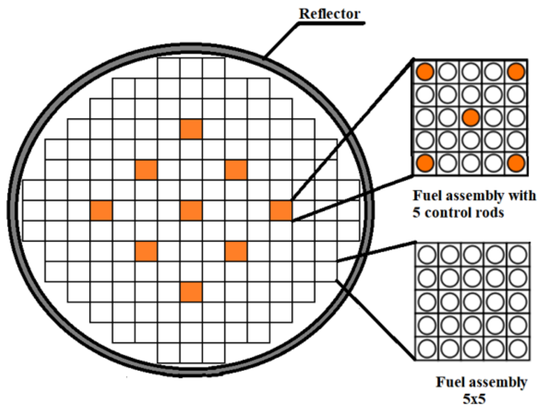

Figure 2. 157 FA and 220 cm core height case.

Table 3 gives the core volume values for the analyzed cases, as well as the thermal power values, pin total number, and the initial and final Keff values (with the standard deviation) for a burnup value of 60 MWd/THM (3.45 years).

Table 3. Main parameters of the different cases analyzed.

Cases	Volume of reactor core (cm^3)	Power (MWth)	No. of rods	Initial/Final Keff values ± S.D
Reference H=150 cm 89 FA	3003 750	25	2180	1.26354 ± 0.00057 1.00133 ± 0.00029
Axial elongation H=190 cm 89 Fa	3804 750	31.66	2180	1.27254 ± 0.00030 1.00849 ± 0.00027
Axial elongation H=220 cm 89 FA	4405 500	36.66	2180	1.27611 ± 0.00028 1.01312 ± 0.00027
Radial elongation H=150 cm 121 FA	4083 750	33.98	2980	1.28001 ± 0.00027 1.01729 ± 0.00028
Radial elongation H=150 cm 157 FA	5298 750	44.1	3880	1.29610 ± 0.00029 1.03138 ± 0.00024
Radial and axial elongation H=220 cm 157 FA	7771 500	65	3880	1.31011 ± 0.00026 1.03171 ± 0.00026

III. RESULTS AND DISCUSSION

The dependency of Keff vs. the working time at nominal power (effective full power day, EFPD) was compared for the different cases analyzed, in order to evaluate the fuel cycle length.

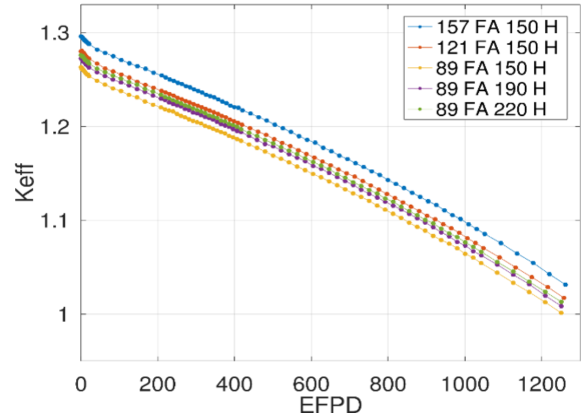

Figure 3. Keff vs. EFPD for different cases under analysis.

Fig. 3 shows that increasing the height of the reactor core slightly increases the value of initial reactivity, and the fuel cycle length, the same behavior is enhanced when the radius of the core is increased. The increment of the number of FA produces a larger increase in the fuel cycle length than the increase of the core height.

In Fig. 4 it is observed an increase of 150 EFPD in the fuel cycle length for the case of 157 FA and 220 cm of height compared with the reference case. Furthermore, it was obtained an increase of 40 MWth in the thermal power, representing 59 750 MWd of the energy produced.

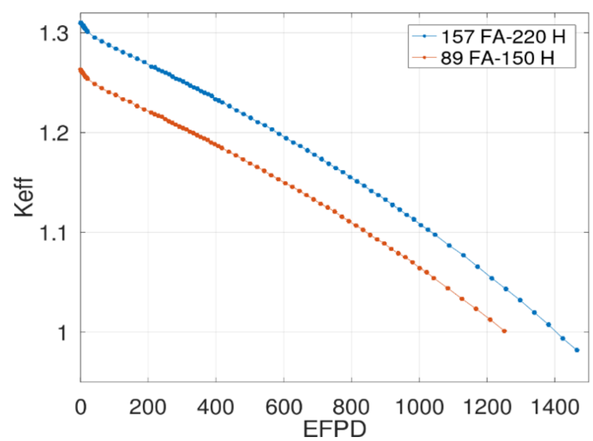

Figure 4. Keff vs. EFPD for 157 FA and 220 cm core height and reference case.

