Natural Uranium as Alternative Fuel for TEPLATOR

Tomáš Peltan
University of West Bohemia
Univerzitni 8
30100, Pilsen, Czech Republic
peltan@kee.zcu.cz

Eva Vilímová, Radek Škoda
University of West Bohemia
Univerzitni 8
30100, Pilsen, Czech Republic
vilimova@kee.zcu.cz, radek.skoda@gmail.com

ABSTRACT

The TEPLATOR is an innovative solution for district heating using nuclear energy. It is a special thermal reactor with specific arrangement of the reactor core with 55 fuel assemblies which is moderated and cooled by heavy water and operated at atmospheric pressure with low output temperatures compared to the commercial nuclear power plants. The TEPLATOR DEMO is designed for using irradiated fuel from LWR reactors. In case that the irradiated fuel is not available in terms of high burnup or other reasons, there is a possibility to use SEU or natural uranium as a fuel. This solution is suitable because of the favourable price of natural uranium. This article focuses on development of the alternative suitable fuel for the TEPLATOR, which is based on irradiated fuel reactor core arrangement. It is mainly concerned with neutronic development of the fuel assemblies with appropriate parameters for this application. This article contains various fuel modifications with different time of operation. All calculations were performed by the Monte Carlo code Serpent.

1   INTRODUCTION

The TEPLATOR is designed as a new type of reactor for operation with the irradiated VVER-440 fuel assembly with optimal burnup. The reactor will be used as a district heating station. This solution could be interesting for countries, which operate VVER-440 reactors, and which have a large amount of irradiated fuel assemblies stored in long-time storage. If some country or operator wants to operate the TEPLATOR and they do not own the irradiated fuel, is it possible to use a special fuel made of SEU or natural uranium.

This article focuses on natural uranium fuel type development which is based on the novel TEPLATOR geometry. Set of calculations was performed using Serpent neutronics code to find an optimal geometry and materials of the fuel assemblies. The input parameters were taken from the existing TEPLATOR design: dimensions of a reactor vessel, materials of the core, reflector and finally pitch of the fuel channels.

1.1   The main input parameters for fuel design

The TEPLATOR is designed as a channel reactor, which operates with 50 MW thermal power output and it will be used mainly for district heating. The power can be raised up to 200 MW with some modification. This alternative design of TEPLATOR core presented in the

article contains 55 hexagonal fuel channels with an optimal pitch [1], which go through a reactor core. Every fuel channel is constructed as two concentric hexagonal tubes with the inner diameter 7.35 cm. Between the tubes is a thermal shielding – low pressure CO_2. The reactor core is surrounded by a 0.5 m thick graphite reflector. This reflector is also placed under and over the reactor core. The heavy water is used as a moderator and as a coolant at the same time. The criticality of the reactor is reached by changing of moderator level inside a calandria. The variable level of moderator serves also as a regulation for the chain reaction. Coolant outlet temperature is now set just below 100 °C and temperature gradient is around 50 °C. The fuel channels work with a slightly higher atmospheric pressure. These main parameters of TEPLATOR were crucial for development of the new fuel design. The reactor core with the new fuel channels can be seen in the Figure 1.
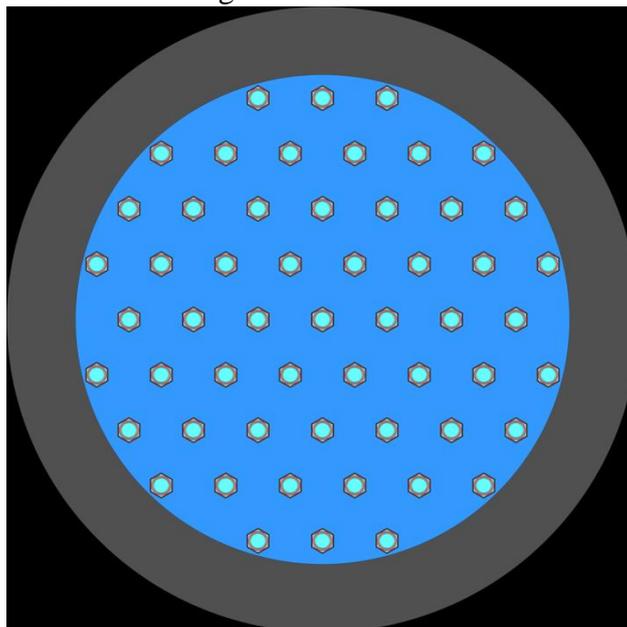

