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ADVANCES IN CONCEPTUAL DESIGN OF A GAS-COOLED ACCELERATOR DRIVEN SYSTEM (ADS) TRANSMUTATION DEVICES TO SUSTAINABLE NUCLEAR ENERGY DEVELOPMENT

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ABSTRACT

The possibilities of a nuclear energy development are considerably increasing with the world energetic demand increment. However, the management of nuclear waste from conventional nuclear power plants and its inventory minimization are the most important issues that should be addressed. Fast reactors and Accelerator Driven Systems (ADS) are the main options to reduce the long-lived radioactive waste inventory. Pebble Bed Very High Temperature advanced systems have great perspectives to assume the future nuclear energy development challenges. The conceptual design of a Transmutation Advanced Device for Sustainable Energy Applications (TADSEA) has been made in preliminary studies. The TADSEA is an ADS cooled by helium and moderated by graphite that uses as fuel small amounts of transuranic elements in the form of TRISO particles, confined in 3 cm radius graphite pebbles forming a pebble bed configuration. It would be used for nuclear waste transmutation and energy production. In this paper, the results of a method for calculating the number of whole pebbles fitting in a volume according to its size are showed. From these results, the packing fraction influence on the TADSEAs main work parameters is studied. In addition, a redesign of the previous configuration, according to the established conditions in the preliminary design, i.e. the exit thermal power, is made. On the other hand, the heterogenity of the TRISO particles inside the pebbles can not be negligible. In this paper, a study of the power density distribution inside the pebbles by means of a detailed simulation of the TRISO fuel particles and using an homogeneous composition of the fuel is adressed.

1. INTRODUCTION

The current growth of the energy demand and the perspective of a great increment for the future, added to the exhaustion of the fossil fuels, have forced the world to look for new viable alternatives of energy production. The use of nuclear energy and the use of Hydrogen as energy vector are some candidates to play an important role in a future energy scenario. In spite of its undeniable advantages, nuclear energy presents four important inconveniences that limit its expansion and development nowadays: safety issues, high investment costs, Plutonium proliferation risk and long-lived radioactive wastes [9] . The sustainability of nuclear energy will depend on the capability of reducing the inventory of nuclear waste and its long-term radiotoxicity, maily dominated by the transuranic isotopes reamining on the spent fuel. The Generation IV of nuclear reactors is expected to solve the problems of the nuclear energy use and to increase its development possibilities. Very High Temperature Reactors (VHTR) are included in the Generation IV technologies. VHTR are under investigation due to their capability of reaching coolant outlet temperatures higher than 1000°C[3], which can be used to produce Hydrogen from heat and water by the thermo chemical iodine-sulfur (I-S) process, or from heat, water and natural gas applying the steam reformer technology. Moreover, the use of nuclear energy will allow a reduction of the greenhouse gases (GHG) emissions in the Hydrogen production process. Countries with quite nuclear energy development are investigating solutions for the nuclear waste disposal. Currently, the most ambitious option and the only capable to minimize the confinement periods is the total fuel reprocessing. With regard to this topic, the development of hybrid systems (ADS) is under investigation. In ADS, neutron cascades, initiated by spallation on heavy materials with medium energy protons (few hundred MeV), are used in a subcritical assembly to transmute the unwanted wastes into less harmful species. Current ADS designs suggest operating with an effective multiplication factor up to 0.95 to ensure subcritical operation under any circumstances and limited neutron source power [1]. One of the technologies that are under investigation for the use of TRISO (tristructural isotropic) fuel in VHTR and ADS is the spherical packing. This is the type of fuel used in pebbles bed reactors. These reactors can reach high burn-up levels due to the characteristics the fuel employed, based on ceramic materials with great potential for fission products retention. In pebble bed systems, the number of pebbles will depend on the way they are distributed inside the core. This is an important parameter in the study since the relation between the volume occupied by the fuel pebbles and the volume occupied by the coolant gas could affect Keff. In previous studies [1], the design of a Pebble-Bed Transmuter (PBT) was made. It is a subcritical system cooled by helium and moderated by graphite that uses as fuel small amounts of transuranic elements in the form of TRISO particles, confined in 3 cm radius graphite pebbles forming a pebble bed configuration. The PBT is a device designed for the transmutation of nuclear waste from the existing Light Water Reactors (LWR). In WONP, 2009, the conceptual design of a Transmutation Advanced Device for Sustainable Energy Applications (TADSEA), was presented [7]. It could be used for simultaneous nuclear waste transmutation and hydrogen generation. In this paper, the results of method for calculating the number of whole pebbles fitting in a volume according to its size are showed. From these results, the packing fraction influence in the TADSEA's main work parameters is studied. Also, a redesign of the previous configuration, according to the established conditions of the preliminary design, i.e. the exit thermal power, is made. Additionally, the simplified design of the plant's general scheme is carried out in order to guarantee core's outlet temperatures high enough for Hydrogen production. The coolant temperature profiles are obtained from the previously calculated power density distributions. Realized studies [10] have demostrated that the performance of this type of facilities is considerably influenced by the way its geometry is modelled within the Monte Carlo approach. The spatial and energy shielding of the neutron flux even in such small particles cannot be neglected for important isotopes which have high resonance cross sections as Pu^{240} and Pu^{241}. On the other hand, there are not studies of PBT which use a detailed simulation of the TRISO particles inside the core, and thouse studies are incapables to describe the shielding effects in the fuel.

2. MAIN PBT AND TADSEA CHARACTERISTICS

The PBT is the main precedent of this work. It is a subcritical system cooled by helium and moderated by graphite that uses as fuel small amounts of transuranics elements diluted in the form of TRISO particles in a graphite matrix, forming a pebble bed configuration. The PBT is a device designed for the transmutation of the nuclear waste from the existing LWR power plants. The initial fuel loaded in PBT includes Plutonium and Minor Actinides in a proportion similar to the existing in the typical spent fuel from LWRs with a burnup of 40 MWd/Kg and after 15 years of radioactive cooling in the plant pools. The core of the PBT is composed by a cylinder containing 20 layers of pebbles disposed in a honeycomb (cubic face-centered) way. The pebbles stand over the holes of the layer immediately below (Figure 1). The central part is occupied by the spallation target that allocates a eutectic lead-bismuth in molten state. The system is maintained by a proton accelerator with beam energy of 380 MeV and intensities close to 10 mA. PBT thermal power is 10 MW at the stationary state. Fuel is confined in 3 cm radius pebbles, with an external layer of 5 mm thickness of pyrolithic graphite, and the remaining 2.5 cm sphere is filled up with TRISO particles of 1 mm diameter containing the fuel in a structure that includes an external isotropic pyrolithic graphite layer, a SiC barrier, an inner isotropic pyrolithic graphite layer and, at the center, a buffer composed by a porous pyrolithic graphite.

