OPTIMIZATION OF A NEW CUBOID NUCLEAR FUEL CELL CONCEPT FOR LONG LIFE SMR

[1]H. Amsil, [2]A. Chetain, [1]A. Benchrif, [2]S. Charouq, [2]O. Lebied, [2]O. Kabach, [2]A. Jalil

[1]Nuclear Center of Energy Science and Nuclear Technics, Rabat, Morocco
[2]Faculty of Science, Rabat, Morocco

ABSTRACT

The mean objective of this work is to optimize a new cuboid concept of nuclear fuel cell which helps extending the life time of nuclear reactors. This new concept is designed for Small and Medium Sized Reactors SMR. The ergonomic of this design is based on safety, ease of refueling, traceability and fuel burnup optimization. As a prospective, this fuel concept cell can have the possibility to be dotted with new High-Tec technologies.

All calculations were made using MCNP5 code and the results of the finale concept were validated with DRAGON code.

Cell calculation was first based on Infinite Multiplication Factor (Kinf) determination. An optimization of fuel dimensions was performed for three fuel types UO_2, MOX and $(Pu-Th)O_2$. Different enrichments has also been studied and the optimal one has been chosen. As a first stage, an optimal unit cell for this new fuel concept was identified and used for deep nuclear parameters evaluation.

The design of this optimized fuel cell will be presented. Unit cell calculation for different nuclear parameters will also be presented.

I. Introduction

In order to meet the increased demand for nuclear energy by underdeveloped countries, several research projects were launched for the development of new nuclear fuel concepts for low nuclear power plants, long and medium life reactors. These fuels have been designed to meet the needs of developing countries and meet all the safety standards required for the use of this type of technology, taking into account in particular the economic aspect.

The ergonomic choice of the cuboid shape is based mainly on the ease of both fuel element manufacturing and fuel assemblies' vertical and horizontal permutations. These assembly permutations will play a great role to increase the life time of the reactor core. In fact, changing assemblies from low reaction rate position (core boundaries) to high reaction rate position (Core center) impacts the Effective Multiplication Factor (Keff).

The challenge of this work is first to optimize the unit cell dimensions, fuel elements, the choice of cladding and moderator, fuel assemblies and the whole core design. Secondly the normal operation reactor cycle life will be determined with possible combinations of assemblies to increase the reactor cycle life. These combinations will imply development of automated mechanical system to facilitate the exchange of fuel assemblies.

As mentioned above, other non neutronic studies should be held for the possibility of GPS tracking chip implementation for each fuel element to prevent the proliferation. This later implies development of high radiation resistant tracking chips. Bare code traceability to categorize nuclear waste and plutonium content after the life time of each fuel elements. This traceability needs software development for the choice of future position of each assembly in the core in order to improve efficiency use of the fuel to increase the life time of the reactor core. The traceability historic of each fuel element can estimate the composition of each fuel element based on a sophisticated algorithm and developed database.

The elaboration of this new fuel concept cell was based on using standards, known and commercial materials. UO2, MOX and Pu-Th were chosen as fuel pallets as candidate for our fuel concept. Zirconium and Zircaloy, efficient for cladding and for fission products confinement, were also chosen with other alloys as candidates.

In this paper, we present Infinite Multiplication Factor (Kinf) results generated using MCNP5 code, for different combinations of fuel, cladding and moderator dimensions. We will also present the result of the three fuel candidates for this new concept. DRAGON code calculation Kinf results for validation are presented also for the identified optimal unit cell. Neutronic parameters as neutron spectra, absorption macroscopic cross-cections, Nu-fission macroscopic cross-cections total macroscopic cross-cections and diffision macroscopic cross-cections at the beginning are presented for this new optimized fuel concept.

II. Methodology used

We started by adopting a standard diameter of the fuel pallet used in research reactors like TRIGA MARK. Our fuel pellet is surrounded by zirconium containing materials, called matrix, as the first fission products barrier and zircaloy as cladding to form a final embedded cuboid fuel (fuel element). The fuel element is submerged in the moderator to form a unit cell (see figure).