Figure 1. The schematic model of TEPLATOR reactor core – floor plan

2   FUEL DESIGN

It is not a new idea to use natural uranium as the fuel for a nuclear reactor. There were a few projects during development of a current reactor types with natural uranium as the fuel. The largest advantage of the fuel made of natural uranium is absence of enrichment and lower price. Natural uranium is relatively common element and fabrication of the fuel is relatively easy and cheap in comparison with the enriched uranium fuel. The MAGNOX [2] and the CANDU [3] reactors are the most known concepts operating with the fuel made of natural uranium and run with some modifications to present time. In the Czech Republic, there are also some experience with operation of heavy water reactors with fuel made of natural uranium. One unit of reactor KS-150 was operated in the former Czechoslovakia between 1972 and 1977. However, this concept did not survive to the present days because of construction features and accidents.

2.1   The material and geometry of natural uranium

First of all, it was necessary to choose a type of fuel and suitable geometry. Due to defined arrangements and a size of reactor core [1], there were only few possibilities of the fuel geometry design. Only two materials of the fuel were considered for these purposes – uranium dioxide (as in CANDU reactors) and metal uranium (as in MAGNOX and KS-150 reactors).

First approach was to use the VVER-440 [4] fuel assemblies with a natural enrichment, because the TEPLATOR DEMO is designed for this type of geometry. Unfortunately, this fuel geometry cannot be used, because the reactor did not reach criticality despite the full calandria of moderator. The next idea was to modify a CANDU fuel bundles and use its geometry. The fuel bundles were modelled as the 3.2 m long assembly with various diameter of the fuel pins. There were calculated three modifications with 7, 19 and 37 fuel pins per one assembly with UO_2 and metal uranium form. The diameter of these fuel pins was optimised to be 2 cm by a series of calculations. All three variants appeared more promising than VVER-440 geometry. The highest k_{eff} was obtained by using a metal uranium in all cases. The 19-pin fuel assembly was the best modification in terms of used amount of uranium and k_{eff}. This type is potentially applicable, nevertheless a few complications were found in deeply analysis. The main complication is the void coefficient during Loss of Coolant Accident (LOCA). It is highly improbable that LOCA will occur in all 55 fuel channels at the same time, however a single channel LOCA could be very serious situation as it is in CANDU [3]. The next disadvantage of this 19-pins CANDU geometry is swelling of metal uranium with an increasing burnup [5]. There is not so much space for material swelling in each pin, so the possibility of fission products leakage from the pins is not negligible. The last problem is a relatively high heat flux per square meter of the fuel pins in terms of thermohydraulic.