In the present work, the study of a Transmutation Advanced Device for Sustainable Energy Applications (TADSEA) is addressed. The TADSEA, like PBT, is a pebble bed ADS cooled by Helium that uses as fuel transuranic elements confined in the form of TRISO particles [4]. With the goal of producing Hydrogen from water and heat in view of the big amounts of Hydrogen required in a future energy scenario, it is important to increase the TADSEA's thermal power as much as possible. Optimal thermal power values for this type of

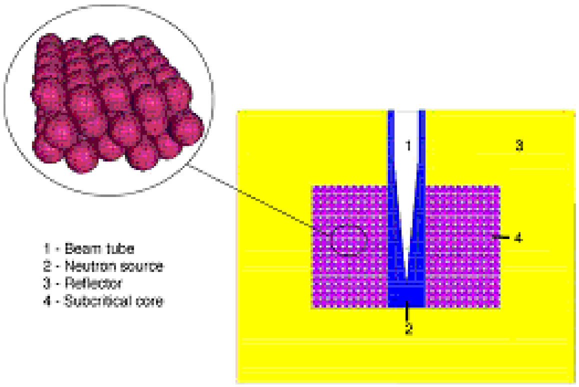


Figure 1: **Sketch of the Pebble Bed Transmuter (PBT).**

systems are between 80 MW y 100 MW [12]. The maximum permitted power density value for this type of systems is around 7 W/cm3 [13], which represents a thermal power of 100 MW for the TADSEA. To obtain the selected value of 100 MW, the proton beam characteristics of the PBT have been increased up to the limits expected in the technical development of accelerators in the near future: 1 GeV and 10 mA. On the other hand, core's geometrical dimensions have been enlarged maintaining the maximum permitted average power density value of 7 W/cm^3, which is possible from a technical point of view. The PBT fuel composition per ball, the transmutation capabilities of the system and the shape of the power density profiles were also conserved. In [7], the TADSEA's preliminary conceptual design was presented. Other preliminary results have been published and presented in some international scientific events [5], [6], [7].

3. THE GEOMETRY OF THE TADSEA

Pebble bed reactors present several operational and safety advantages. Main advantages are the possibility of continuous refueling without plan operation interruption and the efficient fission products retention [2], [1]. In pebble bed systems, the number of pebbles held inside the core, and therefore, the relation between the volume occupied by the balls and the volume occupied by the coolant, which is called 'packing fraction', depend on the way that pebbles are disposed. The packing fraction is an important parameter in the present study since it could affect Keff. The highest packing fraction value in an infinite bed, 0.7405 [13], was selected for the TADSEA's core design. The main design parameters of the PBT and TADSEA analyzed along this section, are summarized in Table 1.

4. PACKING FRACTION OF A PEBBLED BED

The spherical packing density is defined as the spherical volume fraction within an infinite bed. Specifically in the reactor core, it is the fraction of fuel volume into the core's volume. In sphere packing theory, there are three different main models (Figure 2): simple cubic packing, face-centered cubic packing, and hexagonal close packing [14].

For the TADSEA's model, a face-centered cubic packing was assumed. In this case, each layer is composed by spheres forming equilateral triangles. The spheres of each layer lay on the holes formed by the spheres of the layer immediately below. The maximum packing fraction value of an infinite bed is 0.7405, and corresponds to face-centered cubic packing and hexagonal close packing. [14]. In practice it is impossible to obtain that packing fraction because it is very difficult to perform an ordered configuration, like in theory, and in the case it could be performed, it would not be an infinite bed since the core is a container with finite dimensions. Therefore, the ideal configuration assumed in previous works to obtain the power profiles and Keff behavior, is reconsidered, and the influence of a lower packing fraction on the device's main design parameters is analyzed.

Table 1: **Main parameters of PBT and TADSEA.**

Parameter	PBT	TADSEA
Accelerator power (MW)	3.8	10
Proton beam intensity (MeV)	380	1000
Proton beam energy (mA)	10	10
Internal radius (cm)	15.75	15.50
External radius (cm)	75.75	125.75
Height (cm)	97.98	293.94
Total volume (m^3)	1.69	14.38
Fuel volume (m^3)	0.0016	10.64
Fuel mass (Kg)	14.64	124.50
Number of balls	11064	94092
Packing fraction	0.74	0.74
Keff	0.84	0.94
Thermal power (MW)	10	100
Average power density (W/cm^3)	6	7
Reflector thickness (cm)	60	60

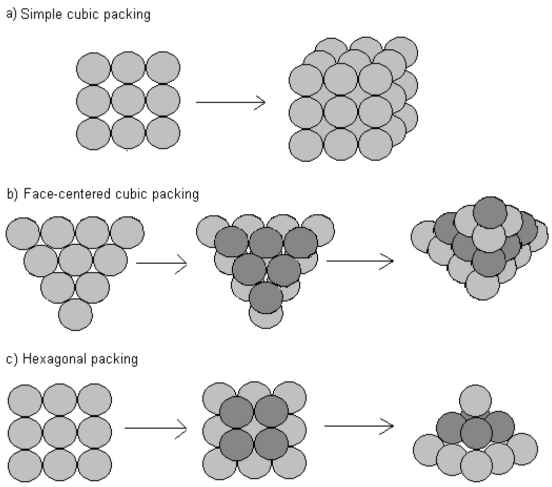


Figure 2: **Three dimensional arrangements for identical balls.**

5. CALCULATION OF THE NUMBER OF BALLS FITTING IN CERTAIN GEOMETRY

In this section, the results of an analytical method to calculate the number of ball fitting inside two concentric cylinders, forming a face-centered cubic packing, are shown. As mentioned above, the face-centered cubic configuration consists in layers of balls placed on the holes formed by three balls of the previous layer. The number of layers is given by:

$$L = \frac{\sqrt{6}}{2}\left(\frac{H}{2r} - 1\right) + 1, \tag{1}$$

Where H is the core's height and r is the ball's radius. If L is an even number, the total number of balls inside the core is $N = \frac{L}{2}(N_1 + N_2)$, and if it is an odd number, $N = \frac{1}{2}\left[N_1(L+1) + N_2(L-1)\right]$. Here, N_1 and N_2 are the number of balls of the lowest layer and the number of balls of the layer placed over the lowest one:

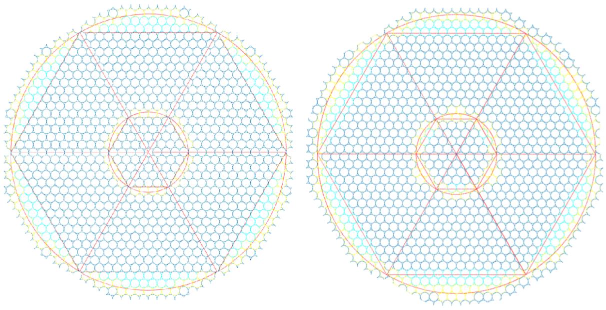


Figure 3: **The lowest layer and the layer immediately above.**

$$N_1 = N_{1H} + N_{1ECin} - (N_{1ICin} + N_{N1ICcut}) \quad (2)$$

$$N_2 = N_{2H} + N_{2ECin} - (N_{2ICin} + N_{2ICcut}) \quad (3)$$

N_H is the number of balls fitting between the hexagons inscribed in the external and internal circumferences, N_{ECin} is the number of balls inside the circular segments formed by the external circumference and the inscribed hexagon, N_{ICin} is the number of balls fitting inside the internal circumference and N_{ICcut} is the number of balls cut by the internal circumference. Subscripts '1' and '2' refer to the lowest layer and the layer immediately above, respectively.

In Figure 3 , the lowest layer (first layer) and the second layer of two concentric cylinders are shown. Also, the balls fitted inside the hexagons inscribed in the external and internal circumferences are represented in dark blue, the balls inside the circular segments formed by both circumferences and both hexagons, are represented in light blue, and the balls cut by both circumferences are represented in yellow.

To calculate N_{1H} and N_{2H}, the following equations are used:

$$N_{1H} = 3(n_{ext}^2 - n_{int}^2 + n_{ext} - n_{int}) \quad (4)$$

$$N_{2H} = 3(n_{ext}^2 - n_{int}^2 - 2n_{int} - 1) \quad (5)$$

In these formulas, n_{ext} and n_{int} are integer numbers given by: $n_{ext} = \frac{1}{2}\left(\frac{R_{ext}}{r} - 1\right)$ and $n_{int} = \frac{1}{2}\left(\frac{R_{int}}{r} - 1\right)$, where R_{ext} and R_{int} are the radii of the external and internal circumferences respectively. The formulas for calculating N_{ECin}, N_{ICin} and N_{ICcut} are not shown in this paper due to space constraints. Adapting the described method to the calculation of the number of pebbles fitting in the TADSEA, the core corresponds to the external cylinder and the spallation target to the internal cylinder. The total number of pebbles in the TADSEA is 82401, corresponding to a packing fraction value of 0.648.

6. INFLUENCE OF THE PACKING FRACTION ON THE THERMAL POWER GENERATED IN THE CORE

The study was performed for three core states: the initial load (IL) of fuel in the TADSEA, the beginning of the stationary fuel cycle (BOC) and the end of the stationary fuel cycle (EOC). The fuel composition used for the steady state was obtained in [11].

The MCNPX 2.6e code has been chosen to simulate the neutronic behavior of the TADSEA because this new version incorporates a set of capabilities that facilitate ADSs simulation.

As mentioned above, TADSEA's preliminary conceptual design was carried out to generate 100 MW of thermal power at any condition. For this reason, the total power generated in the core must be greater than 100 MW for the three considered states.

Using a packing fraction (PF) value of 0.648, the total power does not exceed 100 MW at the EOC and barely surpasses that value at the BOC, as shown in Table 2.

Table 2: **Total power for the different core states (PF=0.648)**

Core state	IL	BOC	EOC
Total Power (MW)	168.93	100.56	91.66

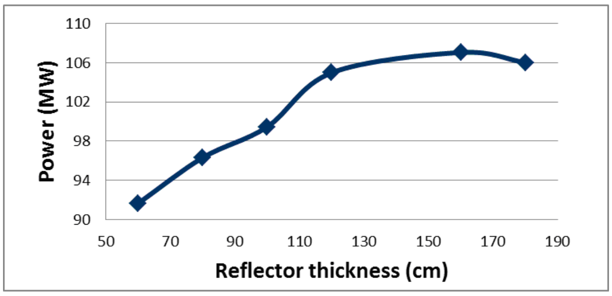


Figure 4: **Total power vs. radial reflector thickness for the EOC.**

7. OPTIONS FOR THE TADSEA'S REDESIGN

With the aim of reaching the desired power levels, some reactor's design parameters were changed. The proposed options in TADSEA's redesign were the variation of the radial reflector thickness and the variation of the fuel mass per pebble.

7.1. Analysis of the Radial Reflector Thickness Influence

The total power has been calculated for the EOC using radial reflector thickness values between 60 and 180 cm. Results are shown in Figure 4.

The increase of the radial reflector thickness causes a power increment, reaching a stable state for thickness values above 120 cm. This value is high enough to consider an infinite reflector boundary condition. In the EOC, power values above 100 MW have been obtained for reflector thickness values larger than 1m.

7.2. Influence of the Pebble Fuel Mass Variation on Different Parameters

The fuel mass per pebbled was modified and neutronic calculations have been made for the IL. Subsequently, the optimum fuel masses selected were used in the burn-up calculations and the fuel composition obtained for the BOC and EOC was analyzed. The behavior of the effective multiplication coefficient (Keff) was studied for different fuel masses per pebble (0.5, 1, 1.5, 3, 4.5 and 6 g). Results are shown in Figure 5.

The fuel mass increment per pebble causes a Keff decrease until a point where a Keff increase is observed (Figure 5). The increment of fuel mass per pebble is equivalent to the fuel mass fraction increase and to the graphite (moderator) mass fraction decrease. Results do not agree with the expected behavior of traditional nuclear fuel. The last is justified by the complex composition of the employed fuel, composed by transuranic