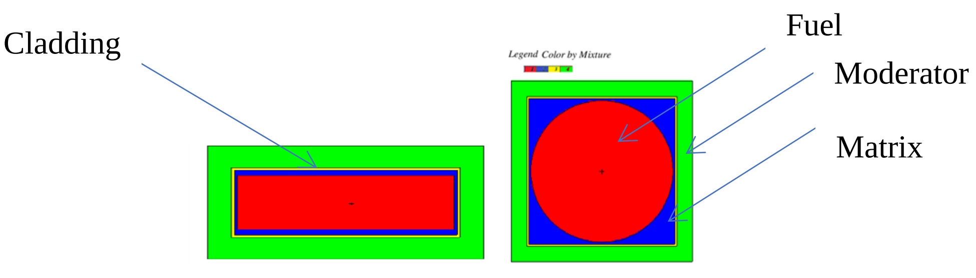


Fig. 1: Unit cuboid cell design structure; On the left: front view of unit cell; On the right: top view of unit cell

Dimension optimization of this unit cell concerns the height of the fuel pellet and matrix, cladding and moderator thickness. After this step we introduced the fuel, matrix, cladding and moderator candidate to determine the materials set showing good results regarding our objective. Materials used in this study are presented in Table 1

Table 1: Material candidates for unit cell optimization

Fuel	Matrix	Cladding	Moderator
UO_2	Zr	Zircaloy-2	H_2O
MOX	ZrH	Zircaloy-4	D_2O
$(Pu\text{-}Th)O_2$	ZrH_2	Zirlo	

Hundreds of calculations have been performed to find the optimal dimensions of all components for the unit cell. We introduce bellow the methodology followed in our study:

1. For each fuel nature (UO_2, MOX and $(Pu\text{-}Th)O_2$) and for a given thickness of the matrix and cladding, calculations were made for three heights (1, 1.5 and 2cm) of the fuel pellet and for different moderator thickness (we started from 0.1 to 1cm with a step of 0.1cm). We obtain in total 190 cells for a chosen height fuel for each fuel nature.
2. The same study above was performed to optimize matrix (Zr,ZrH and ZrH2) and cladding(Zircaloy-2,Zircaloy-4 and Zirlo) thickness with different fuel enrichment (not included in this paper).
3. Unit cells resulting a high Kinf will be used with different enrichments (from 5% to 20% with 1% step) to determine the optimal enrichment for a given fuel nature.
4. Finale unit cell specifications are determined at this step. A validation of the Kinf and the determination neutronic parameters of the identified optimal unit cell is required using a deterministic code.
5. Assembly and core configuration to obtain good performances regarding the life cycle of the reactor core (not included in this paper).