These all aspects led to creation of completely new fuel type geometry. It was concluded from all previous calculations that the largest fuel reactivity is when the fission material is placed as close as possible to the border of the cooling channel compared to placing a same amount of uranium to the channel centre. The question about the fuel pins swelling led to designing a different type of geometry. The heat flux per square meter was also considered. These investigation results led to the design of a tubular fuel. The tubular fuel geometry has not been used yet in any LWR power reactor type but is widely used in a research and experimental reactors [6]. This type of geometry has a lot of advantages. The fuel tube diameter can be adapted to the cooling channels, there is more space for potential fuel swelling and heat flux is sufficiently low for designed output power. In the Figure 2, there are a different existing fuel assemblies geometry which confirm that fabrication of the tube type of fuel is possible and technologically feasible.
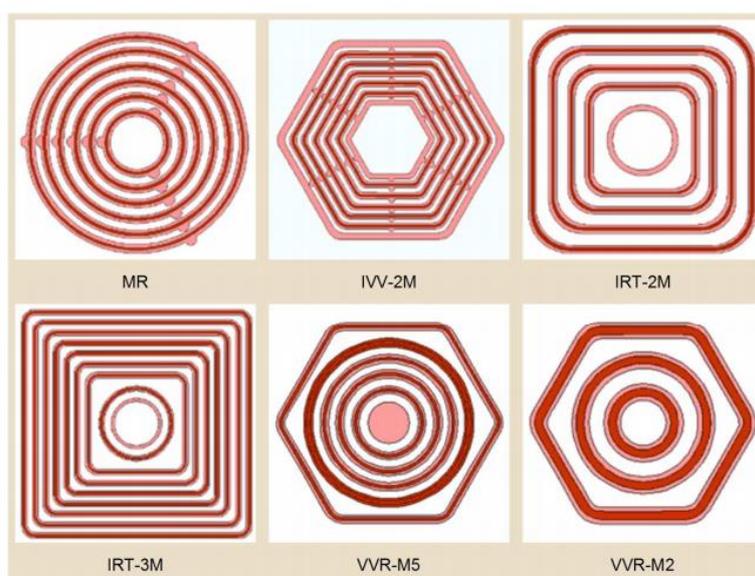

Figure 2. The different types of FA geometries for experimental reactors [8]

3   CALCULATIONS AND MODELING OF FUEL

All calculations of designed fuel parameters and whole reactor core were performed by using Serpent 2.1.30 code [7]. The whole 3D model of TEPLATOR respects all dimensions mentioned above. Each calculation was calculated with 1 000 active generations, 50 inactive generations and with 30 000 neutrons per one generation. All calculations were performed in ENDF/B-VII.1 nuclear data library. The number of neutrons is sufficient in this first design, the uncertainty of all calculations is between 8 to 15 pcm.

Following considerations mentioned above, the two different types of tubular fuel were recalculated - cylindrical and hexagonal tubes. Cylindrical tubes (CYL) were inspired by the MR fuel type [8], hexagonal tubes (HEX) by VVR-5M [8]. One, two and three concentric tube fuel arrangements for both types of fuel assemblies were evaluated– see the Figure 3. The modification with two or three tubes is necessary in terms of increasing a thermal power. The thickness of cladding was set to 1 mm, which is made of Zircaloy-4 [4]. The cladding material and its thickness should be subject of further investigation and optimization. The gap between the individual fuel tubes was set to 5 mm due to sufficient flow of cooling heavy water. For instance, the gap between the tubes in research reactor fuel assemblies IRT-4M is only 1.35 mm with two times higher heat flux per square meter [6]. The height of fuel assembly was set to 3.2 m, which is the optimal height between the upper and bottom graphite reflector. The outer diameter of fuel assembly was set to 7.1 cm in both cases. The designed cylindrical and hexagonal fuel assemblies are shown in the fuel channel in the Figure 3.
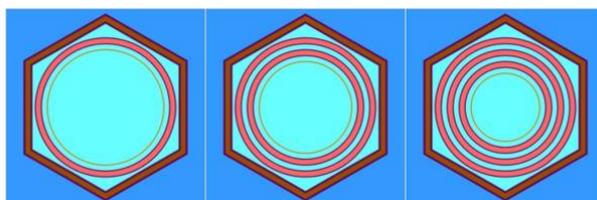
Cylindrical tubes with displacer – one, two and three tube modification
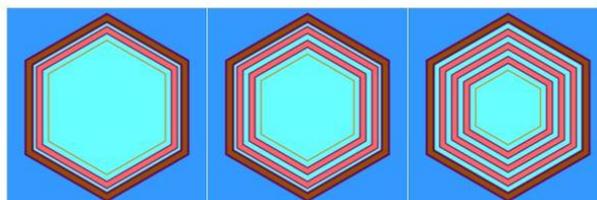
Hexagonal tubes with displacer – one, two and three tube modification