To analyze the released power distributions during the fuel cycles, Fig. 5 shows the radial peak factors distributions for the beginning and end of life states (BOL and EOL), for the analyzed cases. A symmetry of a quarter of the core was considered.

In all cases, there is a slight decrease in the maximum value of the peak factor between the beginning and the end of the fuel cycle. When the number of FA is increased, a greater non-uniformity in the radial distribution of the energy released is observed, which is consistent since all the FA have the same enrichment. Increasing the height of the core has little influence on the radial power distribution.

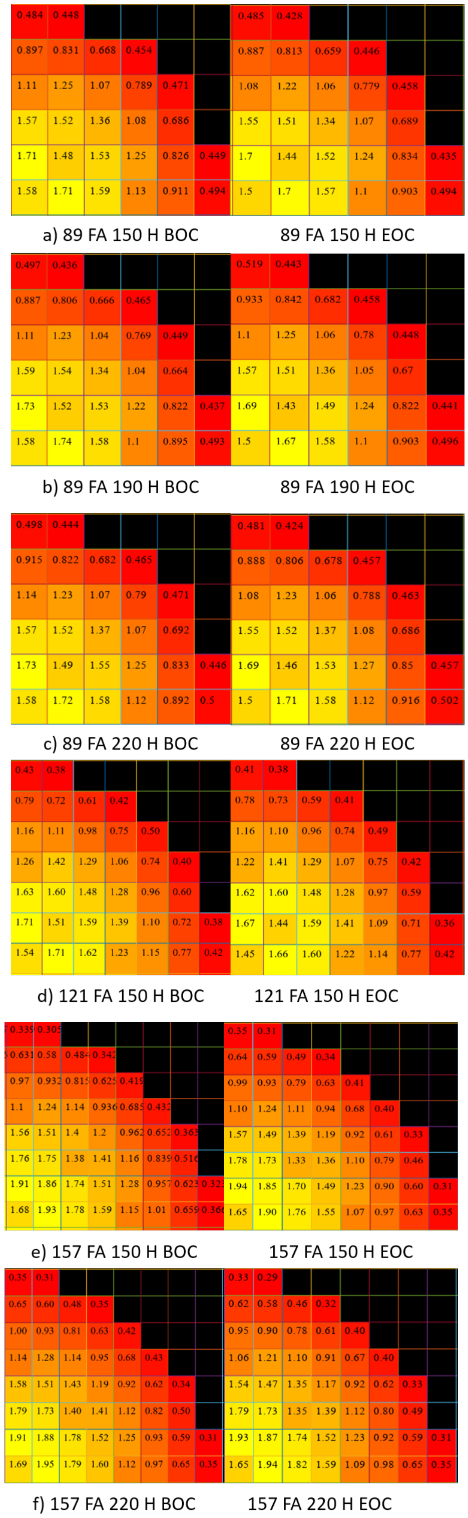

Figure 5. Radial power peak factors distributions for the analyzed cases.

IV. CONCLUSIONS

In this work, the neutronic behavior of a SMR of 25MWt PWR-type with TRISO fuel was studied with different configurations with the goal of increasing the core thermal power.

Several core design possibilities were analyzed, including the increase of the core height, the increase of the number of FAs keeping the standard height, and increasing the core height and radius. For the computational simulation of the fuel cycles, an increase in power proportional to the core volume was considered. Increasing the core axial dimensions does not considerably increase the thermal power or the fuel cycle length in relation to the reference case.

Increasing the core radius by incrementing the number of FA increases the length of the fuel cycle and the energy produced, however, it produces a greater non-uniformity in the radial power distribution.

An analysis using two fuel compositions for the central and peripheral zones of the reactor core, that guarantee an approximate length of 1400 EFPD should be carried out, in order to flatten out the radial power distribution for the axial and radial elongated cases.

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