III. Results

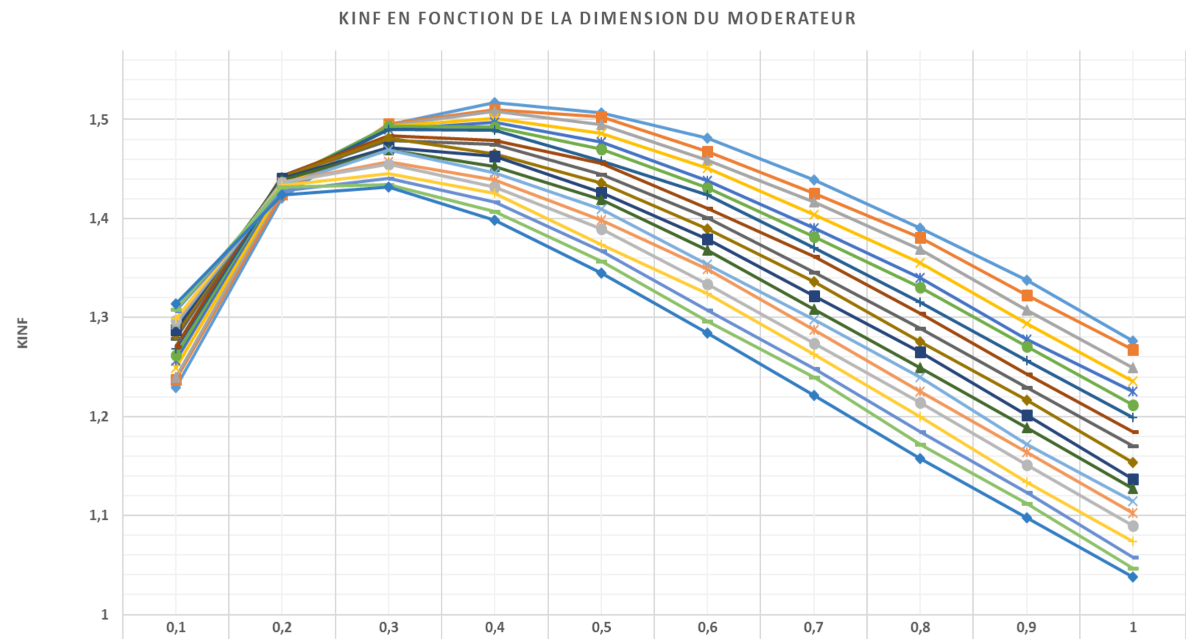
III.1 Fuel pellet height and moderator thickness optimization

At the end of all three tests performed for Uranium Oxide fuel, we see that the best criticality value obtained is that of the fuel height equal to 1cm and 0.4cm for the thickness of the moderator (Figure 2a).

Best kinf obtained for all the MOX fuel tests corresponds to cell n ° 1 with the height of H = 1cm and moderator thickness of 0,5cm (Figure 2b).

At the end of all three tests performed for the Pu-Th fuel, it is clear that the best criticality value obtained is that of the fuel height equal to 1cm and 0.4cm for the thickness of the moderator (Figure 2c).

Kinf values related to each fuel type are presented in Table 2. The highest Kinf value is recoded for UO2 fuel.



	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1
Cellule 1	1,22901	1,42099	1,49508	1,51682	1,50695	1,48092	1,43876	1,39	1,33757	1,27649
Cellule 2	1,23698	1,42479	1,49574	1,51026	1,50278	1,46759	1,42578	1,3805	1,32263	1,26791
Cellule 3	1,23957	1,42968	1,49431	1,50843	1,49455	1,45901	1,41682	1,36884	1,30776	1,2495
Cellule 4	1,24927	1,43136	1,49311	1,50141	1,48637	1,45127	1,40356	1,35527	1,29387	1,23531
Cellule 5	1,25637	1,4357	1,48987	1,49721	1,47759	1,43777	1,39035	1,33994	1,27763	1,22498
Cellule 6	1,26221	1,43781	1,49352	1,49249	1,47027	1,4313	1,38192	1,33017	1,27059	1,21147
Cellule 7	1,26832	1,43804	1,49011	1,48946	1,45815	1,42391	1,37067	1,31522	1,25626	1,1991
Cellule 8	1,27068	1,44327	1,48387	1,47855	1,45544	1,40992	1,36196	1,30432	1,24264	1,1848
Cellule 9	1,27876	1,44217	1,4789	1,47501	1,44433	1,40059	1,34572	1,28932	1,22902	1,1703
Cellule 10	1,28276	1,44152	1,48093	1,46554	1,43611	1,38928	1,33592	1,27579	1,21675	1,15344
Cellule 11	1,28733	1,44073	1,47188	1,46287	1,42585	1,3793	1,32183	1,26551	1,20102	1,13692
Cellule 12	1,29533	1,43872	1,46945	1,45281	1,41901	1,36797	1,30838	1,24922	1,18869	1,12747
Cellule 13	1,29334	1,43373	1,46943	1,44609	1,40924	1,35399	1,29813	1,2396	1,17205	1,11468
Cellule 14	1,29521	1,43691	1,45745	1,43922	1,39836	1,34853	1,28779	1,22553	1,16379	1,10258
Cellule 15	1,29733	1,4368	1,45481	1,43214	1,38934	1,33376	1,27394	1,21409	1,15134	1,09
Cellule 16	1,29863	1,43315	1,44545	1,42569	1,37344	1,32393	1,26255	1,20001	1,13358	1,07379
Cellule 17	1,30649	1,4275	1,44088	1,41685	1,36739	1,30742	1,2486	1,18459	1,12348	1,05786
Cellule 18	1,30794	1,43143	1,43379	1,40716	1,35669	1,29636	1,23957	1,17184	1,11211	1,04697
Cellule 19	1,31399	1,42399	1,43151	1,39863	1,34508	1,28436	1,22117	1,15736	1,0979	1,03792