Figure 3. All calculated geometry fuel types for TEPLATOR

Then the fuel assemblies were gradually placed to cooling channels, the calandria was filled with heavy water and k_{eff} was calculated (see Figure 4). Various thicknesses of the fuel layer with 1 mm step for both fuel materials in each geometry modification (CYL and HEX) were evaluated. The thickness was set from 1 to 15 mm for metal uranium and from 1 to 10 mm for uranium oxide. The layer of UO_2 was conservatively set lower than the layer of uranium metal due to its lower thermal conductivity. Metal uranium has approximately six times higher thermal conductivity compared to uranium dioxide [9], so the thicker layers causes no problem. The calculations of k_{eff} determine the suitable thickness of uranium layer inside the tubes for all modifications with one, two and three-tubes. The highest k_{eff} are listed for all mentioned cases in the Table 1.
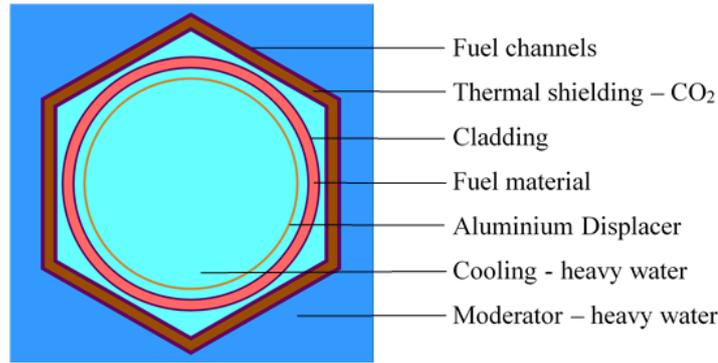
Figure 4. Description of the single tube fuel assembly – floor plan

4   CALCULATION RESULTS

It can be seen from Table 1 that the modification with hexagonal tubes reaches higher k_{eff} in all calculated cases. This is probably caused by a better geometry in fuel channel – there is a same amount of cooling heavy water in hexagonal tube in all directions of the fuel channel compared to over-moderated corner areas of the fuel channel with cylindrical fuel assembly. The metal uranium is clearly preferable than uranium oxide for one and two-tube assembly. The difference between used material is lower for three-tube assembly, nevertheless uranium metal is still better. For better imagination, it can be seen in the Figure 5 the dependence of k_{eff} on the fuel layer thickness.

Table 1: The highest achieved value of k_{eff} for all cylindrical and hexagonal tube modifications and the corresponding fuel thickness d for different fuel material

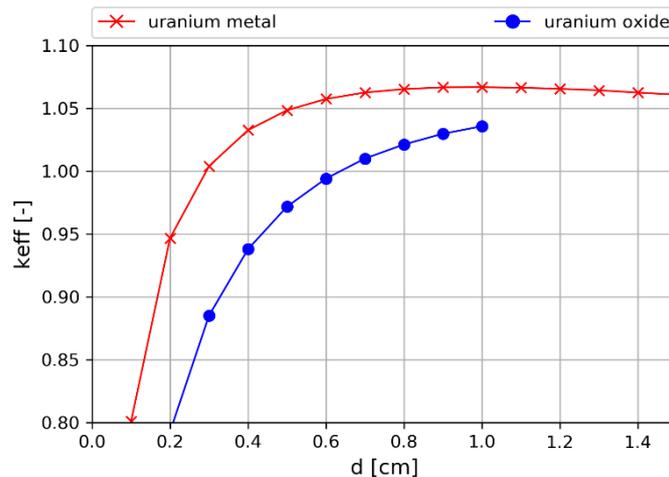| Modification	fuel type	d [cm]	k_{eff}	Modification	fuel type	d [cm]	k_{eff}
1 CYL tube	U metal	1.0	1.06619	1 HEX tube	U metal	1.0	1.06690
	UO_2	1.0	1.03038		UO_2	1.0	1.03578
2 CYL tube	U metal	0.6	1.04854	2 HEX tube	U metal	0.6	1.04888
	UO_2	1.0	1.03482		UO_2	1.0	1.03547
3 CYL tube	U metal	0.5	1.03568	3 HEX tube	U metal	0.5	1.03467
	UO_2	1.0	1.02940		UO_2	1.0	1.02959

