COMPARISON OF THE NEUTRONIC BEHAVIOR OF A PWR TYPE SMR CORE USING CERMET AND TRISO FUEL

COMPARACIÓN EN EL DESEMPEÑO NEUTRÓNICO DEL NÚCLEO DE UN SMR DE TIPO PWR USANDO COMBUSTIBLE CERMET Y TRISO

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The use of non-conventional fuels in traditional Light Water Reactors (LWR) improves their performance in safety, as well as the characteristics of the fuel cycle. Using TRISO (Tristructural Isotropic) or SCF (Spherical Cermet Fuel) particles in a PWR-type (Pressurized Water Reactor) SMR (Small Modular Reactor) core enhances the proliferation resistance, fission products retention and greatly simplifies safeguards oversight. It has been shown that using TRISO fuel at low coolant temperatures can cause swelling induced by irradiation in the SiC barrier, so the use of another type of fuel without this issue and with equivalent neutronic performance to that obtained when TRISO fuel is used, may be more suitable for use in these types of plants. This work compares the neutronic performance of a PWR-type SMR core, using SCF particles with the same core using TRISO fuel in terms of burnup, spectrum, and radial power distributions. TRISO fuel has better multiplicative properties than SCF particles. Using SCF particles, the cycle duration decreases by approximately 8 %, a difference that is lower when the fuel mass is increased. The differences in the spectrum are higher in the thermal zone. The radial power distributions at the beginning of the cycle and at the end of the cycle are similar. Pu-239 production is higher when TRISO fuel is used.

El uso de combustibles no convencionales en los Reactores de Agua Ligera (LWR) tradicionales mejora el desempeño en seguridad, así como en las características del ciclo de combustible. Usando partículas TRISO (Tristructural Isotropic) o SCF (Spherical Cermet Fuel) en un SMR (Small Modular Reactor) de tipo PWR (Pressurized Water Reactor) mejora la resistencia a la proliferación, la retención de los productos de fisión y simplifica considerablemente la supervisión de salvaguardia. Se ha demostrado que con el uso del combustible TRISO a bajas temperaturas del refrigerante se puede producir un hinchamiento por irradiación en la barrera de SiC, por lo que el uso de otro tipo de combustible sin este problema y con un desempeño neutrónico equivalente al obtenido con el combustible TRISO puede ser más adecuado para este tipo de plantas. En este trabajo, se realiza una comparación en el desempeño neutrónico de un núcleo de un SMR de tipo PWR usando combustible SCF y el mismo núcleo utilizando combustible TRISO en términos de quemado, espectro y distribuciones radiales de potencia. El combustible TRISO presenta mejores propiedades multiplicativas que las partículas de SCF. Con el uso del combustible SCF, la duración del ciclo de combustible disminuye aproximadamente en un 8 %, siendo esta diferencia menor cuando aumenta la masa del combustible. Las diferencias en el espectro son mayores en la zona térmica. Las distribuciones radiales de potencia al inicio y final del ciclo son similares. La producción de Pu-239 es mayor cuando se utiliza combustible TRISO.

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I. INTRODUCCIÓN

The study and development of SMR worldwide has had high growth in recent years. Currently, the cost of large nuclear plants ($kW) has grown greatly due to the necessary improvements in terms of safety and performance, thus only a few manufacturers remain in operation. In addition, the time between the signing of the contract and the start of energy production exceeds ten years. SMR technology emerges as a solution to many of these issues in nuclear power today: it has many similar design features to previous designs, reasonably short construction times, and greater design simplicity. Besides, they can be used and designed for different purposes such as energy production (Light Water Reactor type), as well as for applications such as reproduction, and waste management. The latter uses different types of coolants and fuels in their designs and are implemented for a longer term [1]. Most SMR manufacturers are not present in the large nuclear power plant market and newcomers to the nuclear power plant market have joined to bring SMRs to the world market. Moreover, many countries with emerging economies cannot afford the implementation of large nuclear plants, but they can compete in the SMR market.