EPAISSEUR DU MODÉRATEUR 0,1CM

1.

Fig. 2a : Kinf variation according to the moderator dimension in case of UO_2 fuel with 1cm height

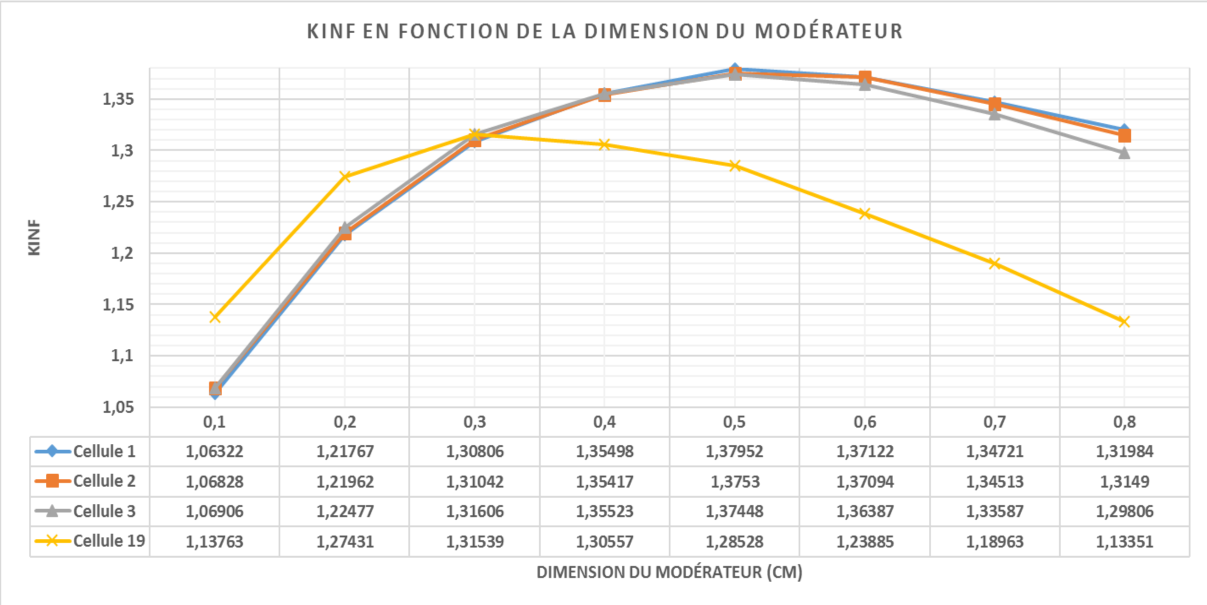


Fig. 2b : kinf variation according to the moderator dimension in case of MOX fuel with 1cm height