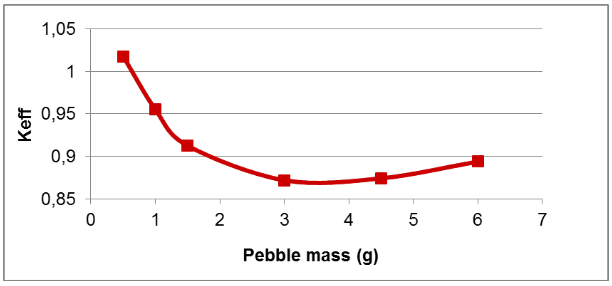


Figure 5: **Keff vs. fuel mass per pebble.**

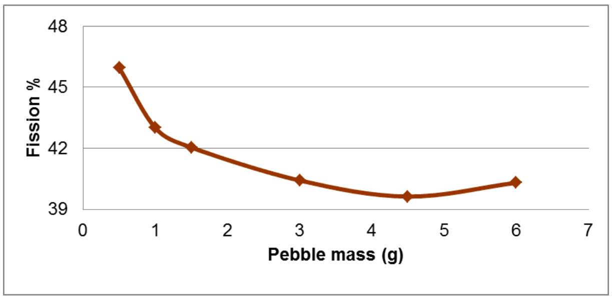


Figure 6: **Total fission in percent vs. fuel mass per pebble.**

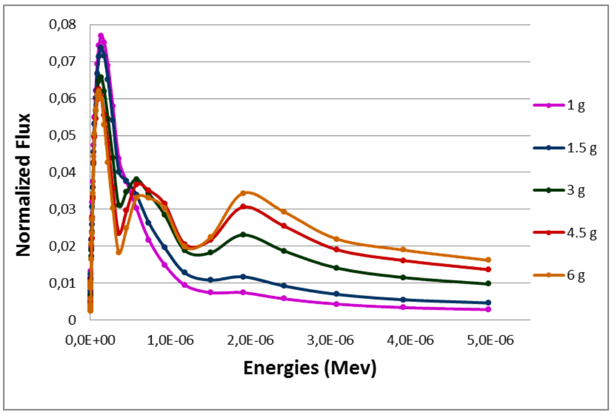


Figure 7: **Normalized energy spectrum.**

elements from the LWR waste. In order to verify this behavior, the dependence of the fission to absorption rate of neutrons of all energies and all fuel components, in percent, on the fuel mass per pebble, was graphed. The neutron absorption rate in all materials conforming the fresh fuel (including the structural elements of TRISO fuel), has been considered. The main contributors to fission rate are Pu^{239} and Pu^{241} while the other isotopes influence mostly on the capture rates. A good agreement between fission to absorption rate and Keff behavior with the mass per pebble is observed (Figure 6).

The Keff dependence on the fuel mass per pebble is explained by the fact that varying the moderator-fuel relation while increasing the fuel mass per pebble, a displacement of the energy spectrum to higher energies is produced, as shown in Figure 7. For fuel mass values over 4.5 g per pebble, the fissile fuel mass increment prevails against the effect of the spectrum hardening.

8. BURN-UP CALCULATIONS FOR THE REDESIGN OF THE DEVICE

From the results of the different options considered to enlarge the thermal power in TADSEA's core, ten burn-up cycles have been performed for two redesign options (Table 3) taking into account the fuel mass per pebble, the radial reflector thickness and duration of the burning cycles between recharges. The selection of the cycle's period between recharges was chosen as function of the masses relation, in order to ensure the same fuel burn-up grade in both options (1/1.5 = 66/99).

Table 3: **Studied options for TADSEA's redesign.**

Option	Mass (g)	Thickness (cm)	Time (days)
A	1.5	100	99
B	1	60	66

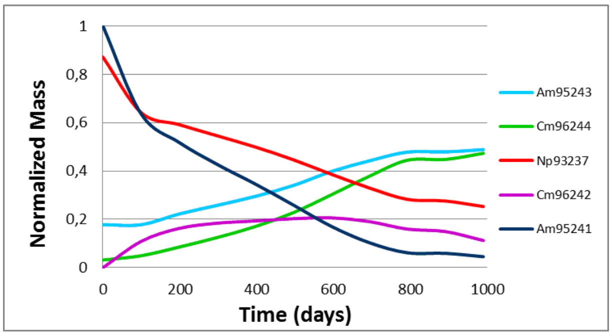


Figure 8: **Variation of the isotopic composition of MA for option A.**

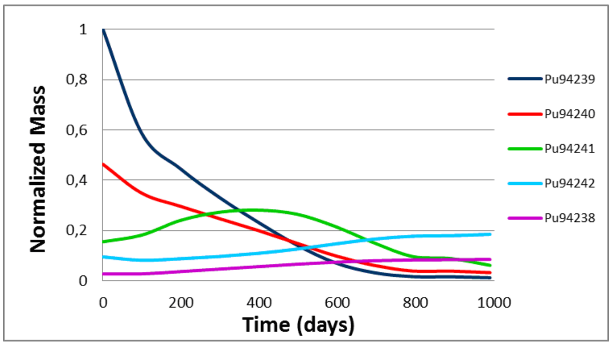


Figure 9: **Variation of the isotopic concentration of Pu isotopes for option A.**

8.1. Variation of the Main Isotopes Masses for Both Redesign Options after the fuel burn-up

One of the main objectives of ADS is the long-lived waste transmutation, especially Plutonium isotopes led by Pu^{239}. Reducing as much as possible the mass of the most dangerous isotopes is indispensable. The behavior of the normalized isotopic concentrations along the time until the stationary state is reached, has been analyzed. In figures 8 and 9, the behavior of the normalized isotopic concentrations during the first 10 cycles for option A is shown. Results for option B are in agreement with results for option A.

Mass variation of main fuel isotopes, as well as their depletion in percent respect to their initial masses, is illustrated in Tables 6 and 7. Minus sign preceding depletion values means increase while plus sign means decrease. The variation of Cm^{242} is referred to the initial mass of MA since it does not appear in the initial fuel.

In the studied options Plutonium isotopes suffer a considerable mass reduction, especially the most abundant isotopes (Pu^{239}, Pu^{240} and Pu^{241}), which is the main goal of the deep burn concept. Np^{237} mass is also considerable reduced. Am^{241} is almost eliminated while Am^{243} mass increases. Np^{237}, Pu^{240} and Pu^{241} masses experiment a greater depletion in option A than in B while the reduction of Am^{241} and Pu^{239} masses is greater in option B. In both cases, the reduction of Pu^{239} mass is around 99% while masses of Am^{243}, Cm^{244}, Pu^{238}, Cm^{242} and Pu^{242} increase. In the preliminary design of the PBT [1], the total mass of MA decreases in 18% and the total mass of Plutonium isotopes decreases in 75%. The total mass of $Pu + MA$ decreases in 69% respect to the initial loaded mass.

Table 4: **Depletion (in percent) of the main isotopes masses for the considered options.**

Option	MA	Pu	MA + Pu
A	34	78.4	73.7
B	39.2	77.6	73.5

Table 5: **Thermal power (MW) for both studied options.**

Option	BOC	EOC
A	328	263
B	156	119

Table 6: **Initial and final fuel composition in TADSEA's core (option A).**

Mass(g)	Np^{237}	Am^{241}	Cm^{242}	Am^{243}	Cm^{244}	Pu^{238}	Pu^{239}	Pu^{240}	Pu^{241}	Pu^{242}
Initial	655.4	752.0	0.0	134.0	24.0	203.2	7512.1	3481.6	1165.4	713.1
Final	190.3	34.2	84.6	367.7	356.1	636.9	90.7	241.8	460.5	1388.0
% Depletion	+71.0	+95.5	-5.4(*)	-174.3	-1385.6	-213.4	+98.8	+93.1	+60.5	-94.6

Depletion in percent of Pu, MA and $Pu+MA$ masses for both redesign options is shown in Table 4. Higher mass reduction values are obtained for the proposed redesign options than for the PBT. A largest reduction of Pu isotopes masses and of the total mass is reached with option A. On the other hand, a greater decrease of MA masses is obtained with option B.