The construction of SMRs for short-term energy production are mostly LWR type, taking into account the accumulated operating experience, and the reliability and performance presented for this kind of reactors. In order to increase the safety levels of PWR-type SMRs, several types of fuels have been studied, as is the case of TRISO fuel. TRISO particle is comprised of an inner sphere where fuel is located called "kernel", and four more layers: one layer of porous carbon (Buffer), two layers of pyrolytic carbon (IPyC and OPyC) and one layer of SiC. All TRISO particles are embedded in a matrix of SiC called "Packing Matrix". This fuel, originally designed for gas-cooled reactors, maintains its integrity at very high temperatures (up to 1600 °C), has an excellent performance in retaining fission products at high burnup levels and very high temperatures, as well as very good properties from the neutronic and thermohydraulic point of view [2–8]. The use of this type of fuel in a PWR-type SMR core allows the use of extended fuel cycles, increasing the safety levels of the core both in safe operation and in the event of an accident.

In several studies [7, 9–11], the performance of a PWR-type SMR core using TRISO fuel has been studied. This innovative core joins the design characteristic of PWR and gas-cooled reactors like moderator materials, enrichment, etc. Safety criteria like reactivity coefficients are met when TRISO particles are used in this core [12].

In [7], new studies are carried out on the conceptual design of a PWR-type SMR core, with TRISO fuel. Using a 2^n factorial design, some design parameters are optimized, such as enrichment, packing fraction, kernel size, to achieve an extended fuel cycle of approximately 1400 days. With the new configuration, the reactor can operate for 1,355 days in a critical state, reaching an average burnup of 65MW/kgU. In addition, temperature distributions are obtained in the zones of interest (fuel, clad, gap and coolant), which are well below the safe operation limits for this type of fuel. The reactor can operate without reaching the temperature limits established for safe operation even with a loss of coolant flow of 40 %.

However, it has been studied that using TRISO fuel at low coolant temperatures (about 260°C or below), the TRISO fuel particles may present a significant irradiation-induced swelling in the SiC coating outer layer of the particle during burnup [13, 14]. For reactors designed to work under these thermohydraulic conditions, another type of fuel is proposed, in which all the graphite layers are eliminated and the UO_2 kernels are embedded in a Zr matrix which is then coated with a protective outer layer of Zr to form the fuel assemblies [13,15]. SCF coated particles were proposed in [16] and presents good retention of fission products, low fuel temperatures, high conductivity at thermal energies and good performance at high burnup.

As can be seen in Table 1 the inlet coolant temperature designed for the reactor is 188°C and the outlet coolant temperature is 212°C. Therefore, the main goal of this work is to study the performance of a PWR type SMR core, with SCF particles and make a comparison with the results for the core using TRISO particles [7], in terms of burnup, spectrum, power distributions and temperature distributions.

The paper is organized as follows: in Section 2, the computational models used for the neutronic simulation of the core and the main parameters of the TRISO and SCF particles are presented. In Section 3 a comparison of the performance of the core using both fuel particles is performed and in Section 4 the conclusions of the work are summarized.

II. MATERIALS AND METHODS

The reactor's core simulated in our work is designed to maintain criticality for approximately 1400 days. It produces 25 MW of thermal power and have 45 control rods of hafnium to control the reactivity. The core has a radius of 110 cm and is surrounded by a beryllium reflector, which has an 8 cm thickness. The core also has two water axial reflectors of 20 cm of thickness each. As the fuel particles of TRISO and SCF have different sizes, a modification in the packing fraction must be made to obtain the same fuel mass at the beginning of the cycle. The main parameters of the core are summarized in Table 1 and Fig. 1 show the cross section of the fuel element using SCF and TRISO particles respectively. The rest of the material and geometric characteristics remain unchanged from those reported in [7]. SCF particles has a radium of 250 μm surrounded by a Zr layer of 25 μm of thickness to form a particle with a diameter of 550 μm [13,16]. The fuel element has a matrix of Zr of 0.97 cm of radium and an outer coating layer of Zr with a thickness of 0.03 cm.

Table 1. Most important parameters of the SMR core.

Parameter (Unit)	Value	Parameter (Unit)	Value
Pin diameter (cm)	2	Packing matrix material TRISO/SCF	SiC / Zr
Fuel	TRISO / SCF	Coolant	water
Enrichment (%)	15	Inlet / Outlet Temperature (C°)	188 / 212
TRISO / SCF packing fraction (%)	30 / 7.5	Flow mass (kg/s)	223.71
Particles per pin TRISO / SCF	220400 / 380852	Pressure (MPa)	6
Particle outer radius (cm) TRISO / SCF	0.0535 / 0.0275	Core height (cm)	150