Figure 5. The hexagonal tube fuel assembly - dependence of k_{eff} on the fuel layer thickness d for metal uranium and uranium oxide

A high attention was paid during calculations to the positive void reactivity coefficient and its overall suppression. One way how to significantly reduce a positive void reactivity coefficient of the coolant is placing a special coolant displacer in the centre of fuel assembly. This displacer was designed as special tube with a welded bottom. There is small drilled hole in the centre on the bottom of the displacer and the top of the displacer is open, see Figure 6 and Figure 4. The hole on the bottom of the displacer ensures at least a small flow of coolant trough displacer. It is necessary to ensure coolant flow due to neutron thermalization and gamma heating in area of displacer. The displacer significantly extends a time until the fuel channel is dried in case of single cooling channel LOCA, which greatly slows down a positive reactivity insertion. An emptying time depends on diameter of the drilled hole in the fuel plug and it should be further investigated after the exact thermohydraulic analysis.
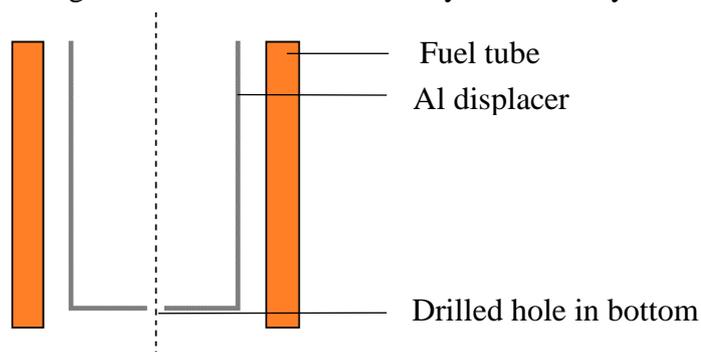

Figure 6. Schematic cut of the displacer

The shape of the displacer corresponds with the fuel assembly geometry, see Figure 3. This special displacer reduces void coefficient in all calculated cases and it has only a negligible effect on reactivity change. The displacer is composed of a 1 mm thick aluminium tube. The diameter of drilled hole on the bottom and thickness of the wall will be investigated in further research. The comparison of k_{eff} with or without displacer can be seen in Table 2.

Table 2: The comparison of k_{eff} in single cylindrical tube fuel assembly using displacer and without displacer, d - thickness of metal uranium layer

d [cm]	without displacer	with displacer	Δk_{eff} [pcm]
0.9	1.06871	1.06470	-401
1.0	1.06897	1.06619	-278
1.1	1.06850	1.06571	-279
1.2	1.06794	1.06541	-253

In Table 3, there is a comparison of reactivity insertion during LOCA accident with or without displacer in fuel assemblies for one-tube type of arrangements with the highest k_{eff}. For these purposes, LOCA was assumed in seven central channels in the same time.

Table 3: The comparison of k_{eff} in standard operation and during LOCA accident in seven central cooling channels after channel drying – cases with and without a displacer

Modification	d [cm]	without LOCA	LOCA - without displacer	LOCA - with displacer	Δk_{eff} [pcm]
1 CYL tube	1.0	1.06619	1.07473	1.06890	+583
1 HEX tube	1.0	1.06690	1.07757	1.07168	+589

It can be clearly recognized from the Table 3 that using a displacer is a very effective solution how to partially inhibit positive reactivity insertion during Loss of Coolant Accidents. An increase of reactivity is obvious in all geometry types during LOCA accident. However, the

reactivity insertion is suppressed and rapidly slowed down by using the displacer, for instance the time to full dry-out of the displacer is around 35 min with a hole 2 mm in diameter. The last column of the table shows a change of reactivity during LOCA between cases with the displacer and without the displacer. From this point of view, the cylindrical tube geometry seems better during this accident. Carried out analysis is very strict in terms of seven channels fault in centre of the core at the same time. This scenario is very unlikely and it belongs to the extended conditions of nuclear safety.