8.2. Thermal Power Generated in the Core for Both Redesign Options

Thermal power values at the end of the 11 fuel cycles for both studied options and for two main states of the system (BOC and EOC), were calculated. In all cases, core outlet thermal power exceeds the established design value of 100MW (Table 5).

Established requirements of TADSEA were satisfied using a core design with a packing fraction value of 0.648 and libraries with constants that consider the actual working temperatures of the system's design. Therefore, the feasibility of a device that uses 1.5g of fuel per ball, increasing the radial reflector thickness, has been verified. Core outlet thermal power is controlled by the proton beam.

9. THERMAL-HYDRAULIC CALCULATIONS

The power extraction from fuel elements is carried out by forced convection of the coolant gas (Helium).

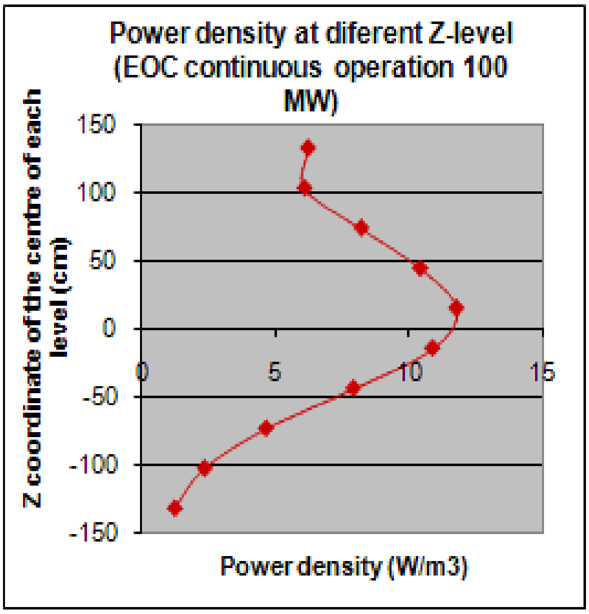
In order to produce Hydrogen by a thermo-chemical process or by high temperature eletrolysis, the coolant outlet temperature must be around 1223 K. Coupling the TADSEA with a Hydrogen production plant separated by an intermediate heat exchanger, and making the temperature balance of both loops taking into account the heat requirements of the Hydrogen production process, a Helium mass flow rate of 53 kg/s through TADSEA's core is needed to obtain the required outlet temperature.

A CFD code, ANSYS CFX 10.0, was used for thermal-hydraulic calculations. For simulation purposes, the pebble bed core was considered as a porous medium with a porosity of 0.36. Temperature profiles were obtained from the radial and axial power density distributions. Helium flows across the core from top to bottom to effectively compact balls and avoid local porosity coefficient variations. Axial and radial temperature profiles for the EOC and the corresponding power density distributions, are shown in Figures 10(a), 10(c), 10(b), 10(d), 10.

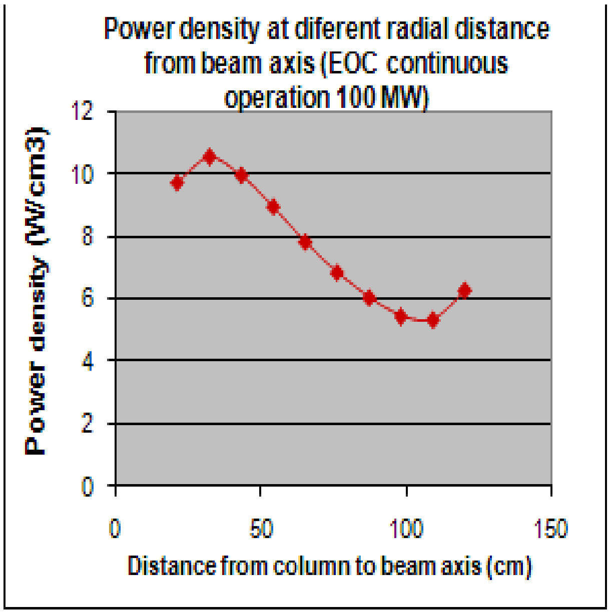
A greater heat exchange is observed near the center (corresponding to the spallation target position) and

Table 7: **Initial and final fuel composition in TADSEA's core (option B).**

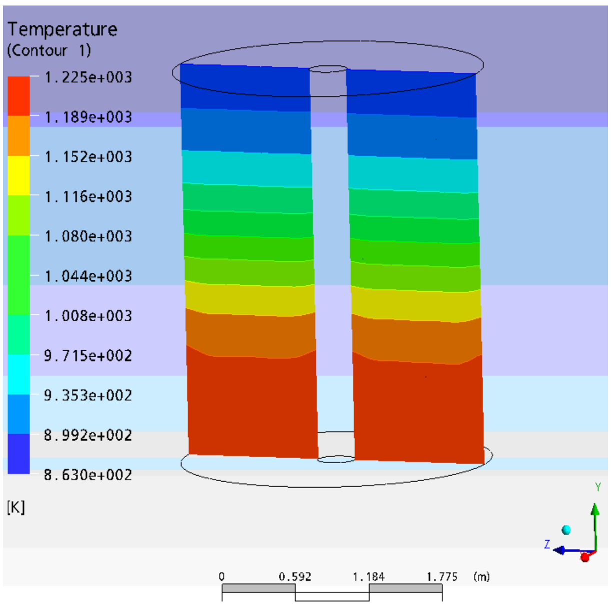
Mass(g)	Np^{237}	Am^{241}	Cm^{242}	Am^{243}	Cm^{244}	Pu^{238}	Pu^{239}	Pu^{240}	Pu^{241}	Pu^{242}
Initial	436.9	501.4	0.0	89.4	16.0	135.5	5008.1	2321.1	776.9	475.4
Final	139.2	19.5	67.2	232.9	175.7	389.4	49.5	209.5	312.3	992.5
% Depletion	+68.1	+96.1	-6.4(*)	-160.7	-999.7	-187.4	+99.0	+91.0	+59.8	-108.8