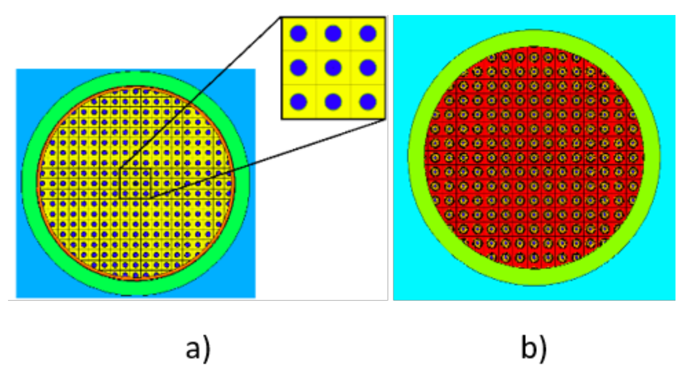

Figure 1. Cross section of the fuel element.

All simulations were carried out using the SERPENT code, Version 2.1.27. This code, based on probabilistic methods, allows the calculation of burnup, power distributions and fuel cycle analysis [17]. 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 are included in the code. Here, JEFF 3.1 library for the cross sections description for all the materials were used.

The use of probabilistic code is more suitable for this kind of problems due to the geometry complexity and the number of zones and materials to be simulated. All the calculations were made with 10,000 histories per cycle and 500 cycles, skipping the first 30, ensuring standard deviation values below 100 pcm in Keff.

Core simulation using random, hexagonal and cubic distributions of the TRISO particles inside fuel elements were made [18, 19]. According with this calculations, there are no significant differences in the results of Keff, power distributions, spectrum, using uniform distributions (Body-Centered Cubic (BCC) or Faced-Centered Cubic (FCC)) or a random distribution to simulate the TRISO particles inside the fuel elements on core scale. Furthermore, the cut effect given by the intersection of the fuel element surface and the TRISO particles surfaces was also analyzed, and the results were similar. According with this results, the use of a BCC lattice to simulate the TRISO particles inside the fuel rods was considered suitable.

III. RESULTS AND DISCUSSION

III.1. Burnup characteristics

The evaluation of multiplicative properties, for the whole core at the Beginning of Life (BOL) state, for both types of fuel was carried out. All calculations were performed for the same temperatures at the kernel and in the coating layers. For these conditions, an initial Keff of 1.25283 (24) using SCF, which is 1.36 % lower than the Keff value obtained using TRISO fuel (1.27004 (24)), reported in [7]. Fig. 2 shows the capture and elastic dispersion cross section for both packing materials.

It can be seen that SiC material has higher elastic dispersion cross sections and lower capture cross sections for almost all the studied energies. For these reasons, the reactor has better multiplicative properties using TRISO fuel particles compared with the reactor using SCF particles. The top subfigures of Fig. 3 show the neutronic spectrum for equal interval of lethargy at BOL and End of Life (EOL) states, and lower subfigures show the differences (%) of the flux values at the studied energies. Those differences were calculated using Eq. 1:

$$Difference(\%) = \frac{\phi(TRISO) - \phi(SCF)}{\phi(SCF)} \cdot 100 \qquad (1)$$

Where $\phi(TRISO)$ is the obtained flux value for a given energy, when TRISO fuel is used and $\phi(SCF)$ is the obtained flux value for the same energy, when SCF is used.

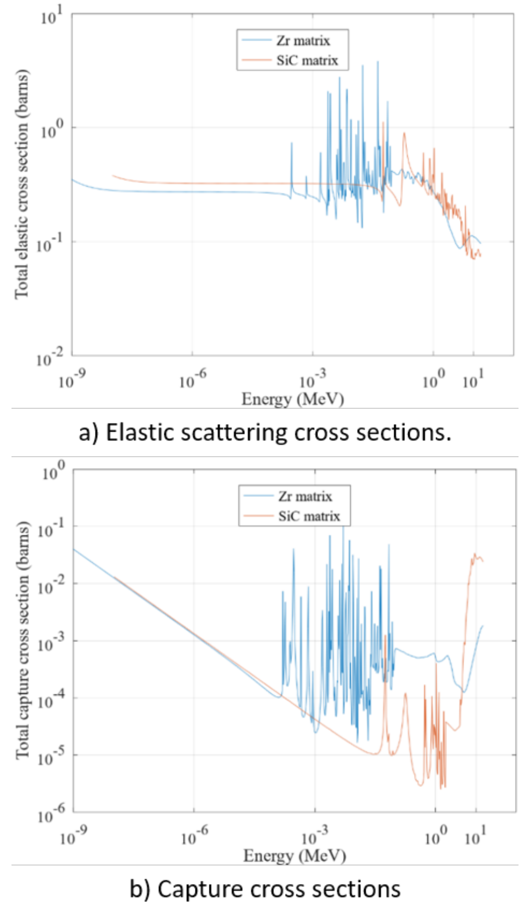

Figure 2. Microscopic cross sections for SiC and Zr.