The final goal was verification of operation time of TEPLATOR at full output power with the new designed fuel from natural uranium. The highest k_{eff} is for the hexagonal geometry with the 1 cm thick fuel layer, which can be seen in Table 1. The cases with 0.9 cm thick layer and 1.1 cm thick layer reach almost the same k_{eff} so these three variants were considered to the following burnup calculations – differences between calculations were within 1σ interval. The comparison of the layers is in the Figure 7. It can be observed that the operation time is much higher for 1.1 cm thickness than for 1 cm thickness with the highest calculated k_{eff}. This phenomenon can be explained by the fact that there is more uranium in the reactor core for the case with the 1.1 cm layer compared to the 1 cm layer. The amount of uranium and operation time can be found for these three examined cases in Table 4.
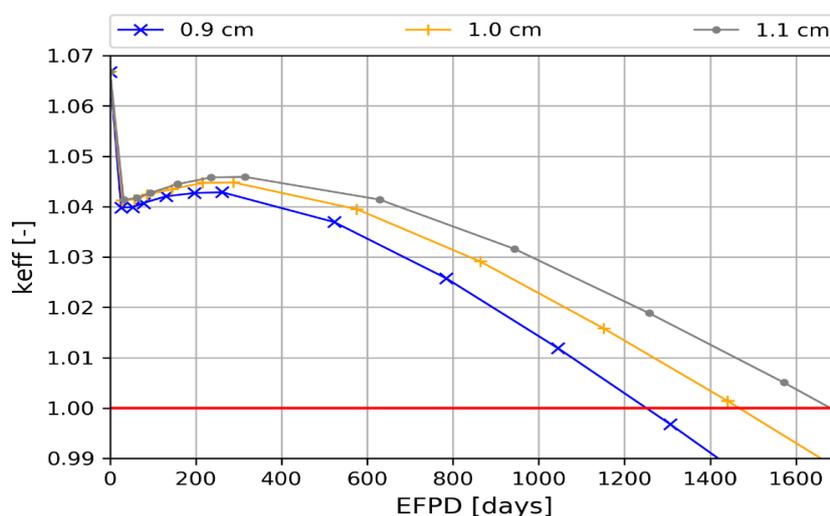

Figure 7. Influence of the fuel layer thickness on operation time, EFPD – Effective Full Power Day, BOC – Beginning of Cycle

Table 4: One hexagonal tube - three different fuel layer thickness *d*, k_{eff} on beginning of cycle, weight of uranium metal *m* and time of operation *EFPD*

d [cm]	BOC k_{eff} [-]	m U metal [kg]	EFPD [days]
0.9	1.06677	13066.2	1252
1.0	1.06682	14403.7	1468
1.1	1.06673	15718.4	1682

5 CONCLUSIONS

This article is focused on development of a fuel made of natural uranium for the new reactor concept - the TEPLATOR. The two fuel materials, uranium oxide and metal uranium, were tested in a few new geometry types of fuel. All the calculations were performed by the neutronics code Serpent. As the best geometry type was chosen tubular geometry and two types of tubes were examined – cylindrical and hexagonal. One, two and three-tube structure for each

type of geometry (cylindrical and hexagonal) were tested and the best thickness of the fuel layer were found for both mentioned fuel materials. The burnup calculations were carried out for the chosen thicknesses of the fuel layer and prove that the designed fuel can be operated for at least 5 heating seasons (10 months each). Optimization of the fuel quantity, operation time and the other aspect are now under investigation.

Finally, an unique structural element of the fuel, a special displacer, was proposed, designed and evaluated after a deep analysis of designed types of the fuel. This special displacer suppresses influence of the moderator positive void coefficient. This tool retains a significant amount of coolant for a certain time during leakage so it can be used as a mitigation of the Loss of Coolant Accident effect. The detailed construction and features of the displaced will be created in further research.

All results obtained in this article are part of the first investigation and further research of the fuel cladding thickness, material, fabrication of metal uranium layers, thermohydraulic analysis etc will be done. Burnup calculations and other results confirmed that there are several possibilities of fuel geometry, which can be used with natural uranium as the alternative fuel for the TEPLATOR.

ACKNOWLEDGMENTS

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