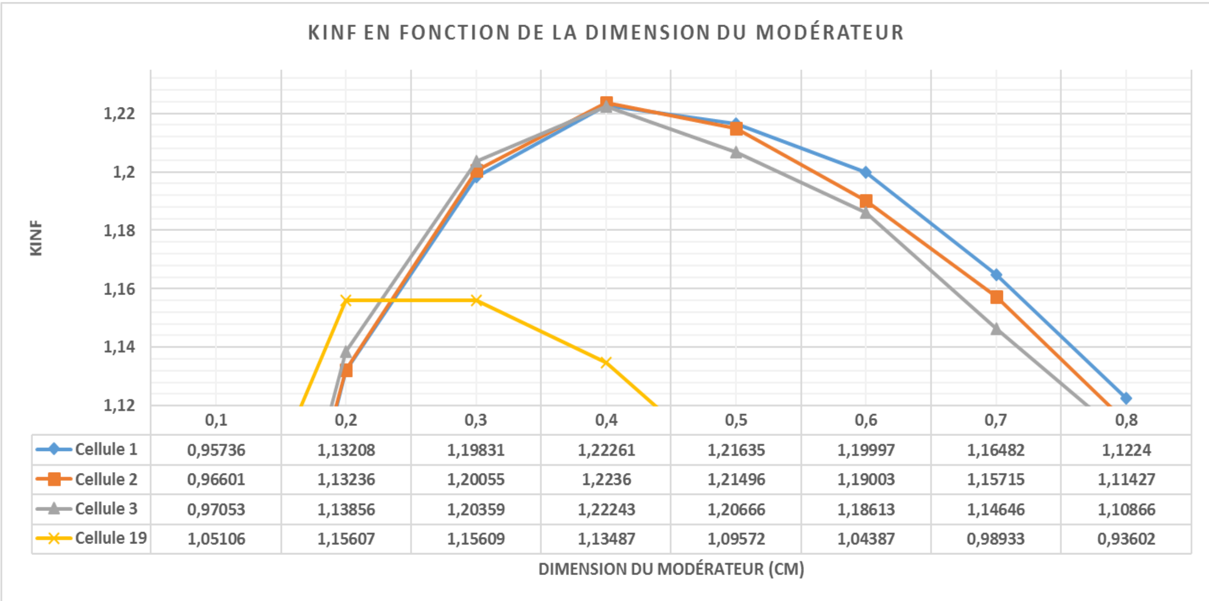


Fig. 2c : Kinf variation according to the moderator dimension in case of (Pu-Th)O_2 fuel with 1cm height

Table 2: summary of the optimal dimensions of the fuel and moderator and the associated Kinf

Fuel	Fuel height (cm)	Moderator height (cm)	Kinf
UO2	1	0.4	1.51682
MOX	1	0.5	1,37952

Pu-Th	1	0.4	1.22261

We decided to choose light water (H_2O) as moderator instead of D_2O for economical purposes. After the optimization of cladding and matrix thickness a finale unit cell configuration was identified for UO_2 fuel with 5% enrichment and more. External dimensions and specifications are presented in Table 3.

Table 3: Summary of the optimized unit cell

	Diameter (cm)	Length (cm)	Width (cm)	Height (cm)
Fuel pellet UO_2 (5%)	3.63	-	-	1
Matrix (Zirconium)	-	3.73	3.73	1.2
Cladding (Zircaloy-2)	-	3.83	3.83	1.3
Moderator (H_2O)	-	4.63	4.63	2.1

III.2 Validation and neutronic parameters

In this chapter, we will make a comparative study using DRAGON as deterministic code. Results of Kinf calculation using some approximations (cylindrization) are presented in Table 4. Comparison between MCNP5 and DRAGON code give 539 pcm differences which validate our calculations.

Table 4: Kinf comparison of the optimized cell according to MCNP and DRAGON codes results

	Final Kinf
MCNP	1.51682
DRAGON	1,51143
Difference	539 pcm

After validation, we proceed to generate nuclear parameters for optimized unit fuel cell for deep analysis purposes. Nuclear parameters like neutron spectra, absorption macroscopic cross-cections, Nu-fission macroscopic cross-cections total macroscopic cross-cections and diffision macroscopic cross-cections at the beginning of cycle are presented in the following figures (Fig. 3 to 8).