This distribution of the relative differences has a positive trend to energies lower than 3e-7 MeV, meaning that the neutron flux is higher at those energies when TRISO fuel is used. In the region between 3e-7 MeV and 1 MeV, there is a change in the behavior of the neutron flux, having a negative trend in the differences. To higher energies, TRISO fuel presents a higher neutron flux.

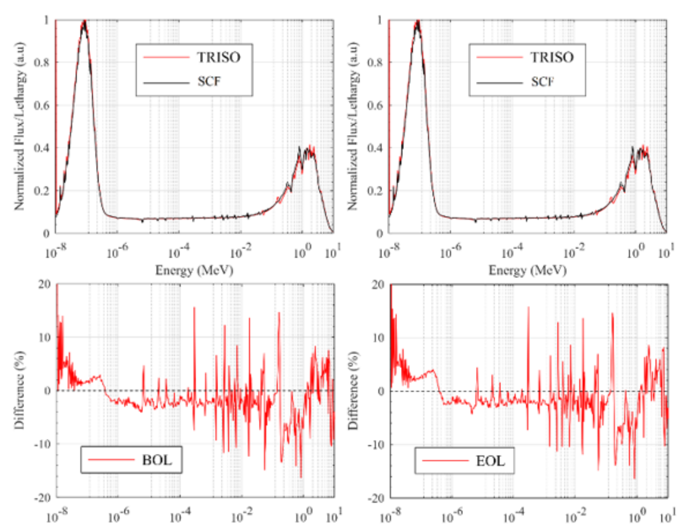

Figure 3. Core spectrum (Up) and spectrum relative differences (Down) for the BOL and EOL states.

of the masses of Pu-241 and U-235 are very similar.

This behavior at differences is the same in both, BOL and EOL stages. The results in this work are in agreement with those obtained in [13] a similar study, although the differences obtained in that work are higher.

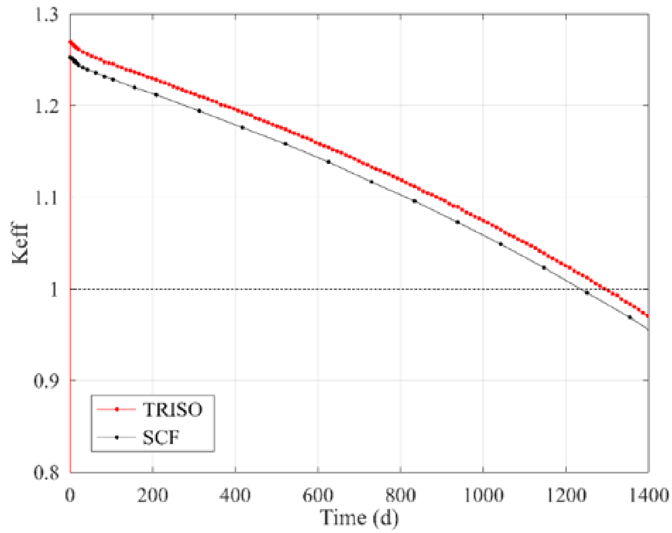

Figure 4. Keff variation along the operating time.

In Fig. 4, the variation of Keff along the operational time, for TRISO and SCF is shown. The operational time using TRISO fuel is approximately 1355 days, achieving a degree of burnup of 65 MWd/kgU. With the use of SCF, the operational time decreases in approximately 7 % (1265 d), achieving a degree of burnup of 60 MWd/kgU. This result is given by the fact that in the Zr matrix exists more absorptions without fission than in the SiC matrix, decreasing the neutron economy, and thus, Keff value. On the other hand, although the differences are slight, the Instantaneous Conversion Ratio (ICR) using TRISO fuel is higher than the one obtained for the SCF, as it is shown in Fig. 5, with a maximum difference of 8.75e-4 at 60MWd/kg. ICR takes into account the mass of U-233, Pu-239, Pu-241, and U-235 on each burnup step.