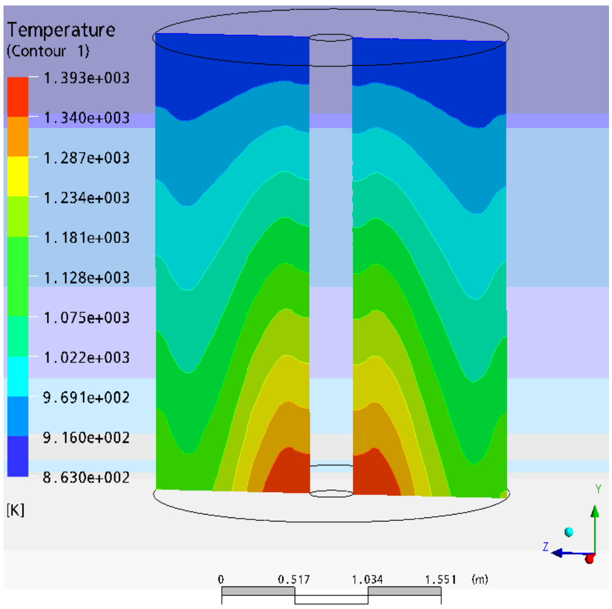
(a) **Axial power density profile.**



(b) **Radial power density profile.**



(c) **Axial temperature profile.**



(d) **Radial temperature profile.**

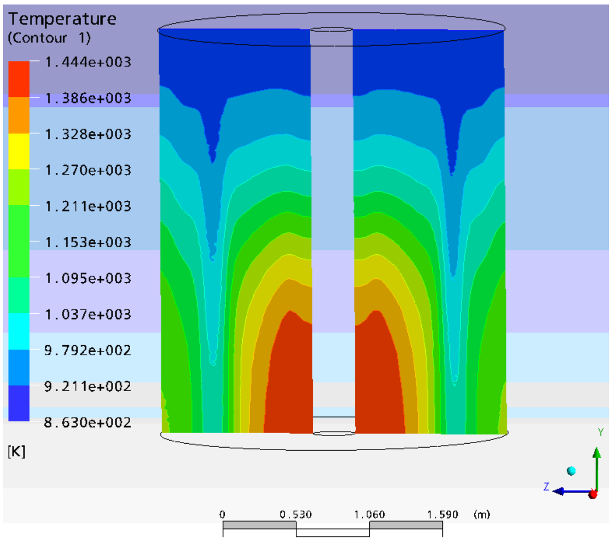


Figure 10: **Axial-radial temperature profile.**

Table 8: **Outlet temperature values.**

Outlet Temperature Values (K)	Axial	Radial	Axial-Radial
Minimum	1218.64	1148.20	1053.94
Maximum	1225.14	1393.42	1443.79
Average	1220.80	1221.20	1222.66

near the reflector. On the other hand, a lesser heat exchange is observed in the lowest part of the core due to the burn up of the fuel at the stationary state. The outlet temperature profiles corresponding to the axial, radial and combined power density distributions, as well as maximum, minimum and average temperature values, are shown in Figures 11, 12 and 13, and in Table 10 respectively.

10. INFLUENCE OF THE DETAILED SIMULATION OF THE TRISO PARTICLE GEOMETRY IN SOME NEUTRONIC PARAMETERS

A Monte Carlo approach is employed to do a comparison of the neutron fluxes, spectrum and power density distributions and inside the tiny 250-mm diameter fuel kernels with an exact and finite geometry description, and using an homogeneous description of the fuel geometry. The main goal of this study is to analyze if there are significant differences in the results in neutronic parameters like Keff., energetic spectrum and flux distribution between the detailed simulation of the TRISO particles in the fuel and an homogeneous simuation of the fuel inside the core.

10.1. Detailed Simulation of the TRISO Particles

In order to do the detailed simulation of the fuel, the layers that compose the TRISO particles and were taking into account in the homogeneous simulation as a unique material to calculate the mixture density and the equivalent mass fractions, now are exactly simulated using the real density and dimensions for all the layers (Table 9). Figure 14 shows the PBT sketch when the detailed simulation of the TRISO particles was made.

To achieve the detailed fuel simulation comparable with the homogeneous fuel simulation, the number of TRISO microparticles in order to guarantee the fuel metalic mass designed for the pebble was calculated. An equation to calculate the number of microparticles fitting in a plane located at x distance from the center of the pebble was obtained and it also depend on the hexagon area ($8.66 * 10^{-3} cm2$) used to made the hexagonal lattice in the simulation.

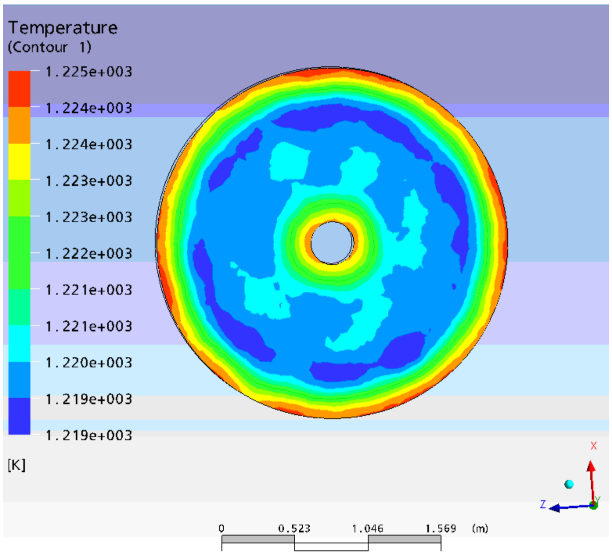


Figure 11: **Outlet temperature profile corresponding to the axial power density distribution.**

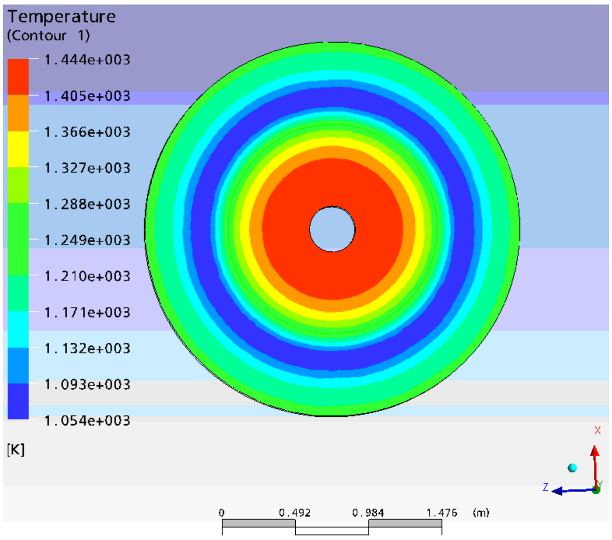


Figure 12: **Outlet temperature profile corresponding to the radial power density distribution.**