- Neutron flux spectra calculation

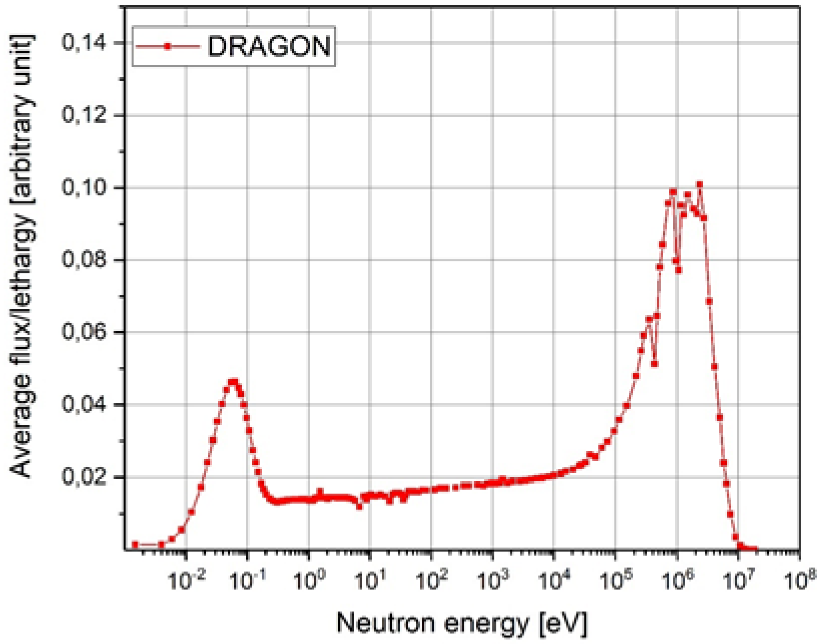


Fig. 3 Homogenized unit cell flux/lethargy vs. neutron energy calculated using DRAGON code

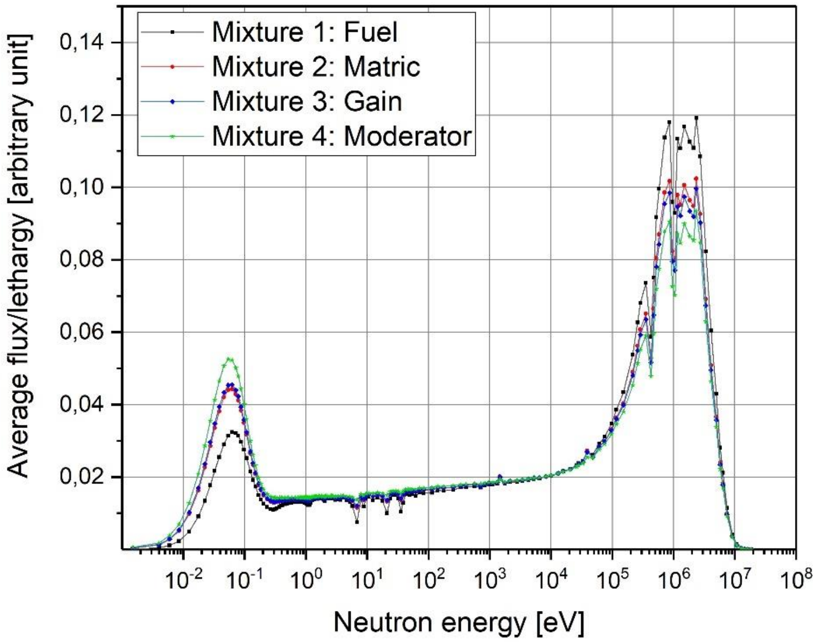


Fig. 4 Flux/lethargy vs. neutron energy in each part of the final optimized cell.