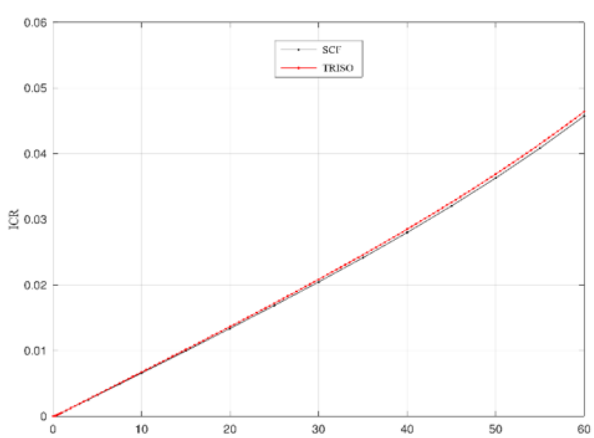

Figure 5. Keff variation along the operating time.

In Fig. 6, the variation of the masses of the main fissile isotopes considered in the ICR factor are shown. The isotopes which have higher differences are U-238 and Pu-239. The variation of the masses of Pu-241 and U-235 are very similar.

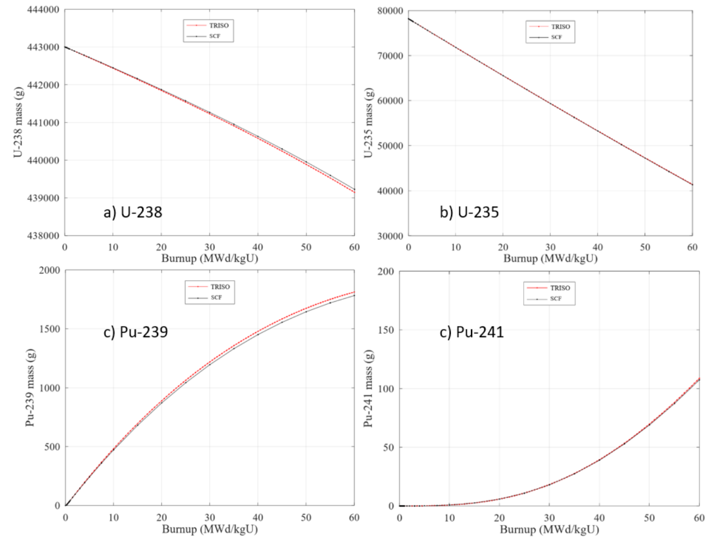

Figure 6. Mass variation of the main isotopes with burnup.

III.2. *Redesign calculations*

According to the previous results, using SCF does not achieve the cycle duration of approximately 1400 days. Assuming that the nuclear plant has a capacity factor of 0.95 (an assumption made for the core using TRISO fuel) [7], the cycle must have a duration of 1330 days. For this reason, the configuration of the core must be changed to achieve the established cycle duration. Taking into account that the fuel enrichment used is high, the first study made was the variation of the enrichment, keeping constant the amount of fissile material in the core. This can be achieved by increasing the number of fuel particles and therefore the packing fraction value.

Table 2. Cycle parameters for different enrichments using SCF.

Enrichment (%)	Packing Fraction (%)	Initial Keff. (S.D)	Burnup (MWd/kgU)	EFPD (d)
9	12.4	1.22405 (24)	35.0	1209.1
12	9.4	1.24055 (24)	51.9	1228.8
15	7.5	1.25283 (24)	60.0	1265

In Table 2 are presented the results of this study where it can be seen that a decrease in the enrichment of the fuel results in a decrease of the initial Keff value, a decrease in the Effective Full Power Days (EFPD) and therefore a decrease in the degree of burnup achieved. Thus, using a lower enrichment and more particles in the fuel element is not the solution to increase the EFPD.

To achieve the established cycle duration, the packing fraction was increased keeping constant the fuel enrichment of 15 %. The packing fraction for the SCF was increased to 8 %. With this new configuration, the core achieves a burnup degree of 65MWd/kgU, with a cycle duration of 1448 days. To evaluate the core performance with this new composition, a comparison with the core using TRISO fuel was made. Thus, the packing fraction for the core using TRISO particles was increased to obtain the same initial fuel mass. Table 3 shows the values of the cycle parameters for the new composition of the core. There is a difference in the cycle duration of barely 1 % and a difference in the burnup degree of 0.6 MWd/kgU which is lower than the differences obtained in the previous composition.

With the changes in the packing fraction, the spectrum becomes more similar between the two types of fuel, making the differences between them in the thermal zone less significant, as can be seen in Fig. 7.