Table 9: **Geometric and material data of the TRISO particles**

Material	**Radii**[μm]	**Density**[g/cm^3]
Kernel	200	10.33
Buffer carbon Layer	287.5	1
Inner pyrolitic carbon layer	375	1.85
Silicon Carbide layer	437.5	3.2
Outer pyrolitic carbon layer	500	1.85
Microparticles number per pebble	4333	-

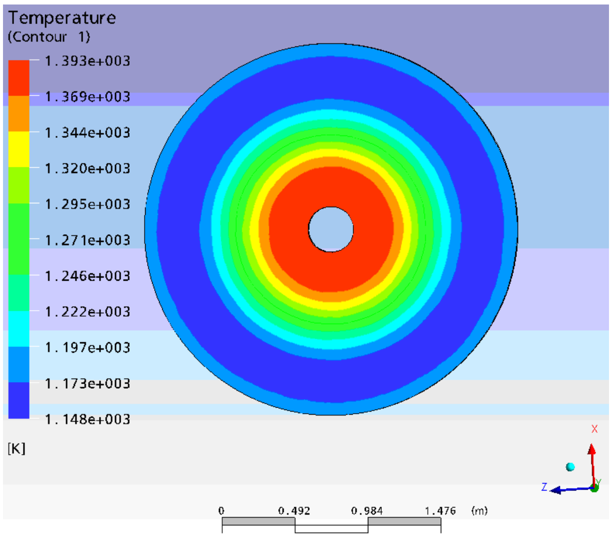
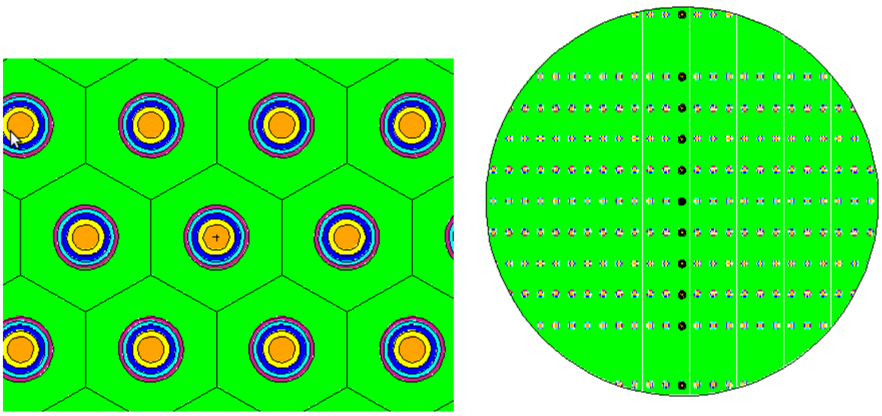


Figure 13: **Outlet temperature profile corresponding to the axial-radial power density distribution.**



(a) **Hexagonal lattice on a plane** (b) **Location of the microparticles per plane**

Figure 14: **Distribution of TRISO particles inside the pebble**

Table 10: **Multiplicative properties of the core corresponding with an homogeneous simulations an heterogeneous simulations of the TRISO particles.**

	Homogeneous simulation	**Detailed simulation**
Keff. $\pm$ Std. Dev.	0.85844±0.00129	0.89751±0.00111
Maximun Energy Production(Mw.)	13.31	21.3
Absolute Average Flux(n/cm^2s)	1.4E+14	5.3E+14
Neutron/Proton relationship per source particle		
Escape	7.8253E+00	1.2667E+01
Capture	1.9747E+01	2.8752E+01
Total	4.5909E+01	7.0744E+01

$$No. = 300.03651 * (1.5625 - x^2) \qquad (6)$$

Once calculated the number of microparticles that can be joined in the planes inside the pebble, the planes were located axially inside the pebble to obtain a uniform distribution of microparticles and the designed fuel metalic mass inside the pebble. Finally, the complete pebble was repeated inside the PBT core to form the honeycomb pebble distribution.

10.2. Influence of the Detailed Simulation of the Geometry of the TRISO Particles on the Multiplicative Properties of the Core

Table 10 shows the values that describe the multiplicative properties of the core, calculated for the PBT using an homogeneous simulation of the geometry of the TRISO particles inside the pebbles and using a detailed simulation of the geometry of the TRISO particles inside the pebbles. There are some differences between both simulation, greater for the detailed simulation. A similar differences were obtained in [10]. As matter of fact, the obtained difference on the eigenvalue in our study is lower than that in the the referred paper. Even when the absolut values are different, the normalized values are very similar, that's why is considered that the obtained difference are because of the difference of models and not related to phenomena that were not taken into account on the homogeneous simulation of the geometry of TRISO particles, significant changes on the multiplicative properties or spectrum changes.

Also besides the calculation was realized using the same number of stories per cycle and the same numbers of cycles. The statistic used in the calculation was the same and this is demostrated by the similar values of the standard deviation of Keff. values.

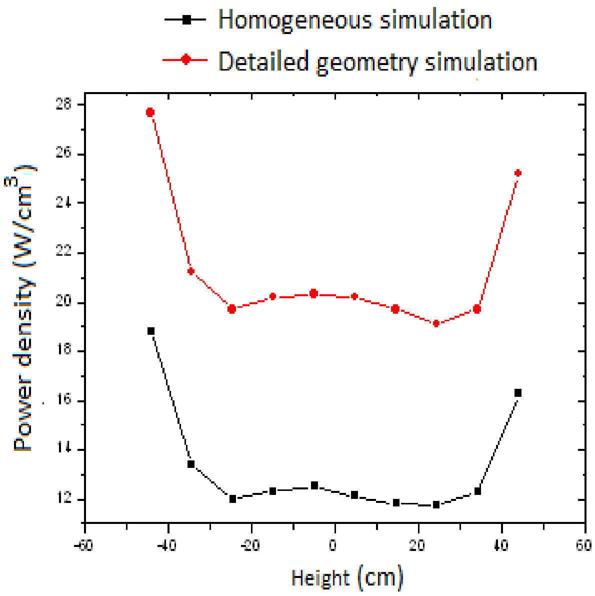
10.3. Influence of the Detailed Simulation of the Geometry of the TRISO Particles on the Power Distributions

The calculation of detailed simulation of the geometry of the TRISO particles were realized at the begining of the cycle using fresh fuel.