- Macroscopic Cross-Section according to 172 groups of energy

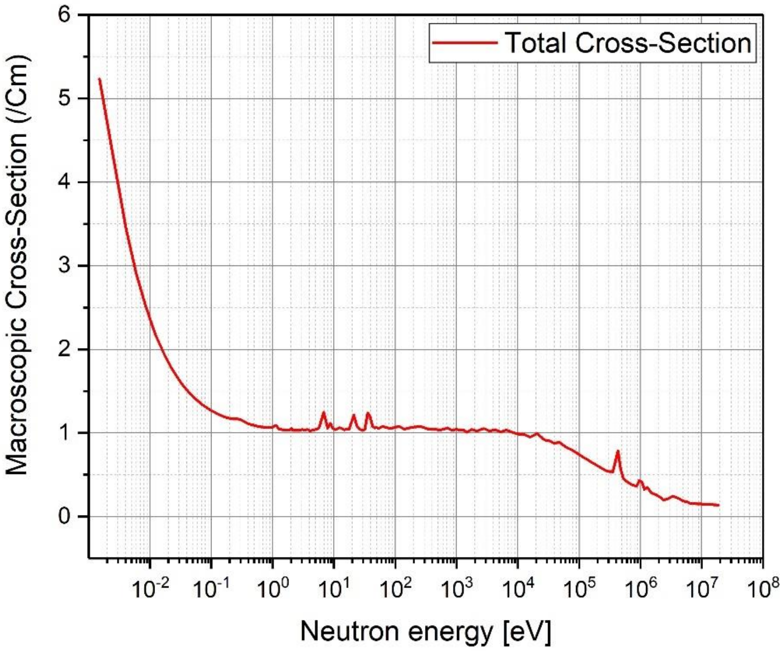


Fig.5 Total Macroscopic Cross-Section vs. Neutron energy

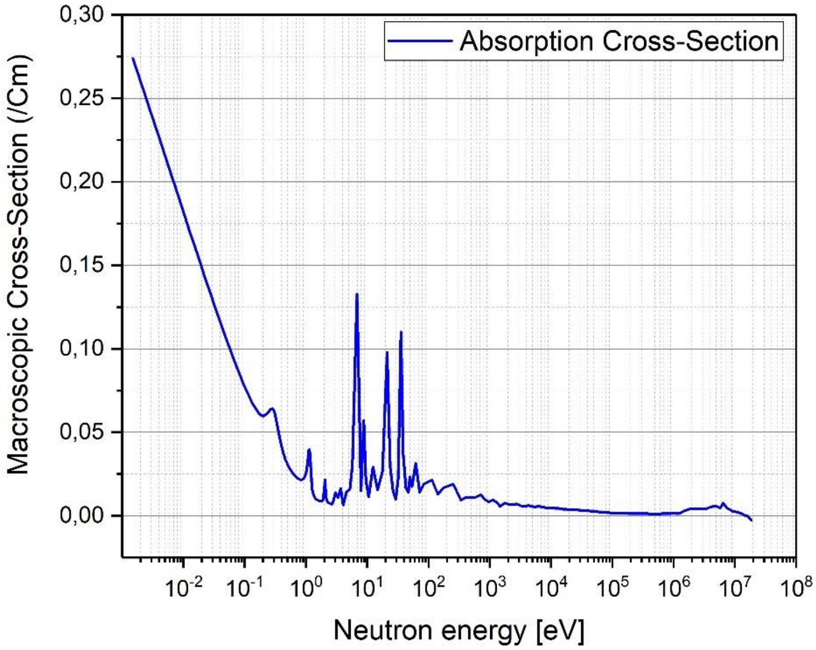


Fig. 6. Absorption Macroscopic Cross-Section vs. Neutron energy

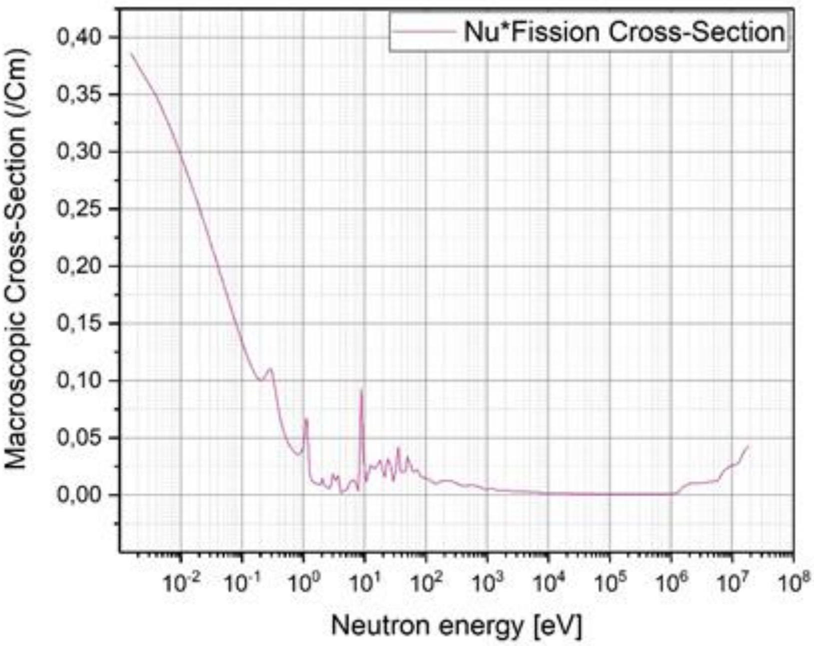


Fig. 6 Nu-Fission Macroscopic Cross-Section vs. Neutron energy

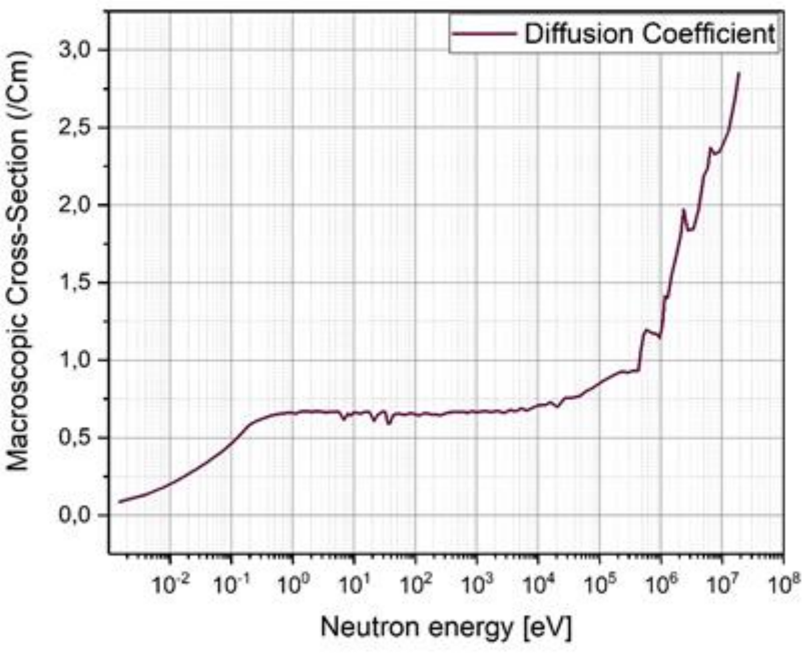


Fig. 8 Diffusion Coefficient vs. Neutron energy

IV. Conclusion and prospects

During this study we succeeded to identify optimal specifications of the new CUBOID fuel cell designated for SMR using MCNP5 code. Results were validated using DRAGON code. Neutronic parameters were also generated in order to perform assembly and code calculations with and without burnable poisons. Kinf burnup calculation for unit fuel cell, assembly and core should be performed in order to determine the life cycle and the added value of this new

CUBOID fuel. Different combination of fuel assemblies should be performed to achieve the maximum possible life cycle.