Table 3. Cycle parameters for the two fuel types with the new configuration.

	Enrichment (%)	Packing Fraction (%)	Initial Keff. (S.D)	Burnup (MWd/ kgU)	EFPD (d)
TRISO	15	32	1.28719 (24)	65.6	1461
SCF	15	8	1.27555 (24)	65	1448

Radial power distributions at BOL state were calculated for each type of fuel, and the distributions of the produced power are very similar, with a maximum value of the radial peak factor of 1.80 (Fig. 8). This value is high compared with the power peak for a PWR's core. But this value does not represent a limitation from the thermohydraulic point of view, taking into account that in [7] a value of 1.78 was obtained, and with this value, the core can withstand up to 40 % of loss of coolant without reaching the limit temperature value for safe operation.

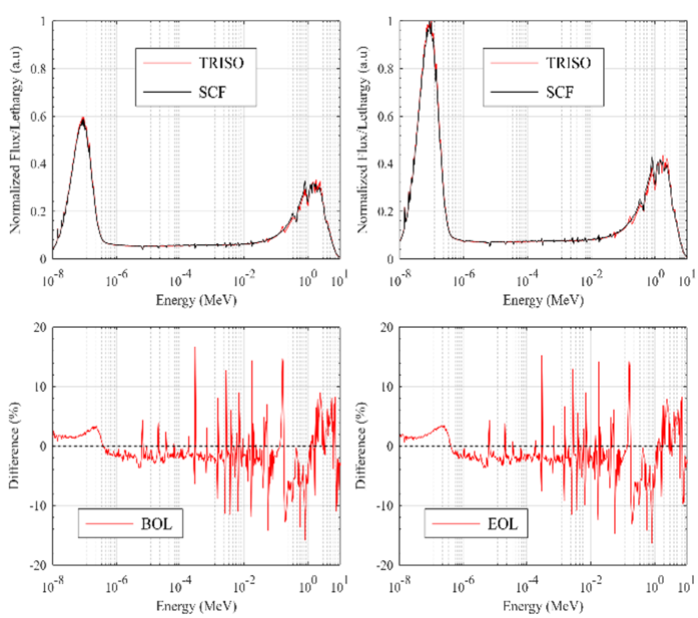

Figure 7. Core spectrum (Up) and spectrum relative differences (Down) for the BOL and EOL states (Redesigned core).

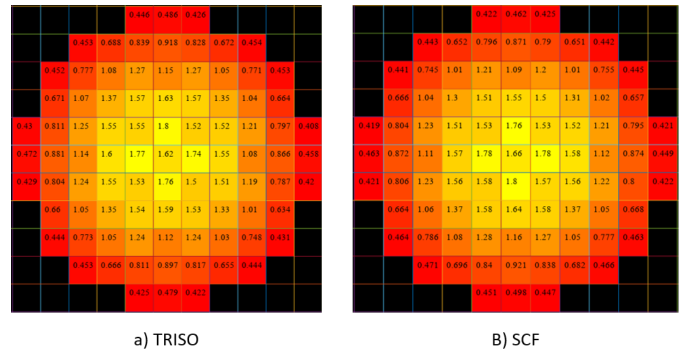

Figure 8. Radial power distributions at BOL state.

IV. CONCLUSIONS

A comparison of the neutronic performance of a PWR-type SMR core using both, TRISO and SCF particles was made. With the initial configuration, a lower value of Keff was obtained using SCF particles. The fuel cycle duration decreases by 7 % compared with the core using TRISO particles. That is given by the better moderation properties of the SiC packing matrix, compared with the Zr packing matrix. ICRs are very similar in both cases. As the cycle duration using SCF particles does not fulfill the requirements of design, a modification was made in the initial configuration. Since a decrease in the enrichment with a higher packing fraction does not increase the cycle duration, the packing fraction value was increased from 7.5 % to 8 %, with 15 % of enrichment. With this change, the cycle duration using SCF particles can achieve 1448 days and the differences in the core performance using both fuel particles are lower. Using SCF, the core has good neutron performance and meets the design goals. According to these results and the study of the thermohydraulic behavior, its use in this reactor may be more suitable than TRISO, since it does not present the structural problems of the latter.

Future works in this topic are carried out in order to evaluated the performance of the core, based on a coupled neutronic and thermohydraulic study of the critical assembly, safety coefficient calculations and reactivity control mechanisms.

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