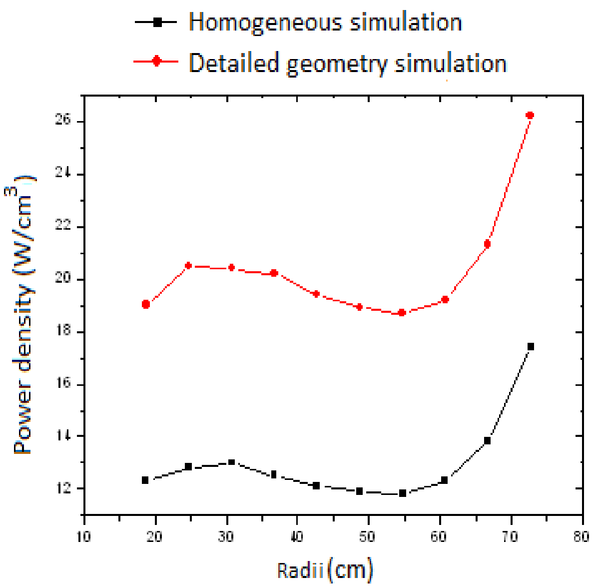
Figures 15(a) and 15(b) show the axial and radial power distributions for the PBT using a detailed simulation of the geometry of the TRISO particles and an homogeneous simulation of the fuel inside the pebbles. It is observed for the homogeneous case that the absolut power distribution is lower than that using a detailed simulation. The obtained differences agree with the differences obtained for the eigenvalues. There is a great agreement between the normalized power distribution in the study cases. (Figures 15(c) and 15(d))

10.4. Influence of the Detailed Simulation of the TRISO Particles Geometry on the Energetic Spectrum

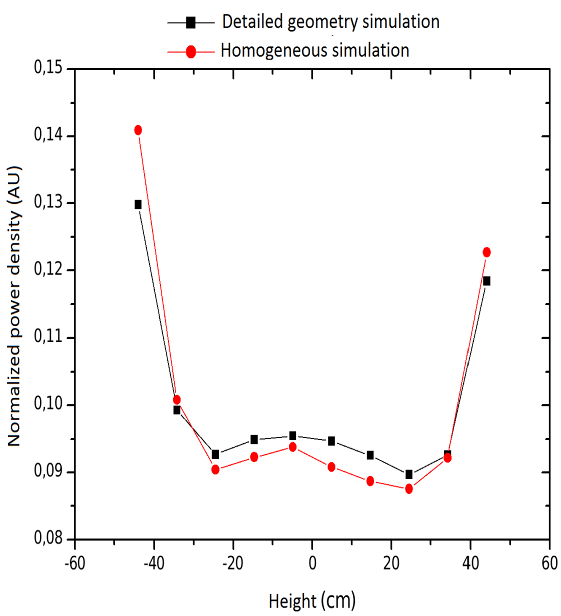
Figure 15 shows the average energetic spectrum for all energies inside the PBT core both for the homogeneous simulation of the fuel and using a detailed simulation of the TRISO particles. The spectrum was calculated for



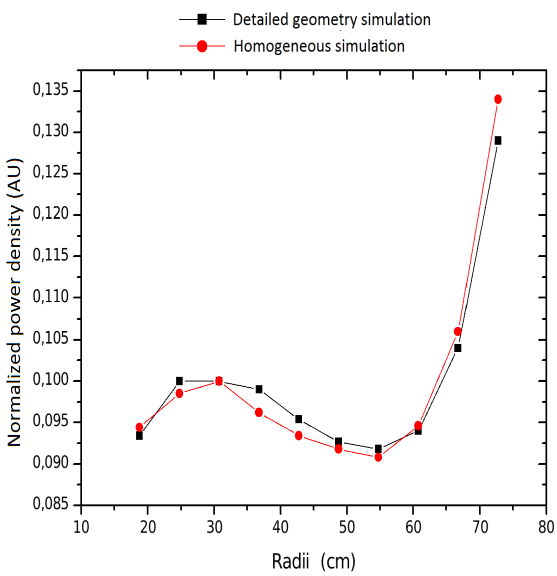
(a) **Axial power distribution.**



(b) **Radial power distribution.**



(c) **Normalized axial power distribution.**



(d) **Normalized radial power distribution.**

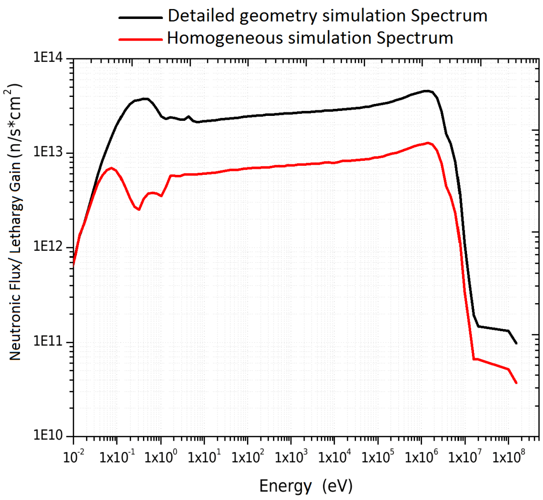


Figure 15: **Comparison between the energetic spectrum obtained using an homogeneous and heterogeneous simulation of the TRISO particles**

continuous energy and for 69 energetic groups: 14 fast groups, 13 resonance groups and 42 thermal groups. The ADS clearly works on the thermal zone with a spectral peak at 0.15 eV, although it has a strong fast contribution due to the neutrons coming from the spallation target. It is observed that for the detailed simulation of the fuel, the flux has the same behavior in terms of form compared with the homogeneous simulation of the fuel, although the absolute value is increased for the detailed simulation, which agree with the differences obtained before. This increase in the absolut value on the spectrum was also obtained at [10].

11. CONCLUSIONS

TADSEA's preliminary conceptual design was carried out to generate 100 MW of thermal power at any condition using the maximum packing fraction value of an infinite bed. In the present work, an analytical method for calculating the number of whole pebbles fitting in a volume according to its size was developed and the main results are showed in this paper.

The packing fraction influence in the TADSEA's main working parameters was studied. A redesign of the previous configuration, according to the established conditions in the preliminary design was made. Two options have been studied: the increase of the radial reflector thickness and the pebble fuel mass variation.

System was optimized to maximum allowable power keeping the transmutation capabilities and maintaining power densities below technological limits, deducing 100 MW as the maximum thermal power.

Average outlet temperatures of 1221 K approximately, are obtained. The maximum temperature values obtained for the EOC do not constitute limit values for the dangerous conditions of the TRISO fuel (1870 K). In addition, the TADSEA is a sub-critical system in which transient states are easier to control, so it is supposed that the peak temperature of the TRISO fuel is always under the currently accepted limit value.

A comparison between an homogeneous simulation of the fuel and a detailed simulation of the TRISO particles inside the pebble in terms of multiplicative properties, axial-radial power density and energetic spectrum was made. There are some differences on the absolute values in Keff, axial-radial power density distribution and energetic spectrum due to the change of models and not because of phenomena that were not taking into account on the homogeneous simulations. The normalized distributions obtained are very similar and there is a good agreement with the results obtained in [10].

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